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Τόμος XLIII, *Νο* 2

BULLETIN OF THE GEOLOGICAL SOCIETY OF GREECE
Volume XLIII, *No* 2

ΕΙΚΟΝΑ ΕΞΩΦΥΛΛΟΥ - COVER PAGE

Γενική άποψη της γέφυρας Ρίου-Αντιρρίου. Οι πυλώνες της γέφυρας διασκοπήθηκαν γεωφυσικά με χρήση ηχοβολιστή πλευρικής σάρωσης (EG&G 4100P και EG&G 272TD) με σκοπό την αποτύπωση του πυθμένα στην περιοχή του έργου, όσο και των βάθρων των πυλώνων. (Εργαστήριο Θαλάσσιας Γεωλογίας & Φυσικής Ωκεανογραφίας, Πανεπιστήμιο Πατρών. Συλλογή και επεξεργασία: Δ.Χριστοδούλου, Η. Φακίρης).

General view of the Rion-Antirion bridge, from a marine geophysical survey conducted by side scan sonar (EG&G 4100P and EG&G 272TD) in order to map the seafloor at the site of the construction (pylons and piers) (Gallery of the Laboratory of Marine Geology and Physical Oceanography, University of Patras. Data acquisition and Processing: D. Christodoulou, E. Fakiris).

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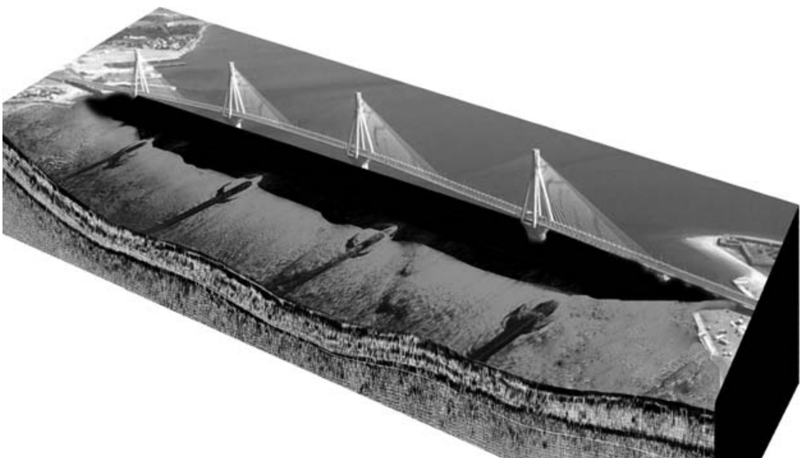
Geological Processes and Sustainable Development



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Geological Processes and Sustainable Development

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ΠΡΟΛΟΓΟΣ

Η Γη είναι ένας πλανήτης με συνεχή και δυναμική εξέλιξη στην ιστορία του. Η γνώση και κατανόηση από τον άνθρωπο της εξέλιξης αυτής είναι μεγάλης σημασίας για τον εντοπισμό, την εκμετάλλευση και τη χρήση των φυσικών πόρων, καθώς και για την ανάδειξη και αντιμετώπιση των περιβαλλοντικών προκλήσεων-προβλημάτων από τη χρήση των πόρων αυτών.

Η περιβαλλοντική αυτή διάσταση απαιτεί μια ολοκληρωμένη, πολυ-επιστημονική θεώρηση του Πλανήτη, που θα περιλαμβάνει τη μελέτη όλων των παραγόντων, όπως της λιθόσφαιρας, της υδρόσφαιρας, της ατμόσφαιρας και της βιόσφαιρας, οι οποίοι συνδέονται μεταξύ τους σε πολύ σημαντικά συστήματα. Τα συστήματα αυτά απαιτούν τη συνεργασία, χωρίς σύνορα και περιορισμούς, των φυσικών επιστημών, όπως η Γεωλογία, η Βιολογία, η Χημεία και η Φυσική. Έτσι μόνο θα κατανοήσουμε τον Πλανήτη μας, θα αναδείξουμε τα περιβαλλοντικά προβλήματα και θα δημιουργήσουμε ενημερωμένες-ευαισθητοποιημένες κοινωνίες, οι οποίες θα μπορούν να αποφασίσουν για το παρόν και το μέλλον του.

Σήμερα είναι γεγονός ότι υπάρχει μια εμπεριστατωμένη άποψη σχετικά με την εξελικτική πορεία της Γης στη διάρκεια των 4,6 δισεκατομμυρίων ετών της ύπαρξής της. Παράλληλα αποτελεί κοινή συνείδηση ότι η ισορροπία του πλανήτη από την καθημερινή πίεση των έξι (6) περίπου δισεκατομμυρίων ανθρώπων που φιλοξενούνται σε αυτόν, είναι πλέον εύθραυστη. Ειδικότερα όσον αφορά στις Γεωεπιστήμες, υπάρχει σοβαρή γνώση σχετικά με τις **Γεωλογικές Διεργασίες**, που έχουν λάβει χώρα στα πλαίσια της ιστορίας αυτής με τη δημιουργία των ορέων και των ωκεανών, τους σεισμούς, την ηφαιστειακή δραστηριότητα, καθώς και την εκδήλωση εξωγενών φαινομένων, όπως οι κατολισθήσεις, οι πλημμύρες, οι ξηρασίες, τα τσουνάμι.

Όσον αφορά στη **Βιώσιμη Ανάπτυξη**, είναι γνωστό ότι τις τελευταίες δεκαετίες η τεχνολογική εξέλιξη και η πληθυσμιακή έκρηξη επέβαλαν μια αλόγιστη και χωρίς σχεδιασμό υπερεκμετάλλευση των φυσικών πόρων, με αποτέλεσμα την υποβάθμιση του περιβάλλοντος για πρώτη φορά στην ιστορία του Πλανήτη μας.

Έτσι, μερικά από τα ερωτήματα που τίθενται επιτακτικά και αναμένουν απαντήσεις από την επιστημονική κοινότητα, δεδομένου ότι εκφράζουν την αγωνία όλης της ανθρωπότητας, είναι τα εξής: α) Οι ανθρώπινες δραστηριότητες έχουν προκαλέσει πράγματι επικίνδυνες τροποποιήσεις του περιβάλλοντος και μάλιστα μη αναστρέψιμες ή οι κλιματικές μεταβολές που παρατηρούνται σήμερα αποτελούν φυσικές διακυμάνσεις; β) Ειδικότερα η βιομηχανική ανάπτυξη και η υπερκατανάλωση ενεργειακών πρώτων υλών αποτελούν κίνδυνο για το περιβάλλον ή θεωρούνται μηδαμινής επίδρασης σε σχέση με τις ηφαιστειακές εκρήξεις και τις αλλαγές των ρευμάτων στους ωκεανούς, οι οποίες προκαλούν δραματικές αλλαγές στο περιβάλλον;

γ) Είναι ακόμα δυνατή μια Βιώσιμη Ανάπτυξη και εάν ναι, ποιο είναι το είδος αυτής στα όρια αντοχής και αποδοχής του πλανήτη μας;

Στα παραπάνω ερωτήματα και προβληματισμούς η επιστήμη της Γεωλογίας έχει να προσφέρει πολλά, δεδομένου ότι οι φυσικές διεργασίες κατά τη διάρκεια της εξέλιξης της Γης έχουν καταγραφεί στους εδαφικούς και βραχώδεις γεωλογικούς σχηματισμούς, χωρίς επηρεασμούς από τις παρεμβάσεις του ανθρώπου. Έτσι οι ανθρώπινες παρεμβάσεις της σύγχρονης εποχής μπορούν να διαχωριστούν και να επισημανθούν, ώστε να αντιμετωπιστούν σωστά. Γενικότερα, η γνώση και κατανόηση της εξέλιξης της Γης μέσα από τις φυσικές διεργασίες μπορούν να συμβάλουν στην αποτύπωση των ρυθμών αλλαγής της Γης στο γεωλογικό χρόνο. Επιπλέον οι ρυθμοί αλλαγής και οι διεργασίες, που είναι υπεύθυνες για αυτούς, μπορούν παράλληλα να αποτελούν δείκτες πρόγνωσης για την πορεία του πλανήτη στο μέλλον. Με άλλα λόγια, το παρελθόν και γενικότερα η γεωλογική ιστορία του Πλανήτη μπορεί να αποτελέσει το «κλειδί» για το παρόν και το μέλλον αυτού.

Συμπερασματικά, η συμβολή της Γεωλογίας και γενικότερα των Φυσικών Επιστημών στην κοινωνία μας είναι πολύ σημαντική για τη γνώση της εξέλιξης της Γης, την έρευνα και αξιολόγηση των φυσικών πόρων, την εκτίμηση των περιβαλλοντικών επιπτώσεων λόγω εκμετάλλευσης των πόρων αυτών, καθώς και την πρόγνωση-αντιμετώπιση των διάφορων φυσικών επικινδυνοτήτων από γεωλογικές διεργασίες και καταστροφικά καιρικά φαινόμενα.

Το 12ο Διεθνές Συνέδριο της Ελληνικής Γεωλογικής Εταιρίας με τίτλο **«Πλανήτης Γη: Γεωλογικές Διεργασίες και Βιώσιμη Ανάπτυξη»** διοργανώνεται από το Τμήμα Γεωλογίας του Πανεπιστημίου Πατρών και πραγματοποιείται στο Συνεδριακό και Πολιτιστικό Κέντρο του Πανεπιστημίου από τις 19 έως 22 Μαΐου 2010. Το Δελτίο της Ελληνικής Γεωλογικής Εταιρίας περιλαμβάνει τα Πρακτικά του Συνεδρίου σε πέντε (5) τόμους των 2.992 σελίδων συνολικά. Οι τόμοι αυτοί καλύπτουν όλο το φάσμα των Γεωεπιστημών σε θέματα της βασικής και εφαρμοσμένης έρευνας. Στα πρακτικά περιλαμβάνονται 267 συνολικά εργασίες από 605 συγγραφείς, όλες στην Αγγλική γλώσσα, δίνοντας έτσι τη δυνατότητα διεθνούς προβολής και χρήσης του επιστημονικού Δελτίου της Εταιρίας. Οι επίσημες γλώσσες του Συνεδρίου είναι η Ελληνική και η Αγγλική.

Στο Συνέδριο υπάρχει σημαντικός αριθμός εργασιών από τον ευρύτερο γεωγραφικό μας χώρο, έχουν δε δηλώσει συμμετοχή πολλοί αξιόλογοι επιστήμονες από την Ελλάδα και το εξωτερικό, καθώς και νέοι ερευνητές και φοιτητές.

Όλες οι εργασίες που δημοσιεύονται, υπεβλήθησαν σε επιστημονική κρίση από εξωτερικούς κριτές, ακολουθώντας τη διαδικασία που είναι διεθνώς καθιερωμένη στα επιστημονικά περιοδικά. Πολλοί αναγνωρισμένοι επιστήμονες, Έλληνες και ξένοι, όλων των ειδικοτήτων, συμμετείχαν στη διαδικασία αυτή. Εκ μέρους της Οργανωτικής Επιτροπής τους ευχαριστώ για τη συμμετοχή και τη συμβολή τους με το σοβαρό έργο που προσέφεραν στην απόκτηση Πρακτικών υψηλού επιπέδου.

Οι επιστημονικές εργασίες εντάχθηκαν σε επιμέρους θεματικές ενότητες, στις οποίες διαχωρίστηκαν τα Πρακτικά και αποτέλεσαν αντικείμενο στις αντίστοιχες Συνεδρίες. Τα κείμενα των ειδικών και προσκεκλημένων ομιλιών, που καλύπτουν το ευρύτερο αντικείμενο της κάθε ενότητας και παρουσιάζουν υψηλού επιπέδου θεώρηση σχετικά με την υφιστάμενη γνώση, τις νέες απόψεις και τάσεις της έρευνας, αποτέλεσαν ιδιαίτερη ενότητα.

Στο Συνέδριο αυτό δίνεται ιδιαίτερη έμφαση στις Γεωλογικές Διεργασίες και τη Βιώσιμη Ανάπτυξη. Όπως αναφέρθηκε διεξοδικά παραπάνω, η κατανόηση της εξέλιξης του πλανήτη Γη μέσα από τις γεωλογικές διεργασίες επιτρέπει στον άνθρωπο να αξιολογήσει τις διάφορες δραστηριότητές του, όπως την αναζήτηση, εκμετάλλευση και χρήση των φυσικών πόρων, καθώς και την κατασκευή διαφόρων έργων υποδομής, χωρίς να προκαλεί επικίνδυνες μεταβολές στο φυσικό και το ανθρωπογενές περιβάλλον. Έτσι μόνο μπορεί να εξασφαλιστεί η Βιώσιμη Ανάπτυξη και να προβλεφθεί η πορεία του Πλανήτη.

Η έγκαιρη εκτύπωση και παράδοση των τόμων του Συνεδρίου στους συνέδρους και στην επιστημονική κοινότητα, καθώς και η γενικότερη οργάνωση του Συνεδρίου γίνεται με την οικονομική στήριξη πολλών φορέων, δημόσιων και ιδιωτικών. Εκφράζονται θερμές ευχαριστίες στο Υπουργείο Περιβάλλοντος, Ενέργειας και Κλιματικής Αλλαγής, που έθεσε το Συνέδριο υπό την αιγίδα του, καθώς και στο Τμήμα Γεωλογίας του Πανεπιστημίου Πατρών, το Ι.Γ.Μ.Ε., και το ΓΕΩΤ.Ε.Ε. Θερμές ευχαριστίες εκφράζονται επίσης στο Κοινωφελές Ίδρυμα Ιωάννη Σ. Λάτση, το Πανεπιστήμιο Πατρών, αλλά και σε ιδιωτικές Τεχνικές και Μελετητικές Εταιρίες, που με τόση προθυμία ανταποκρίθηκαν στην πρόσκλησή μας.

Τέλος, θα ήθελα να εκφράσω τις προσωπικές μου ευχαριστίες στους συναδέλφους της Οργανωτικής Επιτροπής για την αμέριστη βοήθειά τους και την άριστη συνεργασία στη συλλογική αυτή προσπάθεια, καθώς και στο Γραφείο Οργάνωσης Συνεδρίων *«Συνέδρα»*, όπως επίσης στους φοιτητές του Τμήματος Γεωλογίας, που αγκάλιασαν και βοήθησαν στην οργάνωση του Συνεδρίου με απαράμιλλο ζήλο.

Πάτρα, 14 Απριλίου 2010

Γεώργιος Χρ. Κούκης
Πρόεδρος
της Οργανωτικής Επιτροπής

PROLOGUE

Earth is a dynamic Planet that has been continuously changing and evolving throughout its whole history. Knowledge and understanding of the evolution processes is of crucial importance not only to explore and take advantage of the natural recourses that our planet provides, but also to access the degree of environmental impacts that the exploitation of these causes.

This environmental aspect demands to consider a comprehensive and multi-scientific view of our Planet, which involves the study of lithosphere, hydrosphere, biosphere and atmosphere. All the above are closely connected together to form very important and complex natural systems, which need the close cooperation of all sciences involved, such as Geology, Biology, Chemistry and Physics. This is the most effective way to understand our Planet, to consider the environmental problems and enforce societies to become informed and conscious of its present and future.

Nowadays an almost complete and comprehensive knowledge about the evolution of Earth during the 4.6 billion years of its age has been gained. In parallel, it is common sense that our Planet's equilibrium is fragile due to environmental pressures that human causes, since Earth's population exceeds 6 billion people.

In the field of Geo-Sciences, in special, there has been gained sufficient experience about the **Geological Processes** that have been taken place during Earth's history and are evident in the formation of mountains and oceans, by the manifestation of earthquakes, by volcanic activity, as well as in natural phenomena as landslides, floods, droughts and tsunamis.

Concerning **Sustainable Development**, it is well known that during the last decades technological evolution and population growth have imposed an unreasonable and sometimes without design overconsumption of natural resources, which leads to gradual degradation of the environment for the first time in our Planet's history.

Thus, some of the "hot" questions that have been arisen and need to be answered by the Scientific Community, since they express the concern of the whole humanity, are: a) Human activities have indeed caused dangerous and non-reversible modifications of the environment or present climatic changes are a result of normal and natural fluctuations? b) Industrial development and overconsumption of natural recourses are a "red flag" for the environment or they can be considered as of minor effect when compared with volcanic eruptions and changes in the regime of ocean current circulation, which cause dramatic environmental changes? c) Is Sustainable Development still achievable and, if yes, in which form and within our Planet's bearing thresholds?

In the above questions Scientific Community can offer a lot, regarding that natural processes during Earth's evolution have been imprinted on soil and rock geological formations, without any influence by human activities. Present human actions can be clearly distinguished and identified in order to be treated in the right way. The deep knowledge and understanding of Earth's evolution though natural processes can contribute to imprint the rates of Earth's changes through geological time. The changing rates and the processes responsible for them also contribute to obtain indices to predict similar phenomena for the future. In other words the Past and, generally, the geological history of our Planet is the "key" for the Present and Future.

In conclusion, the contribution of Geology and generally of Natural Sciences in our society is very important to understand Earth's evolution, to assist the research and assessment of natural resources, as well as to estimate the environmental impacts from their exploitation. Furthermore, they can provide solutions to the direction of the prevention and confrontation of natural hazards that are triggered by Geological Processes and catastrophic climatic events.

The 12th International Congress of the Geological Society of Greece entitled **"Planet Earth: Geological Processes & Sustainable Development"** is organized by the Department of Geology of the University of Patras in Greece and is held at the Conference and Cultural Center of the University between the 19th and 22nd of May 2010. The *Bulletin of the Geological Society of Greece* includes the Congress's Proceedings in 5 Volumes of 2.992 pages. These volumes cover the whole spectrum of Geo-Sciences in themes of basic and applied research. They include 267 research papers by 605 authors, all written in English making them easily accessible and promoted internationally. Official languages of the Congress are Greek and English. Many renowned scientists from Greece and abroad participate, covering scientific issues from our broad geographic region, as well as new researchers and students.

All submitted papers were reviewed by external reviewers, following the procedure that is established in scientific magazines. Many renowned scientists, Greek and foreigners, of all specialties, participated in this process. On behalf of the Organizing Committee I would like to thank them for their participation and contribution to acquire Proceedings of high quality.

The research papers were included in specific thematic units to which the Proceedings were divided and covered each Congress's session. Special and Keynote lectures about currently acquired knowledge, new insights and modern research trends for each area of interest comprised a special thematic unit.

This Congress focuses on Geological Processes and Sustainable Development. As it was mentioned above, the understanding of Earth's evolution though geological processes allows human to assess his activities, such as investigation and exploitation of natural resources and construction of Infrastructure Works, without causing serious and dangerous damages to the natural and human environment. This is the only way to secure sustainable development and forecast Earth's future.

The on-time production and delivering of the proceedings to the participants and scientific community, as well as the organization of the Congress is sponsored by many public and private Organizations, Services and Companies. I would like to express my special thanks to the Ministry of Environment, Energy and Climate Change, which held the Congress under its aegis, as well as to the Department of Geology of the University of Patras, the Institute of Geology and Mineral Exploration (I.G.M.E.) and the Geotechnical Chamber of Greece for their contribution to organize this Congress. Special thanks are also expressed to the Public Benefit Foundation "John S. Latsis", to the University of Patras and to many private technical and consulting companies which willingly accepted our invitation.

Finally, I would like to personally thank the colleagues of the Organizing Committee for their generous help, support and cooperation to this teamwork, the Congress Organizing firm "*Synedra*", as well as the students of the Department of Geology for their precious contribution.

Patras, 14 of April 2010

George Ch. Koukis
President
of the Organizing Committee

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THE OLVIOS, RETHIS AND INACHOS DRAINAGE SYSTEM EVOLUTION AND HUMAN ACTIVITIES INFLUNCE OF THEIR FUTURE EVOLUTION

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Abstract

Olvios, Rethis and Inachos Rivers are multistory drainage systems that occur in Northern Peloponnesus, and at the present day they have and a reversed, North to South, flow element. Dervenios, Skoupeikos and Fonissa Rivers are the misfit streams of Olvios and revealed as juvenile streams and discharge to the Corinth gulf. Agiorgitikos River is the misfit stream of Rethis River and Seliandros River is the juvenile stream. Asopos, Nemeas and Rachiani Rives are the misfit streams of Inachos River and they also discharge to the Corinth gulf. Asopos River characterized as re-established stream. Physical factors such as tectonic regime (active and inactive faults), lithology, erosion and distance from the source influenced the three drainage systems evolution and could be influence them also in the future. The increase of human activities both in their southern parts and in the distal parts close to the coast could be change the physical evolution of the studied drainages, producing a new wind gap in the coastal area and a lake or a lagoon backwards of the coastal area, destroying villages and towns.

Key words: *wind gap, multistory, reverse, misfit, human activities.*

1. Introduction

North Peloponnesus composes an area that liables to extensive uplift movements during the Quaternary period (Bousquet et al., 1977; Armijo et al., 1996). The dominant structure that affects North Peloponnesus as well as the study area is the Corinth graben.

Intrabasinal basement highs and transfer faults in a distance from the source area, and the underlying geology influence the drainage pattern and the evolution of the 3 drainage basins in the northern Peloponnesus. The river drainages of North Peloponnesus were classified according to Seger and Alexander (1993) while this classification was modified by Zelilidis (2000). We classified the drainage systems as multistory, re-established, and juvenile drainage patterns according to Zelilidis (2000) modified types.

A multistory drainage type consists of both re-established and reverse drainage. Reversed drainage is when the flow direction along a part of a river is reversed, caused by tectonic deformation of the river-bed. This consists of two opposing drainage components: a misfit and a reversed element; the area between these two elements that is the result tectonic deformation, is termed a “wind gap”, is

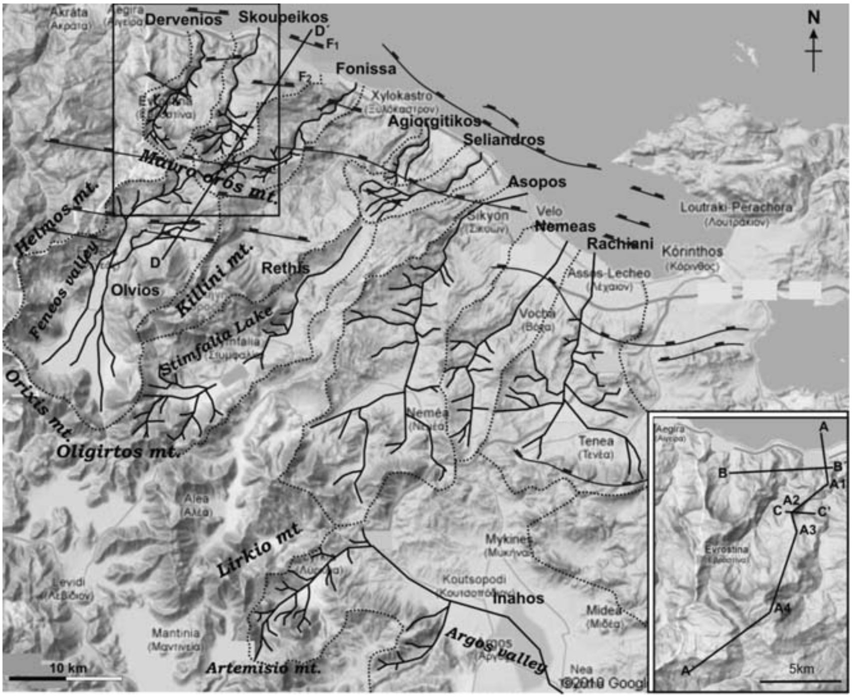

Fig. 1: Topographic map showing the three studied drainage systems with their individual river drainages and main tectonic structures that influence drainage evolution. The topographic relief based on Google map.

a dry valley. An antecedent drainage is when a river has maintained its course an area of the crust that was raised across its path by folding or faulting. A re-established drainage is when a reverse drainage establishes again its initial flow. Juvenile drainage basins consist of small incising and headward-eroding streams.

The aim of the present study is to present the evolutionary potential models of the above drainage networks (Olvios, Rethis and Inachos), based in the existence tectonic regime and the humanities interventions (Fig. 1, 3). For the accomplishment of the study structural, sedimentary and geomorphologic data were used. Topographic sections were constructed along lines parallel and perpendicular to the drainage networks (Fig. 2). The uplift and erosion rates of the study area were also calculated (Fig. 4). At the same time, the human activities and their consequences were also assessed in the aforementioned drainage systems. Eventually, a predictable evolution model of the drainage networks was created, exclusively depending on human act in the coastal zone of the studied area.

2. Geological setting

The Corinth graben is 100km long and 40km wide, and characterized an area of rapid subsidence that separates continental Greece from Peloponnesus. According to Poulimenos et al., (1989), Doutsos & Piper (1990) and Poulimenos (1993), WNW – trend listric faults are the major faults that influence the basin evolution, forming asymmetric grabens. Due to the (synthetic or counter) major faults that deep northwards, several tilted blocks dipping southwards were formed and a wedge – shaped terrigenous clastic sequence accumulated during tilting. Many major faults are accompanied by one to three minor faults that deep southwards, called “backward” or “antithetic faults”, showing smaller displacement, which tend to reduce the structural relief. Numerous WNW – trending master faults terminate abruptly at NNE – trending “cross – faults” or “transfer” faults. The synchronous activity of master (synthetic), minor (antithetic) and cross – faults (transfer) influenced the basin configuration and the depositional environments. As a result, several small sub – basins were formed at the southern margins of the Corinth graben (Poulimenos, 1993; Zelilidis & Kontopoulos, 1996) such as Egio and Kalavryta sub – basins (IGME, 1969, 1970, 1973, 1975).

During the Late Pliocene, the marine Corinth graben was almost twice the width of the modern Gulf of Corinth. Subsequently, the tectonic activity in northern Peloponnesus migrated basinwards, (northwards) with uplift and back-tilting of the footwall of active faults (Poulimenos, 1993). Tectonic activity seems to be stronger at the western parts of the Corinth basins than in the eastern parts.

Olvios River is located at the north of Peloponnesus, especially in the western margins of the Corinth district (Fig. 1). It is bounded from Mavro Mountain in the north, Oligirtos and Orixis Mountains in the south, Kyllini Mountain in the east and Helmos Mountain in the west. It runs through the Feneos valley and ends in the Corinth Gulf with a misfit element and two juvenile rivers. Olvios River flows from north to the south and in relation with the fact that the drainage basin is closed, the drainage is underground through three catavothres which occur in the southern part of the Feneos polje. Dervenios and Skoupeikos are the juvenile rivers and Fonissa is the misfit river. These flow in a direction opposite to the Olvios River flow and their drainages basins are smaller in relation to Olvios River drainage (Tab. 1)(Fig. 1). The three rivers flow into the south coast of the Corinth gulf and have developed in their river mouths small fan deltas (Gaki-Papanastasiou et al., 2006).

Rethis River is located eastern to Olvios River at the north Peloponnesus (Fig. 1). The modern Rethis River consists of a reverse element discharging into Stymfalia Lake, with a north to south direction flow, a misfit element Agiorgitikos and a juvenile Seliandros, which discharge into the Corinth gulf with an opposite in relation to Rethis river flow (Tab. 1)(Fig. 1).

Inachos River is located eastern to Olvios and Rethis rivers in the northern Peloponnesus (Fig. 1). The present Inachos consists of a reverse element, that springs from Artemisio Mountain (Malevo), runs through the Argos valley and ends in the Argolikos gulf, of a re-established river Asopos, a misfit river Nemeas and of a juvenile river Rachiani, discharging into the Corinth gulf (Tab. 1)(Fig. 1).

Table 1. The three studied drainage classification with wind-gap lithology.

RIVER DRAINAGE CLASSIFICATION						
MULTISTORY	REVERSE	ANTECEDENT	MISFIT	JUVENILE	RE-ESTABLISHED	WIND GAP - LITHOLOGY
Rethis	Rethis		Agiorgitikos	Seliandros		1st conglomerates 2nd lacustrine marls 3rd marine terraces
Olvios	Olvios		Fonissa	Skoupeikos Dervenios		1st cohesive conglomerates 2nd cohesive conglomerates
Inachos		Inachos	Nemeas	Rachiani	Asopos	1st cohesive conglomerates 2nd cohesive conglomerates

3. Methods

In order to estimate the future evolution of the three drainage basins and the southeast coastal zone of Corinth gulf, erosion, sedimentation and uplift rates were measured. For succeeding this, topographic sections were constructed along and across of the streambed (e.g. cross-cuts for Olvios drainage in Fig. 2). The geomorphology and lithology of the region were studied and the angle of slope as well, to estimate erosion rates.

Finally, the major faults were traced and the uplift rates were estimated of the extensive Central – North Peloponnesus area, in order to find the erosion – uplift ratio and moved on to the construction of the evolution models of the drainage networks (Fig. 3).

In order to estimate the erosion rate, we used the difference of the altitude between the uplifted areas (higher altitude) and the river banks (lower altitude) (geological maps IGME 1969, 1970, 1973, 1975), taking into account the knowledge of rivers age development (Fig. 2). The estimated erosion rates, which range from 0,027 to 2,4mm/year, and the presence of a wide area on which the produced sediments move, led us to accept that sedimentation rate is practically insignificant.

4. Paleogeographical evolution of drainage networks

Olvios, Rethis and Inachos River hydrographic networks were classified as multistory drainage with a dendritic distribution (Fig. 1). It is obvious, they indicate that the current flow is reversed compared to the initial flow. Their initial flow was northwards with an antecedent character. This northern flow changed due to the presence of three wind gaps, situated within the Plio – Pleistocene formations, at the northern ends of the Olvios, Rethis and Inachos basins, and could be related with Fonissa, Skoupeikos, Dervenios basins, with Agiorgitikos, Seliandros basins, and with Asopos, Nemeas, Rachiani basins, respectively (Tab. 1) (Zelilidis, 2000; Gaki-Papanastasiou et al., 2006).

These wind gaps indicate that the Olvios, Rethis, Inachos upstreams initially flowed in the present Fonissa, Agiorgitikos and Nemea Rivers, respectively. These last Rivers change to misfit elements in the new reverse drainages during this time period.

Especially, Olvios River comprised an antecedent river, during the Upper Pliocene. Its river mouth were placed over 20km southern than the present coastline of the Corinth gulf (Fig. 3). Later, during the Middle – Upper Pleistocene comprised an integrated drainage network primary with Fonissa River, later with Skoupeikos River and then with Dervenios River.

The Olvios River displacement to the north – northwest is attributed to the gradual and in large uplift rates of the eastern part of studied area, probably due to the effect of the Xylocastro fault that passes through the northern part of the area and presents large action to the east. The modern Olvios River is located in the southern part of the Olvios hydrographic network. During Plio-Pleistocene period Dervenios, Skoupeikos and Fonissa networks did not exist. The Olvios network flowed to the north in the old shaped Corinth gulf (Figs. 1,3)(Gaki-Papanastasiou et al., 2006).

Due to the uplift of Northern Peloponnesus, the Corinth coastline was migrated northern and then followed the elongation of the hydrographic network. The high uplift rates exceed the Olvios River ability to erode vertically upstream during the Upper Pleistocene. So, the initial stream course was destroyed and a reversal flow is produced to the south, forming an internal – close drainage basin. This basin was developed in a closed carstic cavity (Feneos polje). During the continual evolution of the downriver of Olvios, owed to the uplift of North Peloponnesus, and the consequent elongation – extension of the hydrographic network in the north in the floated continent, the hydrographic

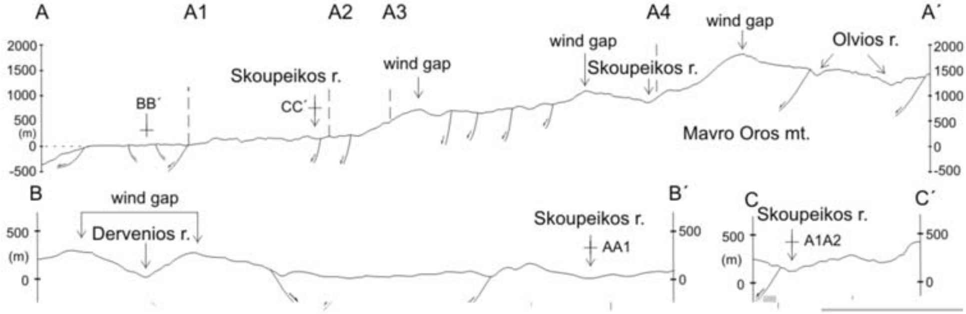

Fig. 2: AA' cross-section along Olvios-Skoupeiko rivers, whereas BB' and CC' are perpendicular to AA' (for details see Fig. 1)(I.G.M.E., 1973, Dervenion Sheet).

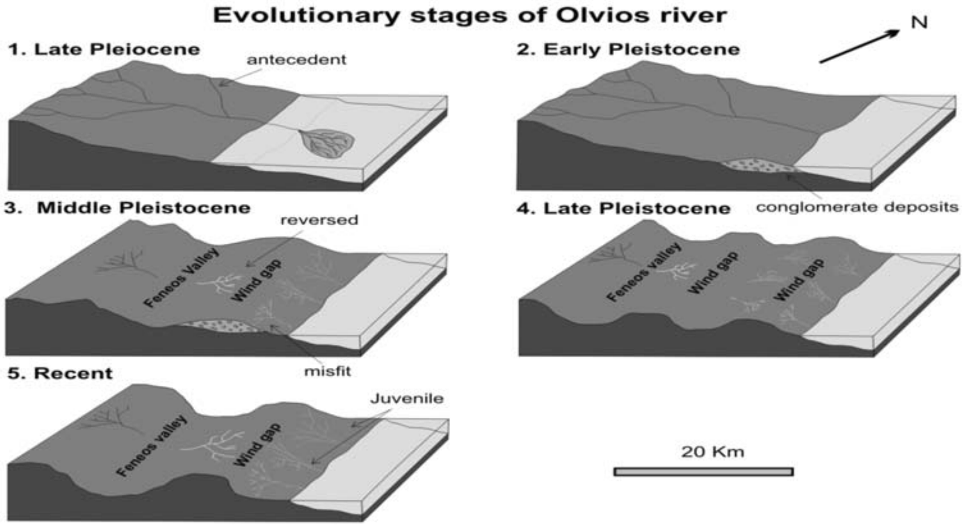

Fig. 3: Multistory drainage evolution models.

networks of Fonissa, Skoupeiko and Dervenio were configured (Fig. 3).

The Rethis River changed to a reverse drainage during Middle Pleistocene (Doutsos & Piper, 1990) and Agiorgitikos was the misfit element. Later, during Late Pleistocene Agiorgitikos River changed again to a reverse drainage system. The reverse element was restricted between the two wind gap areas which were created due to these two successive reverse drainage stages. Human activities (an underground channel) joined the old and the new reverse elements forming the modern Rethis River. During the second reverse drainage evolution Seliandros was developed as a juvenile river. As the tectonic activity migrated basinwards (Corinth gulf), Agiorgitikos and Seliandros changed to reverse drainages, with backtilting of marine terraces, and then returned again to their original flow (northwards) to the Corinth gulf, forming re-established drainages (Zelilidis, 2000).

The Inachos River was poured in its first stages at Corinth gulf. The activity of synthetic and antithetic faults produced a wind gap area, which changed Inachos River to a reverse drainage. Due to this drainage evolution Rachiani and Asopos Rivers were developed as juvenile streams and Nemeas River was the misfit element. As the tectonic activity migrated northwards a second wind gap area was formed. This wind gap area was changed only the Asopos River to a reverse drainage. Later the Asopos River returned to its original flow by eroding the wind gap area, forming a re-established drainage.

Figure 3 is an example from Olvios river drainage and presents the evolutionary stages through the time, of the hydrographic networks from Upper Pliocene till now. The Corinth coastline has approximately plotted, by taking into consideration the present Plio – Pleistocene conglomerates margin, the upper deposits of fans deltas with the Pre-Neogene formations.

5. Discussion and Results

The flow direction of Olvios, Rethis and Inachos multistory drainages and the outcrops aligned in a NNE direction. Synthetic and antithetic faults form intrabasinal highs, while the tectonic activity migrates to the north. The uplift rate in the central part of the Corinth basin is 1,5mm/year (Doutsos & Piper, 1990), which contributes to the intense relief of the adjacent regions. The approximate rate of erosion of the area between the river valley and the adjoining regions about the complex flow systems fluctuates from 0,8 to 1,2mm/year (Zelilidis, 2000).

Generally, the present Olvios river system comprises the area of Feneos Valley, which consists of Pre-Neogene basement, and occurs in altitudes 700 up to 1700m. Additional, the Fonissa, Dervenios and Skoupeikos River drainages, occupy the region from Mauro Mountain up to the coastline of the Corinth gulf and where Plio – Quaternary sediments were accumulated.

Olvios River is evolved in a wide basin which is affected from WNW-directed listric faults, which led to its widening and deepening. The Feneos basin has filled with Plio – Pleistocene sediments, mainly conglomerates, marls, sandy marls and sandstones.

Olvios river in order to recapture its original flow must cover the altitude difference between the lowest point of Feneos valley and the lowest point of wind gap, which is 700m. Based on the measured erosion rate which is over 0,4mm/year and with the assumption that tectonic uplift and sedimentation are zero factors, as the Mauro Mountain area and the Feneos valley were totally uplifted on 1,5mm/year (Doutsos & Piper, 1990) and sedimentation is spread in a large area, Olvios River will approach the wind gap and recapture its first northwards flow in 1.750.000 years (Fig. 4).

Rethis river must cover the altitude difference of the lowest point of Stymfalia Lake and the lowest point of wind gap, which is 230m. Based on the measured erosion rate which is over 0,15mm/year, Rethis River can recapture its first flow direction after 1.533.000 years (Fig. 4).

Inachos River must cover the altitude difference of the lowest point of Lyrkio valley and the lowest point of wind gap, which is 600m. Based on the calculated erosion rate which is over 1,6mm/year can be estimated in what time Inachos River can recapture its first flow direction. Consequently, Inachos River will approach the wind gap and recapture its first northwards flow in 108.750 years (Fig. 4).

From the previous measurements we could conclude that Olvios, Rethis and Inachos rivers are impossible to change naturally due to:

The existent tectonic conditions: The general tectonic of the wider region that is migrated northwards shows a relatively high rate of uplift which have estimated at 1,5mm/year. This suggests the presence of an active tectonic regime. The absence of transfer faults in the region behind the first

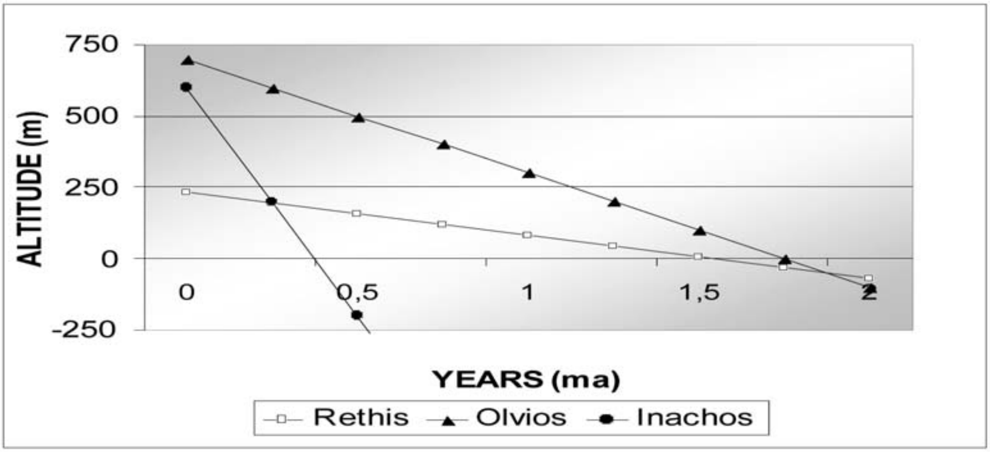

Fig. 4: Re-capture flow diagram for the 3 drainage systems. It shows the time that they need to recapture their original flow correlating with the corresponding erosion rates.

wind gap obstructs the flows of the rivers systems and prevents the regaining of their flow northwards.

The existent lithology: In the north of the Feneos and Lyrkio valley cohesive conglomerate exist, which make the erosion difficult and as a consequence prevent the regaining of the flow of the reversed Olvios and Inachos Rivers because the pace of erosion is slower than the one of lifting.

The human activity: Human activities contribute to the increase of erosion, because of the increasing cultivating activity, the creation of settlements, the uncontrolled pasturing and the construction of a dam in the Feneos valley, strengthening the human impact. Only if human activities which affect the mountain section of the river, that is the source area, erode the area of the wind gap, there is a possibility of regaining its initial flow.

Studying the coastal zone we focus on the active tectonic regime and the depositional conditions, especially in the region between the F1 and F2 faults (Figs 1, 5), in order to establish a future evolution of Dervrnios, Skoupeikos, Fonissa, Agiorgitikos, Seliandros, Asopos, Nemeas and Rachiani river flow.

The northern offshore fault (F1) is placed over 100m from coastline, while the southern onshore fault (F2) is placed over 1km from coastline. (Figs 1, 5) These faults are normal, with a listric geometry producing an uplift rate on their footwall of the order of 1,5mm/year (Doutsos & Piper, 1990). Taking into account the uplift rate on the footwall (1,5mm/year) and in relation to results concerning the uplift/subsidence ratio, estimated 1/2, which corresponds to the Egio and Helike faults (Koukouvelas & Doutsos, 1996; Koukouvelas et al., 2001), we could estimate that subsidence rate of the studied F1 and F2 hangingwalls is about 3mm/year. During the tectonic activity, the block between F1 and F2 faults turns backwards, due to uplift of the footwall of F1 and the subsidence of the hangingwall of F2. The hangingwall of the southern fault (F2) altitude is 80m above sea-level (IGME, 1973), and according to the previous results we could estimate that this region due to subsidence will reach sea level in 26.600 years, without further human influence. This part between the two faults has a sedimentation rate that act against subsidence and was estimated more than 0,2mm/year, as the erosion rate in the footwall of the fault is over 1mm/year. So, finally the hangingwall of F2 will reach the sea level in more than 28.600years.

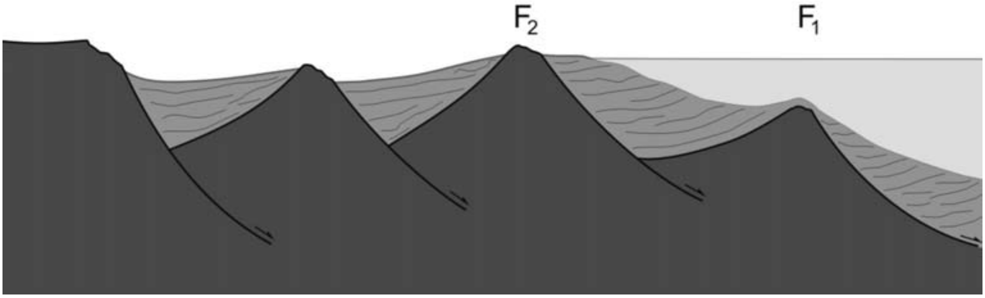

Fig. 5: Schematic cross-section D-D‘ (Fig.1). It shows wedged basins that bounded from listric faults, showing backward turn of the blocks due to surface curve of these faults. The block which bounded between the two faults turns backwards, due to the uplift of the footwall of (F1) and the subsidence of the (F2) fault hangingwall. The above scenario based on the decrease of the erosion on the hangingwall of (F2) and the increase of the erosion on the footwall of (F2).

The measurements with respect to the subsidence rates are the result of natural processes but if taken into account the human factor, that protects the coastal zone by the wave erosion, intensifies the erosion progress to the part that is sung and prevents the sedimentation process in this part, all could be changed. So, considering that the natural erosion rate is 1,2mm/year, the difference subsidence of this region is 4,5mm/year (1,5mm/year uplift rate in coastal zone and 3mm/year subsidence rate in the dipping part) (Fig. 7), the human rate erosion which is 1mm/year and the zero sedimentation, we could estimate that this region will reach in the same altitude in 11.900years (in detail, the dipping part from 80m altitude, will subside 62m, while the raising part from 0m, will uplift 17m) (Fig. 7).This scenario will bring the whole area in a same level, producing a lake. Meanwhile, after 15.380 years the subsiding part will reach the sea level, when the coastal zone will be in a 23m altitude, and so the area could change in a narrow lagoon. Obviously, as human activities increase the erosion rate will also increase. If we will suppose that the human erosion rate will increase at 2mm/year in the next 50years, then the above changes will take place in 10.380years. Concluding we could estimate that every millimeter erosion increase, we decrease about 1500years by the time of change and the creation of a lake in the studied area (Figs 6, 7).

6. Concluded remarks

Considering the above, the coastal zone of North Peloponnesus subsides continuously due to the active tectonic regime. The improvident human interferences can increase the subsidence regime. That event will lead the area behind the coastal zone to become a topographic lower area and as a result the rivers flow direction will shift creating a lake. It is obvious that precaution and the fight of natural disasters which a river system creates, depends on the community will to adjust their inspirations and activities within the framework of constant living and development. This means that communities have to be informed about the dangers, which involved in the uncontrolled exploitation and downgrading of natural resources. Thus they will design adopt and apply policies and strategies of precaution and confrontation of the phenomenon. The achievement of such target demands the common effort of the Government and citizens. This must be within the frame of natural Plans of action against the flooding phenomena, according to the relative Contract of the European Union. The action scheme must comprise a series of technical and social-economic measures and suggestions on the way of their application.

The river ecosystem must be developed without restrictions and it also needs to be acceptable that

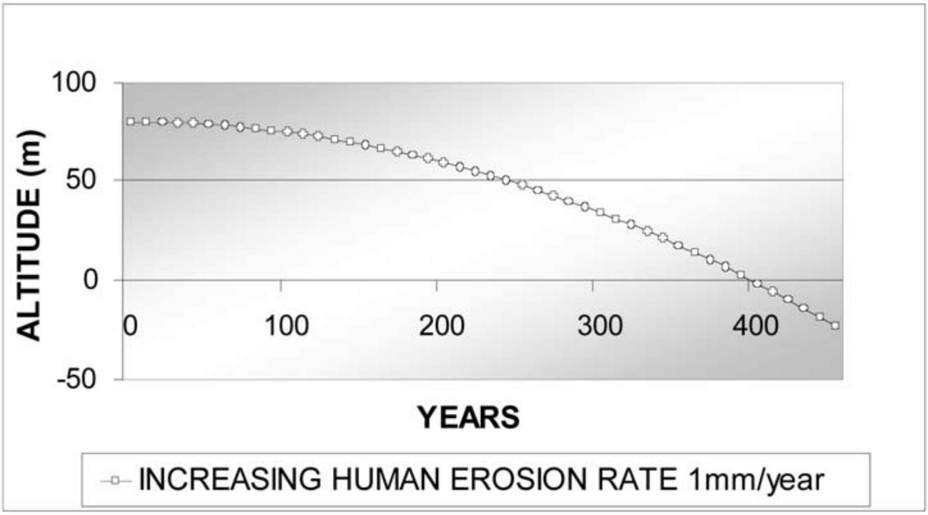

Fig. 6: The diagram represents human erosion rate that increasing 1mm/yr. It is revealed that in over 400yr the altitude will reach the sea level, resulting the transform of coastal zone into a lake.

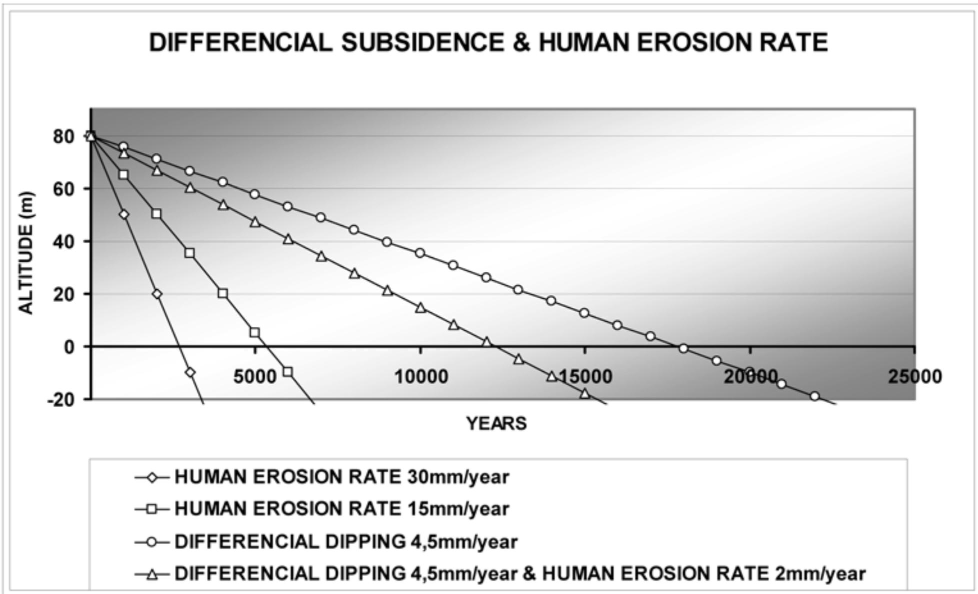

Fig. 7: Differential subsidence and human erosion rate diagram that represent the altitude–ages correlation. The max altitude of the coastal zone is 80m.

the disastrous phenomena are totally essential for the cycle of life and it must not be obstructed by human. Human must organize communities according to their needs but with respect, understanding towards natural – geological processes.

Settlements must be construction according to a city scheme which bans the construction on the floodplain of the river and only specific activities must be permitted on this, like parks, sports stadiums, parking, e.t.c. Boxing of bank of the rivers must be forbidden or any kind of interference on the bank of the river channel, as well as the uncontrolled collection of the bank's materials.

The development of a delta is a natural process which balances the river system and with the contribution of the wave erosion it spread the fertile sediments by building the coastal zone, balancing the wave erosion of coasts.

Consequently, we are all called to take over our responsibilities.

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SEDIMENTOLOGICAL AND GEOCHEMICAL CHARACTERIZATION OF HOLOCENE SEDIMENTS, FROM ALIKES LAGOON, ZAKYNTHOS ISLAND, WESTERN GREECE

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Abstract

The study area is the Alikes wetland (an old salt pan) which is located in the northern part of Zakynthos island. In the Alikes lagoon an exploratory borehole (GA-1) were drilled in a depth up to 21.20m. A total number of forty six (46) samples were analysed for their particle size, calcium carbonate and total organic carbon content. Moreover, bulk sample chemical analyses for major and trace elements were carried out on 12 samples, as well as mineralogical analysis for bulk, oriented and the clay fraction (<2 μm) were determined by powder X-Ray diffraction. The grain size characteristics, statistical parameters and TOC, for the Holocene analysed samples, suggest a coastal environment (restricted-shallow) with reduced salinity such as a lagoon margin and in a tidal flat and/or marsh particularly. Depositional environments and the source material affecting the geochemical signature indicating that that Al, Mg, K are mainly associated with the aluminosilicate fraction of the sediments analyzed, Fe and Ti consistent with detrital phases, while Ca, Si, P, and Mn showing different geochemical patterns.

***Key words**: sedimentology, geochemistry, Holocene sediments, Alikes, Zakynthos.*

1. Introduction

There are different approaches in reconstruction the Holocene coastal – lagoon environmental changes, which are based on geological, geochronological, sedimentological and geochemical analyses methods. Studies in western Greece, investigating and reviewing the Holocene environmental changes in coastal lagoonal areas, have been carried out by Kontopoulos and Avramidis (2003), Kraft et al. (2005), Vött (2007), Avramidis et al. (2008), Kontopoulos and Koutsios (2009), Avramidis & Kontopoulos (2009) and Engel et al. (2009).

Geological processes that affect the chemical composition of sediments include hydraulic sorting, weathering and diagenesis (Fralick and Kronberg, 1997). Significant improvement has been made in geochemical approaches to monitoring sediment provenance, especially through the introduction of discrimination diagrams based on the relationship of major and trace elements (Condie, 1993; Cullers, 1994; Bauluz et al., 2000). Whilst trace element geochemical studies have tended to focus on aspects of sediment provenance, their application to paleoclimate reconstructions has been rela-

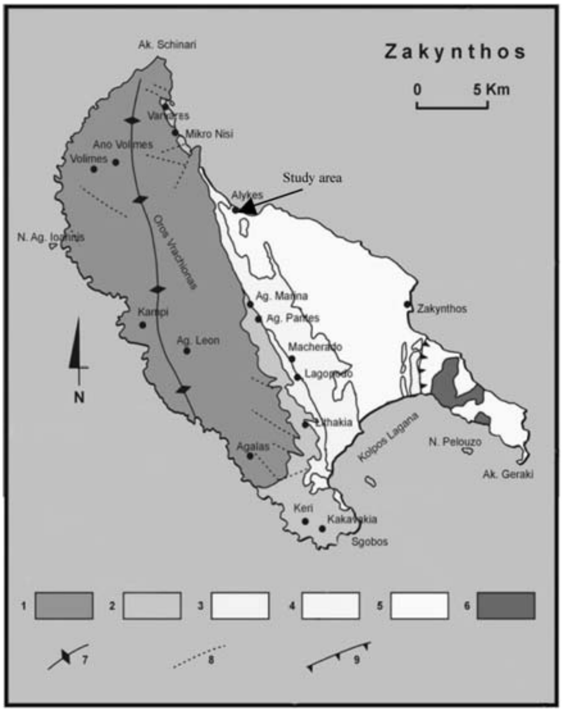


Fig. 1: Simplified geological map of Zakynthos Island. Legend: 1. Cretaceous carbonates, 2. Eocene carbonates, 3. Oligocene marly carbonates, 4. Miocene clastics and carbonates, 5. Pliocene-Quaternary alluvial deposits, 6. Ionian evaporites and breccias, 7. Anticline, 8. Fault, 9. Main thrust.

tively neglected, with most paleoclimate studies focusing on biogenic components, such as carbonate, opal, organic carbon and authigenic elements (Elderfield, 1990). On the other hand, the geochemical behaviour of trace elements in natural systems may often reflect changes in the chemical, biological, and physical conditions of the environment. For example, Mn and Fe change their chemical forms and concentrations according to the redox condition (Stumm and Morgan 1996), while distribution profiles of some bio-elements such as Ca, P and Si, are sensitively affected by biological activity (Riley and Chester 1983).

The purpose of the present paper is to study the Holocene sedimentological environments of the Alikes lagoon, Zakynthos island (Fig. 1) as well as the geochemical and mineralogical changes, based on a 21.2m sediment core. An effort is made to record the Holocene palaeonvironmental evolution – changes of the area and to correlate them with the sediment geochemical and mineralogical distribution.

2. Geological setting

The study area is the Alikes wetland (an old salt pan) which is located on the northern part of Zakynthos island (Fig. 1), and expand in an area of 400.000 m^2. The Zakynthos island is characterised by two geotectonic zones the Pre-Apulian and the Ionian zone. It is located near the north-western terminus of the Hellenic Trench, very close to the convergent boundary between the African and European plates and the diapirism area of the evaporates, that belong to the Alpine basement. The sedimentological evolution of the island was influenced by both compresional and extensional tectonics (Zelilidis et al,. 1998) while sedimentation can be distinguished in carbonates Cretaceous to Miocene and clastic Plio – Quaternary (Fig. 1).

Fig. 2: The narrow inlet in the northern part of the lagoon.

Fig. 3: General view of the lagoon with maximum depth up to 45cm.

In the study area, Alikes lagoon, during the last decades human activities such as agriculture, irrigation works and building development influenced, the water surface of the lagoon. On the northwest side, the Alikes lagoon is separated from the Ionian Sea by a low relief sand barier and has limited communication with the open sea with a sort and narrow inlet (Fig. 2). The maximum water depth of the lagoon is up to 45cm and an average depth only up to 15 cm (Fig. 3). Holocene sedimentation rates for Alikes lagoon area have been estimated by Avramidis & Kontopoulos (2009) and reveal two different stages of sedimentation rate: the first one between 8280 BP and 5590 BP (5.3 mm/yr) and the second one between 5590 BP and modern times (1.03 mm/yr).

3. Methods

The exploratory core GA-1 (Fig. 4) was bored in February 2008, at the geographical position N $37^0 50' 32''$, E $20^0 45' 51''$. The drilling equipment was a rotation Longyear 38, with single tube core barrel with tungsten carbide bit and 101mm diameter. All the segments of the core were sealed with cling film. Sediment types, structure, colour, as well as contact depths and bed characteristics, were recorded. Colour were identified using a Minolta CM-2002 hand held spectrophotometer. Standarised sedimentological analysis were carried out, on 46 samples including particle size analysis, calcium carbonate and organic carbon content. Particle size distribution was made using a Malvern Mastersizer 2000, while moment measures were calculated using GRADISTAT V.4 and based on Folk (1974) nomenclature. The organic carbon content was estimated by the titration method according to Gaudette et al. (1974).

Bulk sample chemical analyses for major and trace elements were carried out on 12 samples at the Activation Laboratories and were performed using a Thermo Jarrell-Ash ENVIRO II ICP for INAA and a Perkin Elmer Optima 3000 ICP. Silica, SiO_2 was determined using the X-ray Fluorescence method after $LiBO_2$ fusion and Zr was measured by the xylenol orange colorimetric method (Roser et al., 2000).

The mineralogical composition of bulk samples and of the clay fraction (<2 μm) separated by sedimentation was made on 12 samples and were determined by powder X-Ray diffraction (XRD), using a Bruker D8 advance diffractometer, with Ni-filtered CuKα radiation. Powders from oriented samples were prepared by the dropper method and were scanned at $1^o 2\theta$/min from 3 to $70^o 2\theta$. Random powder mounts were prepared by gently pressing the powder into the cavity holder. For each < 2 μm specimen, the clay minerals were identified from three XRD patterns (after air-drying at 25^o C).

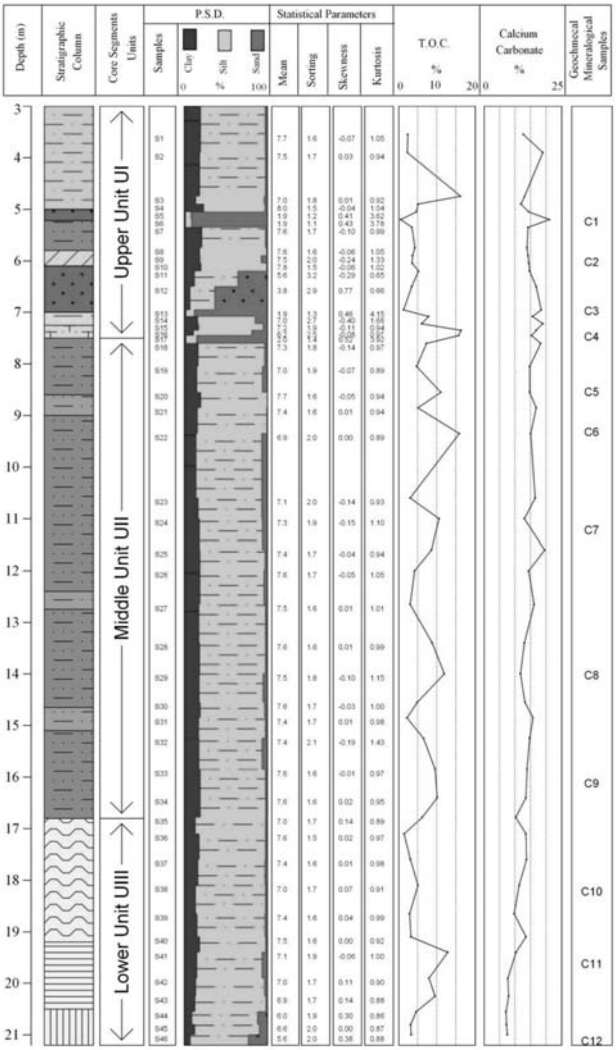


Fig. 4: Borehole profile GA-1 modified after Avramidis & Kontopoulos (2009), showing the sedimentary units, the P.S.D. - statistical parameters, TOC, carbonate content and geochemical – mineralogical analyzed samples.

4. Results

4.1 Sedimentology

The sedimentological core description is based on Avramidis & Kontopoulos (2009) discrimination of three major sedimentary units. The upper unit UI (3.00–7.50m), middle UII (7.50–16.80 m) and lower UIII (16.80–21.20 m) (Fig. 4).

<u>Upper Unit (3.00-7.50 m):</u> refer to the upper part of the core segment between depth 3.00m to 7.50m (Fig. 6), we didn't take into account material between depths 0.00–3.00m as it is classified as filling material (pave) for road construction. The unit consist of poorly to very poorly sorted, grayish olive, laminated fine to medium silt, rich in organic matter with bioturbation structures and shell fragments. Silt

is intercalated by three main horizons of poorly sorted, olive brown to dark olive, fine to medium sand (5.00–5.22 m, 6.00–7.00m and 7.25–7.50 m). Contacts between silt and sand are characterised as slightly erosional. The sand fraction consists of foraminifera, ostracodes and molluscs 15 in proportion less than 2% to the clastic grains. Also, there are carbonate – cementing aggregates in abundance in the sand fraction. The calcium carbonate content in the upper unit ranges from 11.90 to 21.00% with an average value 13,07%, while TOC between 0.54 to 16.30% with an average value 5.36% (Fig. 4).

<u>Middle Unit (7.50-16.80 m):</u> consist of poorly sorted, very dark greenish gray fine silt, with shell fragments, thin layers rich in organic matter with plant remains and abundant shell fragments and 20 *Cardium* shells. The sand fraction contains mostly micro- and macrofossils and abundance plant remains. Caliche-like evaporate, largely of a calcium carbonate type, is found cementing some of the grain together into aggregates. Internally to this unit we distinguish three layers (8.60–9.00 m, 12.40–12.60m and 14.65–15.10 m) consisting of poorly sorted grayish olive fine silt and is characterised by ripple lamination. The calcium carbonate content in the middle unit ranges from 11.71 to 19.48% with an average value 14,97%, while TOC between 2.16 to 15.79% with an average value 7.90% (Fig. 4).

<u>Lower Unit (16.80–21.20 m):</u> consist of poorly sorted, greenish gray fine to coarse silt. This unit is characterized by the presence of *Cardium, Cerithium* and *Hydrobia*, *Ammonia* shells and abundant organic matter. Also, there are carbonate-cementing aggregates in abundance in thesand fraction. In the lower part of the unit we observe an increase in sand participation and we distinguish a layer of poorly sorted, light olive gray to grayish olive, coarse silt. The calcium carbonate content in the lower unit ranges from 7.09 to 13.65% with an average value 9.94%, while TOC between 1.4 to 12.81% with an average value 5.23% (Fig. 4).

4.2 Geochemical analysis

Results of chemical analysis for the sediments collected from the Alikes Lagoon, are summarized in Table 1. The SiO_2 contents of the samples range from 37.92 to 64.02 wt.% and are enriched relative to Clay Shales (CSH). The Al_2O_3 contents of the samples are higher than of CSH (8 wt.%), except of the samples with codes C2 and C5. By contrast, the CaO contents are remarkably higher than that of CSH (2,20 wt.%). Most samples show that the Na_2O contents are enriched relative to CSH, while K_2O contents shown slightly lower values relative to CSH, with their average values being of 1.70 wt.% and 2.13 wt.% respectively. MgO contents of the samples range from 0,92 to 4,49 wt.%, with their average value being higher (3,42 wt.%) than the CSH (1,50 wt.%). The Fe_2O_3 concentrations are slightly higher than the CSH values, with the samples C2, C4, C5 and C12 showing lower concentrations than CSH. The MnO content of the samples ranges from 0.043 to 0.112 wt.%, while TiO_2 concentrations range from 0.08 to 0.686 wt.% being in the same magnitude with the CSH values. The P_2O_5 contents of the samples are enriched compare to the CSH concentration, with their average value being 0,089 wt.%. The LOI (Lost Of Ignition) values ranges from 9,89 to 21,21 wt.% with an average value of 17,98 wt.%.

4.3 Mineralogical analysis

The mineralogical composition of samples C1-C5 is characterized by the dominant presence of quartz, calcite, albite, chlorite and illite, while lepidocrocite presence was detected in samples C4, C5 (Fig. 5). The sample C6 shows a different mineralogical composition and halite and gypsum coexist with calcite, albite, chlorite, quartz and illite (Fig. 5). Samples C7-C12 are characterized by the dominance of illite and the presence of quartz, albite, chlorite and calcite and traces of lepidocrocite.

Table 1. Results of chemical analysis for the sediments collected from the Alikes Lagoon borehole GA-1.

Sample Code	Core Depth	SiO_2	Al_2O_3	Fe_2O_3 (T)*	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	LOI**	Total	Rb	Cs
Upper Unit: core segment between depths 3.00m to 7.50m															
	(m)	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	ppm	ppm
C1	5,12	39,13	10,94	5,89	0,103	4,49	13,41	1,82	2,21	0,574	0,13	20,63	99,32	93,0	4,5
C2	5,9	61,74	2,78	1,16	0,043	0,92	15,74	1,14	1,09	0,088	0,04	15,49	100,2	36,0	1,0
C3	6,85	39,23	11,55	5,81	0,097	3,95	13,5	1,63	2,49	0,577	0,11	20,5	99,44	111,0	6,2
C4	7,35	44,72	9,19	4,5	0,091	3,31	14,02	1,71	2	0,452	0,1	19,42	99,5	81,0	4,0
Middle Unit : core segment between depth 7.50–16.80m															
Sample Code	Core Depth	SiO_2	Al_2O_3	Fe_2O_3 (T)*	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	LOI**	Total	Rb	Cs
	(m)	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	ppm	ppm
C5	8,42	55,94	5,57	2,78	0,067	1,86	14,97	1,17	1,41	0,26	0,06	16,45	100,5	53,0	2,3
C6	9,2	37,92	11,24	6,11	0,112	4,3	13,47	1,96	2,37	0,563	0,09	21,21	99,36	111,0	6,6
C7	11,1	40,11	11,52	6,38	0,087	4,02	12,81	1,78	2,36	0,59	0,09	19,59	99,33	108,0	5,9
C8	13,9	40,59	11,47	5,58	0,091	3,97	13,15	1,86	2,34	0,581	0,09	19,92	99,64	101,0	5,2
C9	16	40,77	12,31	6,45	0,094	4,28	12,42	1,56	2,51	0,629	0,1	19,02	100,1	106,0	6,0
Lower Unit : core segment between depth 16.80–21.20m															
Sample Code	Core Depth	SiO_2	Al_2O_3	Fe_2O_3 (T)*	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	LOI**	Total	Rb	Cs
	(m)	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	ppm	ppm
C10	18,1	48,62	11,8	5,97	0,084	3,63	10,13	1,82	2,33	0,658	0,1	15,62	100,8	110,0	5,6
C11	19,5	42,97	13,49	6,71	0,058	3,82	8,84	1,95	2,61	0,686	0,09	18,01	99,23	138,0	7,9
C12	21,1	64,02	10,07	4,26	0,067	2,48	5,51	1,97	1,8	0,645	0,07	9,89	100,8	79,0	3,5

* (T): Total, **LOI: Lost of Ignition

Increasing depth the amount of chlorite as well as calcite is decreasing while illite is increasing. Vermiculite is present in samples C9-C12 (Fig. 5).

5. Discussion

The particle size distribution throughout the core indicate a relative uniform distribution of grain size. Sediment types are fine to coarse silt with three intercalations of medium sand in the upper unit. The presence of sand is low, ranging between 0 to 5%, clay percent ranges between 2 to 20% and silt between 69 to 85% (Fig. 4). Almost all the analysed sediments are characterised as poor to very rich in organic matter (TOC>0.5), while carbonate content participate in a portion >8%.

Based on statistical parameters, in the upper core segment, the silt material is characterised as poorly to very poorly sorted, while skewness indicate basically a symmetrical distribution and values of kurtosis propose a mesokurtic distribution. The sand layers of the upper unit appear to be poorly to very poorly sorted while skewness in all sand samples indicate very fine skewed distribution while kurtosis propose mainly an extremely leptokurtic distribution. The very fine skewed value is caused by the presence of a fine tail in the sand-dominate size frequency curve. This fine tail in combination with the poorly to very poorly sorting and extremely leptokurtic kurtosis may be suggesting an event analogous with a fluvial flood. This event may occur in a coastal environment such as a sandy tidal flood. If this happens then the silt beds of this unit which have a very low sand content, poorly to very poorly sorting and normal distribution, have deposited in a sheltered muddy tidal flat or marshy area. The middle unit indicate a uniform distribution of poorly sorted fine silt while skewness and kurtosis in-

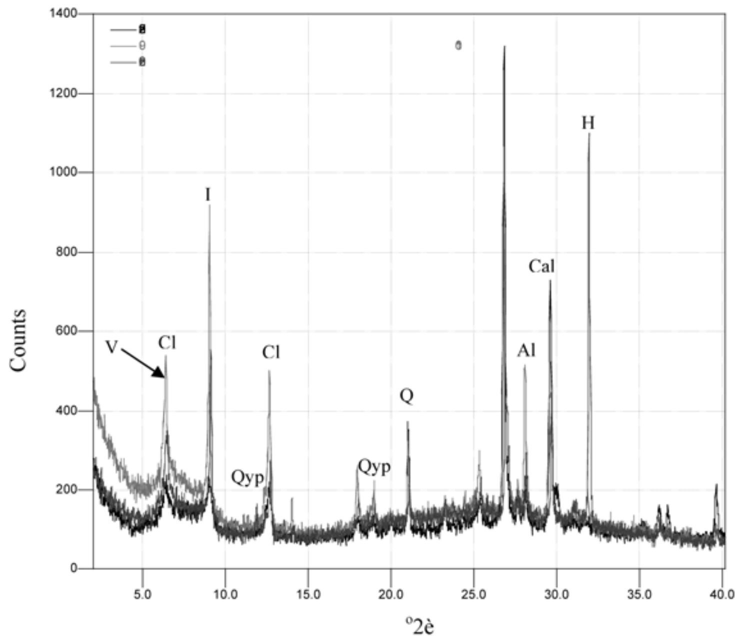


Fig. 5: X-ray diffraction patterns of representative oriented samples C3, C6, C10. Cl:Chlorite, I:illite, Qyp: Gypsum, Q: quartz, Al:Albite, H: Halite.

dicate mainly a symmetrical and mesokurtic distribution. The participation of sand is very low <5% (Fig. 4). These grain size statistical parameters are the same as those of the silt beds of the upper unit. This event and the very low sand content suggest also a sheltered muddy tidal flat or marshy area. The lower unit of the core is characterized by poorly sorted fine to medium silt and the increase of the sand participation in the lower part, depth 20.55– 21.20 m, where we have the presence of coarse silt. Participation of sand is low <7% with exception the lower part of the unit where increases up to 23%. Skewness present a symmetrical to fine skewed distribution, while kurtosis a mesokurtic one. According to the grain size statistical parameters the mainly part of the unit III has deposited also in a sheltered muddy tidal flat or marshy area. The lower part of the unit III where the sand content increases, the skewness is near symmetrical to fine skewed and the kurtosis is slight platykurtic, may have deposited in a mixed flat environment.

However geochemical analyses may contain additional new paleoclimate information that provides important new constrain on sediment depositional environment and climate. In this case, we examine the geochemical characteristics of the sediments from Alikes Lagoon, Zakynthos island, Western Greece, by calculating enrichment factors for the elements relative to CHS (Clay Shale; Salomons & Forstner, 1984). The enrichment factor (EF) for any element is given by the following equation:

$$EF= (C_{sample} / C_{Al\ sample}) / (C_{standard} / C_{Al\ standard}),$$

where C_{sample} is the concentration of the element and $C_{Al\ sample}$ is the concentration of Al in the sample (Yan et al., 2007). The Al normalization is utilized because concentrations of most elements show correlation with Al_2O_3. CSH is used as the standard. Enrichment factor diagrams are shown in Figure 6a-d.

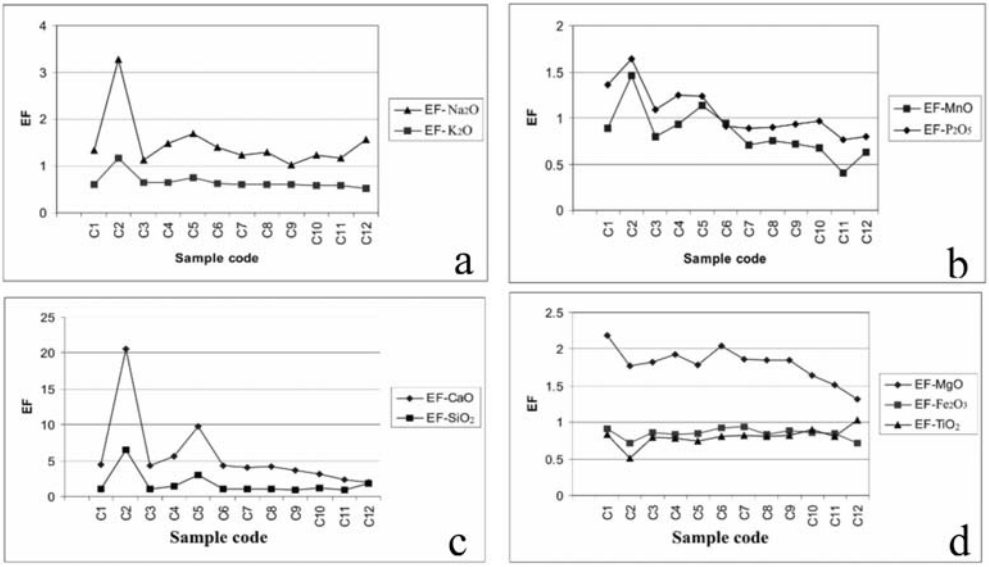
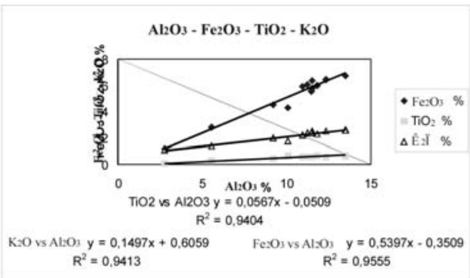


Fig. 6: Element enrichment factor (EF) plot (relative to CSH) for the samples from the Alikes Lagoon, Zakynthos island, Western Greece: a) EF for K_2O, Na_2O, b) EF for MnO, P_2O_5, c) EF for CaO. SiO_2 d) EF for MgO, Fe_2O_3, TiO_2. (CSH composition from Salomons & Forstner, 1984).



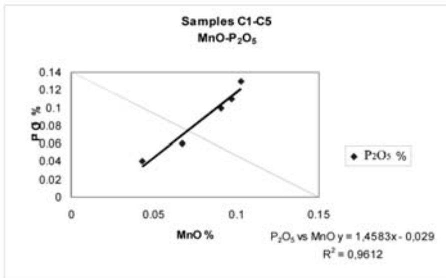


Fig. 7: The *x–y* plots among Fe_2O_3, TiO_2, K_2O and Al_2O_3 data from the Alikes Lagoon, Zakynthos island, Western Greece sediments.

Fig. 8: The *x–y* plot among MnO and P_2O_5 data from the Alikes Lagoon, Zakynthos island, Western Greece, sediment samples C1-C5.

The samples show that Na, Ca and Mg content are enriched relative to CSH (Fig. 6a, c and d), while Mn and P enrichment factors show variations relative to CSH (Fig. 6b). K, Fe and Ti enrichment factors show depletion relative to CSH (Fig. 6a and d). Samples C2 and C5 display an abnormally high enrichment factor for Ca, and Si thus it is possible these data related to the carbonate cementing aggregates, the shell fragments and the presence of quartz and calcite as it is shown from the XRD analysis. By contrast, Mg enrichment factor for C2 and C5 samples having a tendency to degrease due to the lower amounts of chlorite. The same pattern is obvious for Fe and Ti, although their enrichment factors are lower than CSH. It is known that the chemical composition can be influenced by weathering, dissolution and adsorption-desorption processes and these may produce irregular chemical variations in some major and trace elements (Mass and Mc-

Culloch, 1991). This is consistent with the significant positive linear correlation between Al, Fe and Ti classified as a detrital element group, (Al-Fe: R^2=0.9555, Al-Ti: R^2=0.9404, Fig. 7), while strong positive linear correlation between Al and K (R^2=0.9413), indicating their association with the phyllosilicate fractions such as illite and chlorite (Bauluz et al., 2000), which are present in our samples (Fig. 5).

In the case of Mg, its significant negative linear correlation with Ca in the horizon extended between 5m and 8m of the core (R^2=0.988) implies that this element is consistent with the aluminosilicate fraction.

In addition Mn is a redox-sensitive element that easily reduced or oxidized by changes of the biogeochemical conditions of the environment (Stumm and Morgan 1996). Mn geochemical behaviour shows differences between 5m to 8m, and 9m to 21m downcore. In the upper part of the sediment column there is a variation in the Mn enrichment factor relative to CSH, while its significant negative correlation with Ca (R^2=0.9855) and the very strong positive correlation with Al (R^2=0.9678), indicating Mn association with the clay fraction and/or oxide-hydroxide phases. In the down part of the sediment core, its depletion compare to CSH (Fig.6b), is compatible with the dissolution of Mn-solid phases due to the presence of abundant organic matter.

The Si enrichment factors (Fig. 6c), together with its significant positive linear correlation with Ca in the upper part of the core (R^2 = 0.9937) suggesting the biogenic origin of the element. From 9m to 21m sediment depth, Si is mainly associated with the fraction of resistance aluminosilicate minerals, by having a strong negative linear correlation with Ca and TOC (Ca-Si: R^2 = 0.8324, TOC-Si: R^2 = 0,7362). Additionally in the core-top samples, P is mainly related with manganese oxides/hydroxides phases due to their strong positive linear correlation (R^2 = 0.9612, Fig. 8, Yuan-Hui Li et al., 2007).

However, Ti usually behaves as conservative element in a weathering profile, and thus Ti normalized ratios help to track the behaviour of elements during chemical weathering. Additionally chemical weathering affected from environmental changes such as climate and redox conditions (Yan, et. al 2007). Furthermore, the Ti content show no covariance with SiO_2 content (R^2 = 0,2828) and significant inter-sample variations, hence Rb and Cs are normalized to Ti. The Rb and Cs are very sensitive to climatic influences and may become leached during chemical weathering. As chemical weathering is largely controlled by moisture and temperature, a wet and warm climate may enhance the chemical weathering (Nesbitt et al., 1980). Variation of Rb/Ti, Cs/Ti ratios, $CaCO_3$ contents and TOC values imply a warm and wet climate which result in greater vegetation cover (Yan et al., 2007).

6. Conclusions

Although the sediment chemical properties variation, can be related to different sediment sources, the rich Ca and Si content of the samples indicate high primary production rates during deposition in the past. The higher rate of sedimentation in the Alikes lagoon until mid-Holocene from 5.3 mm/yr to 1.03 mm/yr in modern times, the grain size statistical parameters, the silt beds and the low sand content of the sediment samples analyzed, suggesting a warm, sheltered muddy tidal flat and/or marshy coastal deposition environments. The grain size statistical parameters, suggests a coastal environment (restricted-shallow) with reduced salinity such as a lagoon margin and in a tidal flat and/or marsh particularly. Depositional environment and the source material affecting the geochemical signature indicating that Al, Mg, and K are mainly associated with the aluminosilicate fraction of the sediments analyzed, while Ca, Si mainly related with the biogenic fraction of the sediments in the core top samples. Iron and Ti classified as a detrital element group, while the P and Mn correlation in the top core samples showing its relation with manganese oxides/hydroxides phases.

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PLANKTON BIOSTRATIGRAPHY AND PALEOCLIMATIC IMPLICATIONS OF AN EARLY LATE MIOCENE SEQUENCE OF LEVKAS ISLAND, IONIAN SEA, GREECE

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Abstract

Planktonic foraminiferal biostratigraphy is carried out in an Early Tortonian tectonically active setting, located in the Pre-Apulian Foreland Basin in Levkas Island. The studied section (Manassi section) is composed of hemipelagic silty clays and turbidite sandstones, reflecting sedimentation as a result of thrust activity. The distributional pattern of biostratigraphical significant species suggests that the Manassi section has been deposited during the time interval that Globigerinoides obliquus occurs regularly, the neogloboquadriniids are present in low percentages and Paragloborotalia siakensis is continuously present. The correlation with astronomical tuned sections allowed dating the studied section as ranging between 11.54Ma to 11.2Ma, having a lower Tortonian age, above the Serravallian/Tortonian boundary (Paragloborotalia siakensis planktonic foraminiferal zone).

On the basis of the obtained palaeoclimatic curve, a series of palaeoclimatic events are recognized. The faunal composition suggests a cooling trend in the lower part which has been correlated with the Mi5 event. This cooling is followed by a warm-temperate phase, punctuated by several negative peaks in the palaeoclimatic curve. The palaeoclimatic evolution of the study area generally corresponds to the global palaeoclimatic trend with some subtle differences, supporting that the regional climate of this area was not merely controlled by global changes in climate.

Key words: *planktonic foraminifera, early Tortonian, palaeoclimate, Mediterranean.*

1. Introduction

The Miocene epoch represents a bridge between the warm interval of the Paleogene and the cold Neogene period. There is enough evidence available to suggest that the Miocene was a critical time in the evolution of the Earth's climate marked by a major expansion of Antarctic ice volume, deep-sea cooling, isotopic excursions (Savin et al., 1981; Kennett & Barker, 1990) and widespread deep-sea hiatuses (Keller & Barron, 1987). The increased ice volume on Antarctica during the Miocene steepened the latitudinal thermal gradients and caused sea-level fluctuations. Late Oligocene–middle Miocene physico-chemical conditions of the deep ocean were considerably different from those of today, while the late Miocene deep ocean was in several ways similar to the present day.

The period from Middle to early Late Miocene (15-11 Ma) is regarded as a major period of expansion of the Antarctic ice and a deep-water benthic faunal turnover (e.g., Miller et al., 1991; Kaiho, 1994). This period is thus a period of major interest in Cenozoic climate development. High-resolution oxygen isotope records have been used to reconstruct the history of the Antarctic ice sheet (e.g. Miller et al., 1987; Woodruff & Savin, 1991; Miller et al., 1991b; Flower & Kennett, 1993; Flower & Kennett, 1995) and have revealed a step-like pattern of ice-volume expansion during that period. Miller et al., 1991 summarized the oxygen isotope stratigraphy for this time interval and indicated four $\delta^{18}O$ maxima labelled Mi3, Mi4, Mi5 and Mi6 events respectively, which have been regarded as evidence of ice-growth events. The Mi3 and Mi4 maxima correspond to the early and middle phases of middle Miocene climatic cooling and/or Antarctic ice-sheet expansion (Shackleton & Kennett, 1975; Savin et al., 1975; Woodruff et al., 1981), whereas Mi5 has been interpreted to be the first significant ice sheet.

The early Tortonian is characterized by a stable climate system, based on previous stable isotope analyses from ocean drilling cores and stratigraphic studies (Turco et al., 2001; Miller et al. 1991; Zachos et al., 2001; Ohta et al., 2003; Holbourn et al., 2004). Understanding the early Late Miocene climate is integral to the study of global climate interactions. Sedimentary sequences from the Mediterranean basin are commonly used for studying Cenozoic climate variability as their marine sedimentary outcrops reflect climate changes in the rock record through alternating, rhythmic colour and lithological variations.

The present study refers to the early Late Miocene (early Tortonian) palaeoclimatic evolution of eastern Mediterranean and more precisely, of the Ionian Sea (Levkas island, Manassi section). The results are based on the analysis of the high-resolution planktonic foraminiferal record from this section. The data of calcareous plankton are compared with $\delta^{18}O$ variations for Gibliscemi section described by Turco et al. (2001), and for ODP Site 926 described by Turco et al. (2002). This analysis enables us to examine the interactions among the variables (foraminiferal species) and identify a series of palaeoclimatic events of long and short duration that took place in the Mediterranean area during the early Tortonian. Our main objectives are to provide a detailed time-stratigraphic correlation on the basis of planktonic foraminiferal studies that aim to unravel the evolution of sedimentary basin and the influence of past climatic changes on sedimentary properties and faunal distribution pattern on a regional as well as on a global scale.

2. Materials and methods

2.1 Geological setting and lithology of the studied section

The studied section is located in one of the most tectonically active regions of the Eastern Mediterranean, the Ionian Islands in western Greece (Fig. 1).

The Ionian Islands constitute part of the para-autochthonous Apulian foreland of the Hellenide orogen and include rocks of the Pre-Apulian (or Paxos) and Ionian isopic zones (Aubouin 1965; Underhill 1989) (Fig. 1). The Pre-Apulian or Paxos zone corresponds to neritic sedimentation, reaching into the Aquitanian, overlain by Miocene marl sequence, represented on Paxos Island, western Levkas and parts of the islands of Cephalonia and Zakynthos (IGRS-IFP, 1966). More specifically, in Levkas Island, the Pre-Apulian zone is represented in Agios Petros area which covers the southwestern part of the island (Fig. 2).

In the northern part of Agios Petros area, the Manassi section may be considered an early Late Miocene representative sequence of the Pre-Apulian zone (Fig. 2). During Early Tortonian a fundamental change in the palaeogeographic configuration of the Pre-Apulian zone took place: the preexisting shallow platform, on which bioclastic calcareous sedimentation took place, rapidly subsided and marls and clays were deposited until the Pliocene (Bornovas, 1964; de Mulder, 1975).

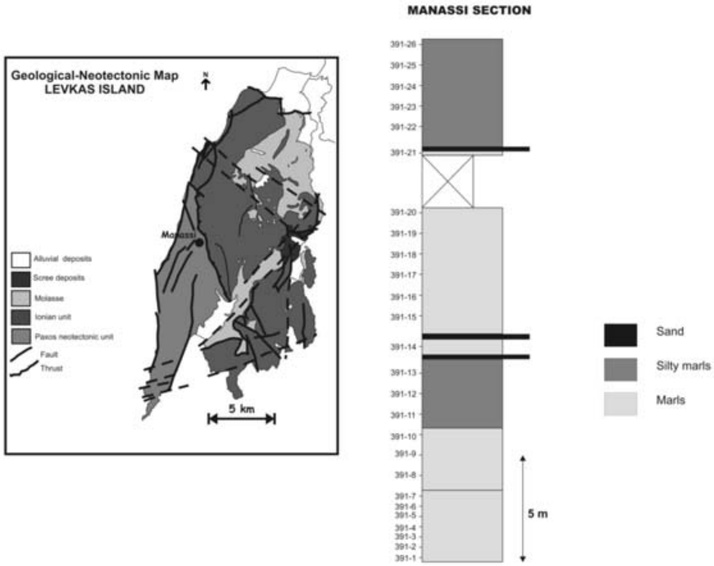


Fig. 1: Geological and Neotectonic map of Levkas Island (after Lekkas et al., 2001, modified), depicting the location of the studied area. Lithology and position of samples of Manassi section

The Manassi section is located on the eastern slope of a N-S running valley, near the homonym village. The studied succession consists of blue grey marls and clays with some fine grained sandstone interbeds. The intercalations of these thin, clastic beds and especially of positively graded sandstones in the studied succession reflect the influence of density currents, which supplied coarser material from a distant hinterland (de Mulder, 1975).

2.2 Planktonic foraminifera

The Manassi section (25 m thick) was sampled with 0.5 to 1 m resolution. A total of 26 samples were collected. A preliminary bulk rock composition analysis indicated that the stratigraphic interval from 19.9 m up to the top of the section is marked by increased phyllosilicates and quartz and decreased calcite. The decrease in calcite is likely to be a function of increased dissolution, dilution by terrigenous input and consequently changes in primary productivity. As no significant dissolution has been recorded, all samples were processed for micropalaeontological analyses using standard laboratory procedures.

One hundred grams of dried sediment, for each sample were washed over a 63 μm sieve and subsequently the coarse fraction was dry sieved over 125 μm sieve. The fraction >125 μm was then investigated for planktonic foraminiferal content.

Planktonic foraminiferal quantitative analysis was carried out on each sample, subsampled into aliquots through a micro splitter, in order to obtain at least 300 specimens. Planktonic foraminiferal specimens were identified and counted following the taxonomic concept of Dermitzakis (1978), Kennett & Srinivasan (1983), Iaccarino (1985), Hilgen et al. (2000) and Foresi et al. (2002). Taxon abundance is expressed as a percentage of the total planktonic fauna.

For a reliable quantitative analysis it is necessary to adopt a wide taxonomic concept, which remains

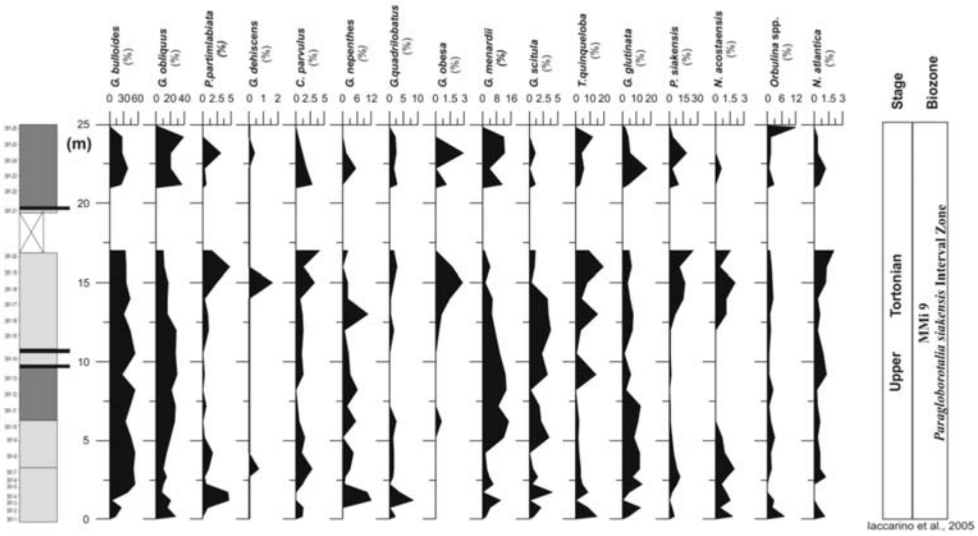


Fig. 2: Planktonic foraminifera biostratigraphy of Manassi section. Quantitative distribution of planktonic foraminifera marker species.

unchanged even under poor preservational conditions and taxonomical problems. For this reason we introduced some supra-specific categories (Foresi et al. 2002), reducing the number of species which are really present in the planktonic foraminiferal data set.

Planktonic foraminiferal preservation is generally good, although at times is poor. A total of 18 taxonomic categories have been recognized: *Globigerina bulloides* group, *Globogerinoides obliquus*, *Globoturborotalita apertura*, *Paragloborotalia* cf *partimlabiata*, *Gatapsydrax parvulus*, *Globoturborotalita nepenthes*, *Globogerinoides trilobus*, *Globogerina obesa*, *Globogerinella. siphonifera*, *Globorotalia. menardii* group, *Globorotalia scitula* group, *Globoquadrina dehiscens*, *Turborotaliata quinqueloba*, *Globigerinita glutinata*, *Paragloborotalia siakensis*, *Orbulina* spp., *Neogloboquadrina. atlantica preatlantica* and *Neogloboquadrina acostaensis*.

The label *G. bulloides* group includes small-sized and poorly preserved specimens which cannot be assigned to either *G. bulloides* or *G. falconensis*. All tightly coiled globoturborotaliids showing a small arched aperture with lip were grouped under the label of *G. nepenthes*. Keeled globorotaliids are also counted under the label of *G. menardii* group. The *G. scitula* group is the label used for all the unkeeled globorotaliids except the *P.* cf *partimlabiata*. The latter species is planoconvex and has typical 4-5 chambers, an arched aperture and a relatively coarsely perforated wall structure (Hilgen et al., 2003). Relative abundance fluctuations of the most important taxonomic units are plotted in Figure 2.

The palaeoclimatic curve inferred from planktonic foraminifera assemblages was obtained by the formula (w-c)/(w+c)x100 of Amore et al. (2004), where *w* represents the warm-water indicators and *c* the cold water indicators. *G. obliquus, G. apertura, G. dehiscens, G. trilobus, G. siphonifera*, *G. obesa, G. menardii* group, *P. siakensis* and *Orbulina* spp. were considered warm water species, while *G. scitula, G. nepenthes, T. quinqueloba, N. atlantica preatlantica, N. acostaensis* and *G. glutinata* were considered cold water indicators (Hemleben et al., 1989; Rohling et al., 1993; Pujol & Vergnaud-Grazzini, 1995).

2.3 Statistical Analysis

The results of quantitative analysis were processed using a statistical program (SPSS13.0) in order to perform Principal Component Analysis (PCA). The analysis has been carried out in order to extract the most important factor which determines the overall faunal change. The initial dataset was condensed, and only taxa with percentages larger than 2% were considered for the analysis.

3. Biostratigraphic results

3.1 Faunal changes

Among the taxa more or less continuously present, *G. bulloides* gr., *G. scitula* gr., *G. obliquus/apertura* and *G. glutinata* show an overall upward decrease, whereas, *G. quadrilobatus* and *Orbulina* spp. show an overall upward increase. Among the species having discontinuous distribution, *G. nepenthes* occurs mainly in the lower part and reaches significant abundance near the base. *G. obesa* reaches significant percentages in the middle-upper part, whereas *T. quinqueloba* occurs in high abundance in the middle part. *G. menardii* gr. shows two main intervals of significant occurrence: in the lower and upper part of the section. *C. parvulus* and *P.* cf. *partimlabiata* are also present in our data set, but in small percentages.

Main changes in the faunal pattern are determined by the distribution of taxa having biostratigraphic significance. Within the studied interval we recorded the absence of *G. subquadratus*. On the contrary, *G. obliquus* exists in all the samples. *P. siakensis* also occurs in the majority of the samples, exhibiting high percentages in the middle–upper part of the section. *N. atlantica praeatlantica* is present from the base of the section and increases upward, although in small percentages. *N. acostaensis* displays a significant distributional pattern with random coiling specimens. This taxa is discontinuously present in our record in relatively small percentages (2-3%), showing a paracme interval in its distributional range in the Mediterranean recorded at 11.54 to 11.2 Ma (Foresi et al., 2002).

The first principal component analysis (PCA-1) describes the 21,2% of the total variance (Fig. 3). Species yielding high negative loadings such as *Orbulina* sp., *G. quadrilobatus* and *G. siphonifera* are surface species indicative of warm oligotrophic conditions. Species with high positive loadings are *G. bulloides* which is a cold intermediate upwelling species and *G. obliquus* which is a warm subtropical species. The increase in abundance of the last species has been used in the middle Miocene records in Mediterranean and N. Atlantic to interpret the influence of Mi5 global cooling event in the Mediterranean record. Actually, the increase of this species at 11.54 Ma reflects the replacement of a dominant tropical fauna by a subtropical one (Zachariasse & Spaak, 1983; Turco et al., 2001).

3.2 Biostratigraphy

The planktonic foraminifera biostratigraphic study of the Manassi section has been previously referred in Drinia et al. (2007). The aim of the present study is to refine and where necessary to modify the existing planktonic foraminiferal biostratigraphy of the Manassi section, by presenting the detailed distribution pattern of the marker species and all the species involved and furthermore to compare the biostratigraphic results with those have been revealed for the time equivalent astronomically tuned Mediterranean section Monte Gibliscemi (Hilgen et al., 2000). The correlation is based on the distribution pattern of selected planktonic foraminifera species (*Paragloborotalia siakensis*, *Neogloboquadrina acostaensis, Globigerinoides obliquus*).

The taxonomy and the distribution pattern of the main biostratigraphic marker species are discussed in more detail in the following paragraphs.

***Globoturborotalita apertura* (Cushman), 1818 / *Globigerinoides obliquus* Bolli, 1957, group**

In this study *G. apertura* and *G. obliquus* were lumped into the same group in order to make our data comparable to with that observed in Monte Gibliscemi and other Mediterranean sections. This group is continuously present showing a common and regular distribution from the base up to the top of the section. The significant absence of *G. subquadratus* and the regular occurrence of *G. obliquus* is considered to be a very useful event, suggesting that the section starts after the FRO of *G. obliquus*, which have been recorded in Monte Gibliscemi and Tremiti Island at 11.54 (Hilgen et al., 2000; Foresi et al. 2002).

The LCO of *G. subquadratus* followed by the FCO of *G. obliquus* are near synchronous in Mediterranean calibrated at 11.54 Ma (Hilgen et al., 2000). This succession is also recorded at Site 926 (equatorial Atlantic, Turco et al., 2002), although the FRO of *G. obliquus* (11.17 Ma) there, is about 400kyr younger than LO of *G. subquadratus*. In addition, both at site 926 and the Mediterranean the LCO of *G. subquadratus* is slightly preceded the by the LCO of *D. kugleri*.

***Paragloborotalia siakensis* (Le Roy), 1939**

Although this species is abundant and continuously present shows a decline in its distributional pattern from 6 to 12 m. *P. siakensis* is a long ranging species displaying several distributional changes of biostratigraphic significance. According the Hilgen et al. (2000) and Foresi et al. (2002), the LO occurrence of this species has being dated at 11.2 Ma.

***Neogloboquadrina* Bandy, Frerichs and Vincent, 1967: *N. acostaensis* (Blow), 1959, *N. atlantica praeatlantica* (Berggren), 1972**

The neogloboquadrinids are represented by *N. atlantica praeatlantica* (small-sized *N. atlantica* of Hilgen et al., 2000; Hilgen et al., 2003) and *N. acostaensis*. These two species are separately plotted, although their distributional pattern seems to be the same being rare and discontinuously present in the section ranging between 2-5% of the total data set, with random coiling specimens. The arrival of neogloboquadrinids into the Mediterranean has been dated at 11.78 Ma (Hilgen et al., 2000). A paracme interval of this group has been recorded in several Mediterranean sections dated at 11.54-11.21 (Hilgen et al, 2000; Turco et al., 2001; Foresi et al., 2002; Hilgen et al., 2003); In Monte Gibliscemi rare and scattered occurrences have been recorded between 11.54 and 11.17 Ma, whereas this group become the major faunal constituent up to that point. The base of the paracme interval coincides with the LCO of *G. subquadratus* and the FRO of *G. obliquus*, whereas the end of this interval postdates the LO of *P. siakensis*.

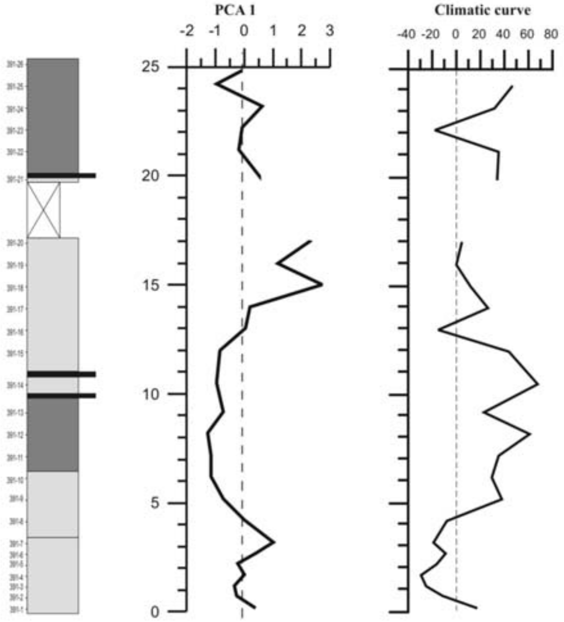
***Catapsydrax parvulus* Bolli, Loeblich and Tappan, 1957**

The species is almost continuously present in small number showing similar distribution with the Tremiti section (Foresi et al., 2002).

***Paragloborotalia partimlabiata* (Ruggieri and Sprovieri), 1970**

This species is present in the section in low percentages. Peaks in abundance of this species coincide with low occurrence of *P. siakensis*.

The comparison with astronomically calibrated sequences allowed us to consider as starting point



Loadings of plankonic foraminifera taxa

Variables	PCA-1
G. bulloides	0,57
G. obliquus	0,10
G. glutinata	0,08
G. menardii	0,06
P. siakensis	0,04
G. druryi	0,02
G. scitula	0,02
T. quinueloba	0,01
C. parvulus	0,01
Neogloboquadriniids	0,01
G. obesa	0,00
G. quadrilobatus	-0,01
G. sipohonifera	-0,02
Orbulina spp.	-0,81
Variance 21,1%	

Fig. 3: PCA-1 scores plotted and palaeoclimatic curve.

of our tuning, the regular occurrence of *Globigerinoides obliquus*, and the total absence of *Globigerinoides subquadratus*. The LCO of the last species is dated at 10.539 Ma in Monte Gibliscemi, whereas the FRO of *G. obliquus* is recorded at the same time. The paracme interval of *N. acostaensis* and *N. atlantica* recorded at Monte Gibliscemi as well as in Monte dei Corvi (Hilgen et al., 2003) and in Tremiti Island (Foresi et al, 2002) dated at 11.55-11.21 Ma. These biochronological datums together with the distribution pattern of *P. siakensis* yielded ages for the studied section between 11.54 to 11.2 Ma, determining the *Paragloborotalia siakensis* planktonic foraminifera Interval Zone of Iaccarino et al., 2005, for Manassi section.

4. Palaeoenvironmental-palaeoclimatic implications

A surface-water temperature approach in this study has been based on planktonic foraminifera ecological preference. On the basis of the obtained palaeoclimatic curve (Fig. 3) and the planktonic foraminifera abundance fluctuations, we could recognise the following climatic intervals during the deposition of the Manassi section.

The first interval extends from 0.75 to 4.2 m, showing higher percentages of cold-water planktonic foraminifera and negative values of the palaeoclimatic curve. In this interval, *T. quinqueloba* and *G. glutinata* are generally abundant occurring in high percentages, whereas *G. scitula* shows low frequency values. More precisely, at 1.2 m, *G. nepenthes*, a cold intermediate species, first appears with maximum frequency value about 50% and then strongly declines to very low values. In parallel, the warm-water species occur in low percentages. Therefore, we interpret this interval as a period characterised by generally cool conditions.

On the other hand, from 5.2 to 12 m, a warming phase is distinctively recorded. This climatic improvement is recorded by the increase of the warm-water species *G. obliquus* and *G. menardii* gr.

and the decrease of *T. quinqueloba* and *N. acostaensis* and *N. atlantica*. The planktonic foraminiferal assemblage is dominated by the tropical-subtropical surface dwellers *G. obliquus/apertura* and the tropical intermediate species *G. menardii*.

The above mentioned warming interval continues up to 24.2 m, punctuated by several negative peaks in the palaeoclimatic curve. The overall warming trend is reflected by the relative high abundance of *P. siakensis, Orbulina* spp., *G. obliquus* and *G. apertura*. Negative values are recorded by the temporary decrease of warm water taxa and increase of cool fauna.

The long-term trend in PCA-1 reveals that the faunal composition of the studied interval changed significantly at 4.2 and 12 m of the section. The first distinct shift to positive loadings at the base of the section actually reflects the relative high abundances of *N. atlantica, G. scitula T. quinqueloba* and *G. nepenthes*, an association of cool water indicators.

The shift towards negative values at 4.2 m marks a significant reduction of neogloboquadriniids and a coincidently increase of the tropical species *G. menardii*. This observation fits well with the warming phase which is observed in the palaeoclimatic curve.

The positive shift recorded at 15m and 23 m in the PCA-1 is not well understood as this is in contrast with the palaeoclimatic curve. Both intervals are characterized by an increase in *P. siakensis* and *N. atlantica*. This opposite configuration in the PCA-1 is probably reflecting changes in nutrient supply rather than climatic fluctuations. As it has been previously reported *P. siakensis* is not a typical oligotrophic taxon, as it is related with sediments where eutrophic conditions prevail (Lirer et al., 2004).

5. Discussion

In order to attempt a palaeoclimatic reconstruction of early late Miocene in Ionian Sea area, evidence from the Atlantic and other Mediterranean sections are compared based on ecologic biostratigraphic and climatic data derived from planktonic foraminifera. The early late Miocene open ocean isotope record is characterized by an increased value known as Mi5 event (Miller et al., 1991). Mi5 event is positioned at the base of chron C5r by Miller et al. (1991) at about 11.7 Ma and biostratigraphically within the range of *D. kugleri* (Turco et al., 2001) between 11.868 and 11.573 Ma (ages after Turco et al., 2002). It is worth mentioning that at Site 1085, the *D. kugleri* zone is located between 11.9 and 11.5 Ma, indicating that this increase corresponds to the Mi5 event. Recent results from an astronomically dated deep marine succession in the Mediterranean (Gibliscemi section) indicate that the Mi5 event occurred at 11.4 (Turco et al., 2001), representing a deep water cooling. The onset of this event has been micropaleontologically correlated with the invasion of the neogloboquadriniids (*N. atlantica* and *N. acostastaensis*) into the Mediterranean, as well as the successive entries of the cool subtropical species *G. falconensis* and *Globoquadrina* sp. According the same authors the earliest neogloboboquadriniids vanished from Mediterranean at 11.55 Ma predating the maxima of $\delta^{18}O$. The upper part of Mi5 event is marked by the near absence of neogloboquadriniids and the replacement of a tropical fauna association by a subtropical one.

Our data support these assumptions and point to a pronounced global climatic cooling affected the Ionian basin. The cooling event is followed by a warming phase characterized by an increase in the tropical *G. menardii* and the tropical-subtropical *G. obliquus* species, whereas *P. siakensis*, a general warm but not typical oligotrophic species exists in its minimum abundance. The further reduction of the neogloboquadriniids during this interval suggests oligotrophic and warm conditions prevail probably due to intensification of monsoons. More explicitly, the intensification of monsoons is related to eccentricity maxima (precession minima), when high amplitude oscillations occurs in summer insolation. During precession minima, high temperature and oligotrophic conditions are evident by high abundances of *G. obliquus* and *G. quadrilibatus*. The intensification of monsoon is possible accompanied by intensive run off and low salinities in surface water column, as evidenced by an increase of *P. siakensis*, reflecting a period of eutrophic conditions.

6. Conclusions

Plankton biostratigraphy in this study confirms the interval between 11.54 Ma to 11.2 Ma for the deposition of the sediments of Manassi section by the regular occurrence of *G. obliquus* the absence of *G. subquadratus*, the near absence of neogloboquadriniids and the distribution pattern of *P. siakensis*. The surface-water temperature approach based on planktonic foraminifera ecological preferences allowed the recognition of five palaeoclimatic events superimposed on the long-term climatic trend supported by the principal component analysis applied on the total data set. The faunal composition suggests a cooling trend in the lower part, which has been correlated with the Mi5 event. This cooling event is followed by a warm-temperate phase, punctuated by several negative peaks in the palaeoclimatic curve. This interval has been attributed to the intensification of monsoon activity with an increase of run off that occurred at times of precession minima.

The palaeoclimatic evolution of the study area generally corresponds to the global palaeoclimatic trend with some subtle differences, supporting that the regional climate of this area was not merely controlled by global changes in climate. Further studies based on other palaeoclimatic proxies (e.g. $\delta^{18}O$) are needed in order to establish the palaeoclimatic reconstruction of the studied area.

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CONTRIBUTION TO THE LATE NEOGENE STRATIGRAPHY OF THE ANCIENT GORTYS AREA (SOUTHERN CENTRAL CRETE, GREECE)

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Abstract

Most of the basal Neogene sediments of Crete Island (South Aegean Sea) were unconformably deposited during synsedimentary extensional tectonics and subsequent transgression on the basement. This work mainly focuses on the marine stratigraphy of south central Crete and specifically on the sedimentary deposits of the Gortys subbasin-area located in the basin of Messara. Four selected profiles north of Gortys ancient ruins (Heraklion Province) are lithostratigraphically presented. Profiles Gortys-1 and -2 (combined to one: 1+2) represent the basal Neogene deposits (older strata-commence of sedimentation) and are interpreted as of fluviatile to lagoonal origin, while profiles Gortys-4 and -4a are considered the younger, marine development of the Gortys subbasin. Between profiles –4 and –4a are developed evaporites of the Messinian Salinity Crisis (MSC). Profiles are biostratigraphically studied and correlated on the basis of either identified macrofossils or calcareous and siliceous nannofossils. The recorded assemblages range in age from Serravallian-Tortonian to Messinian and Zanclean respectively. The good preservation and abundance of the fossil phytoplankton establishes a well-constrained biostratigraphic framework, which will further contribute to the understanding of the evolution of the Messara sedimentary basin.

Key words: *Biostratigraphy, calcareous nannofossils, Gastropods, Miocene, Pliocene, Gortys, Messara, Crete, Greece.*

1. Introduction

It is generally believed, that southward retreat of the trench in the Hellenic Arc System induced the arc migration, giving subsequently birth and shape to the modern Hellenic Arc System configuration (Wortel & Spakman, 1992). The Aegean Sea extension (mainly at the southern part of it) and the southward movement of Crete Island were both caused by the rollback effect of the slab and broadly the subduction zone (Le Pichon, 1982; Meulenkamp et al., 1994). According to the later authors, this rollback process is believed to start about 12 my ago. In addition, the active tectonics deformation of the Aegean region is dominated not only by extensional but by combined strike-slip motions and compressional tectonics as well (Jackson, 1994; Meulenkamp et al., 1994). The concentration of slab pull forces causes a pattern of subsidence with development of depocenters and uplift migrating along strike. Subsequently, it prevailed a maximum crustal thinning and subsidence in the region of Cretan Sea (mainly of Neogene age, but it continues nowadays as well), which produced the back-arc basin(s) at the north of Crete as it was firstly suggested by studies of Makris (1978), Angelier et al. (1982) and Wortel & Spakman (2000).

Presumably, the Neogene basins of Crete are generally considered the result of the prementioned subsidence and subsequent extension. Two successive marine sedimentation cycles (of Miocene and Pliocene age respectively) were originally distinguished on the island (Christodoulou, 1963; Meulenkamp et al., 1979; Frydas & Keupp, 1996). A third cycle representing the Pleistocene transgression known from Psarianos (1961), was documented by calcareous nannofossil stratigraphy by Keupp et al. (1994) and Keupp & Bellas *in collab*. with Frydas & Bartholdy (2000).

The present work contributes to the completion of previous stratigraphical investigations in the south part of central Crete (Messara plain) and it is particularly focused in the marine sedimentary record of the Gortys subbasin (upper facies: profiles Gortys-4 and -4a), its biostratigraphy and relative age estimation of deposition based on calcareous nannofossils. A rather rough description of the lower and middle facies (fluvial to lagoonal) will be presented (profiles Gortys-1 & -2), since a detailed analysis is under progress and it is far beyond the scope of this study [Demske, Keupp & Bellas (in prep.)]. Furthermore, the reliability of some known biohorizons of nannofossils has been evaluated along the studied sections and their applicability concerning the biochronological correlation in the eastern Mediterranean Sea is commented.

2. Geological setting

The study area is found on Crete Island, Heraklion Province (Fig. 1). The Miocene-Pliocene deposits of Heraklion are considered among the most extended of Crete. Two wide fault zones or systems, developed relative perpendicular to each other, tectonically control the configuration of Heraklion Neogene Basin of central Crete. The first, adjacent to Heraklion city, is running in the N-S direction and represents a shoal, while the second segment situated to the south of Heraklion, produced the Messara fault-trough along the E-W direction (Delrieu et al., 1991; 1993) and it is bordered to the south by the Asteroussia Mountain range. Further tectonic data on central Heraklion for Late Pliocene to Recent are given in Papanikolaou & Nomikou (1998), Fassoulas (2001), Ten Veen & Kleinspehn (2003), Peterek & Schwarze (2004), Hinsbergen & Meulenkamp (2006) and recently by Papanikolaou & Vassilakis (2009). The later authors propose that formation of the Messara supra-detachment basin in Middle Miocene time is related to a south dipping extensional detachment fault of the main E-W trending zone (tectonic horst).

Since there is very extensive literature concerning the lithostratigraphy and micropaleontology of Crete, the authors refer to Keupp & Bellas *in collab*. with Frydas & Bartholdy (2000) and for central Crete to Frydas et al. (2008), which include most of relative references. The prolongation of Heraklion Basin to the South and southwest of central Crete is called Messara Basin or Plain. Previous micropaleontological studies on this area like Zachariasse (1975), Jonkers (1984), Theodoridis (1984), Driever (1988) and Frydas & Bellas (2009) were focused on isolated outcrops and/or cores. Frydas (1985, 1987, 1990, 1999, 2004) and Frydas et al. (1994) concentrated much of his Neogene stratigraphical research in the central Crete (Heraklion Basin) using calcareous and siliceous fossils. Preliminary biostratigraphic data concerning the NE Mires area in Messsara have been published by Bellas & Keupp (2004). Among other authors, Drinia et al. (2005) and Koskeridou (2006) reported on central Crete benthic and planktonic Foraminifera and Mollusc issues of Pliocene age (Atsipades section, eastern Messara Basin). Brachert et al. (2006), Reuther et al. (2006) and Mertz-Kraus et al., (2009) refer to Tortonian-Messinian age shallow-marine clastics and carbonates with exceptionally well reef-growth from Messara, while recently α large part of the Messara marine stratigraphy was investigated by Frydas et al. (2008).

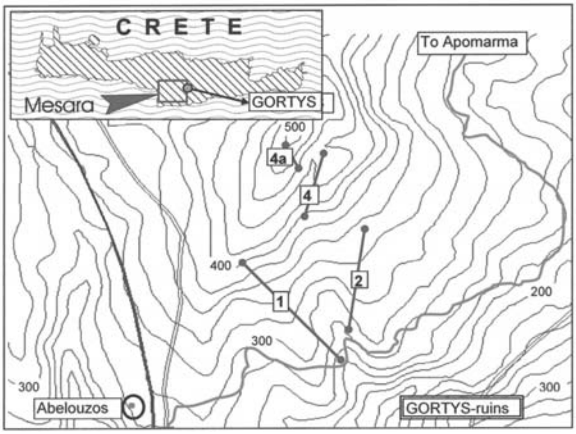

Fig. 1: Map with the location of the studied profiles (1, 2, 4 and 4a) in the Gortys subbasin (NW of ancient Gortys ruins, Messara, Crete Island, Greece. Contour interval 20m. Scale 1:50,000 (IGME, 1984 and Jarvis et al., 2008, SRTM digital elevation data slightly modified).

3. Methods

3.1 Geographical location

For the location of the studied sections it was used the Geological Map of IGME (1984), sheet "Tymbakion" (scale 1:50,000) and satellite data (SRTM digital elevation data, Jarvis et al., 2008). All studied outcrops are situated within a small gorge, running along a NNW-SSE direction and are located at the eastern part of Mesara Graben, to the N-NW of Agii Deka and to the N-NE of Abelouzos villages respectively, near the main street driving from Abelouzos to Apomarma, at ca. 1.2 km after the former village to the west. Further to the south, the ancient Gortys acropolis is to be seen, where the names of the outcrops come from [Gortys: The ancient city-acropolis of Gortys was founded and well developed between the 11th and 8th c. BC (Geometric Period) in the plain–basin of Mesara (Central Crete)] (Fig. 1).

3.2 Studied Material - Methods

During fieldwork, originally sediments of two outcrops to the west (Gortys-1) and east (Gortys-2) flank of the gorge were lithostratigraphically studied. They found to be very well correlative, therefore they were combined in one profile presented in this study (Gortys-1+2: basal and middle part). The other two studied outcrops (representing the marine record) are individually described (Gortys-4 and -4a: upper part). Decompaction of sediment was not taken into account. Fifty-four (54) samples in total collected and laboratory processed; thirty-one of them (Gortys-1) proved nannofossil free, while twenty-three samples taken from Gortys-4 and -4a sections provided useful biostratigraphic data. Smear slides preparation of soft sediment (mainly sandy marls) followed standard techniques. Micropaleontology was based on calcareous nannofossils identification under normal light microscope (LM at magnifications of ca. 1000x). A quantitative and subsequently semiquantitative study of them has been also performed. Quantification of species (counting 300 individuals per sample –i.e. smear slide-) is presented in Tables 1 and 2 for each section, based on the following pattern: **A** (Abundant)= >20%, **C** (Common)= 10-20%, **F** (Few)= 4-10%, **R** (Rare)= 1-4% and **+** for **P**resent. Reworking is shown by r. Biostratigraphic schemes used are the «standard» zones of Martini (1971) (NN) and Okada & Bukry (1980) (CN), the Mediterranean Nannoplankton Zonation for Neogene (MNN) of Rio et al. (1990) and those of Raffi & Flores (1995) emended by Fornaciari (2000). Taxonomy, additional useful bioevents and their paleomagnetic position and biochronological calibration are based on Theodoridis (1984), Perch-Nielsen (1985), Martini & Müller (1986), Driever (1988), Flores et al. (1992), Young et al. (1994), Berggren et al. (1995), Schackleton at al. (1995), Sprovieri et al. (1996), Rio et al. (1997), Negri & Villa (2000), Van Couvering et al. (2000), Lourens et al. (2004), Raffi et al. (2003, 2006) and Morigi et al. (2007).

4. Results

4.1 Lithostratigraphy-facies

The Gortys subbasin is built by a few minor horst and graben structures. Based on main sedimentary facies, this subbasin deposits can be distinguished into three parts, the lower (a), middle (b) and upper (c). The strata of the lower part rest uncomfortably on the Preneogene basement. They are mainly representative by (a) fresh-water deposits and range from (a1) fluviatile (at the base), with various types of conglomerates and sandstones in alternation with mudrocks, to (a2) lacustrine mudrocks with non-marine gastropods fauna and a coal layer at the top. There follow strata of the middle part, possibly lagoon in origin (b), starting with a stacked Oysters (*Crassostrea* sp.) bank. Further upwards, follow mudrocks bearing marine gastropods (b1) and strata barren of macrofossils (b2), while at the upper part (c) a well-developed thick marine succession dominates the latter being indicative of a marine transgression with hemipelagic character (c1). After a few covered meters with chaotic Evaporites (d: Messinian Salinity Crisis, MSC), a new but not as thick as previously, shallow-water facies marine succession is developed (c2), which finally closes deposition in the subbasin.

4.1.1 Combined Profile Gortys-1+2

As prementioned and based on field work and the descriptions of two outcrops at the left and right flank of the Gortys gorge structure (old subbasin), we could reconstruct a composite profile for the lower (fresh-water: fluvial to lacustrine) and middle (lagoon) sedimentary facies (Gortys-1+2). This succession comprises ca. 63.0 metres (m) in thickness (Fig. 2).

Sedimentation began with fresh-water deposits (facies a). Various fluvial deposits (a1) rest on the preneogene basement. They consist of alternations by medium-bedded conglomerates (an exceptionally useful stratigraphic horizon of conglomerate which measures 3.75m in thickness is present near the base of both flanks), green-grey pelites (mudstones) with fine to medium bedded clayey to silty sandstones, coarse-grained sandstones (indurate or not) and a few concretions layers in between. A conglomerate bed of 4.0m in thickness completes the fluvial facies at the top, which presents a total of 29.0m in thickness. Lacustrine deposits (a2) overlay the conglomerate. They are mainly consisted of green-grey mudstones (5.80m thick) and a lignitic layer of 0.40m in thickness. A rich limnic gastropods fauna dominated by *Potamides bidentatus* accompanied by *Ancilla* sp. and *Natica millepunctata* recovered from these strata.

The following upwards succession is considered of lagoonal origin (facies b). It comprises 27.80m in thickness and starts with a 0.80m thick stacked Oysters bank (*Crassostrea* sp.), overlying by 5.0m of grey mudstones bearing a rich marine gastropod fauna, like *Arca (Anadara)* spp., *Cerithium* sp., *Conus (Conulithus) dujardini*, *Dentalium (Antale) fossile*, *Natica millepunctata tigrina,*

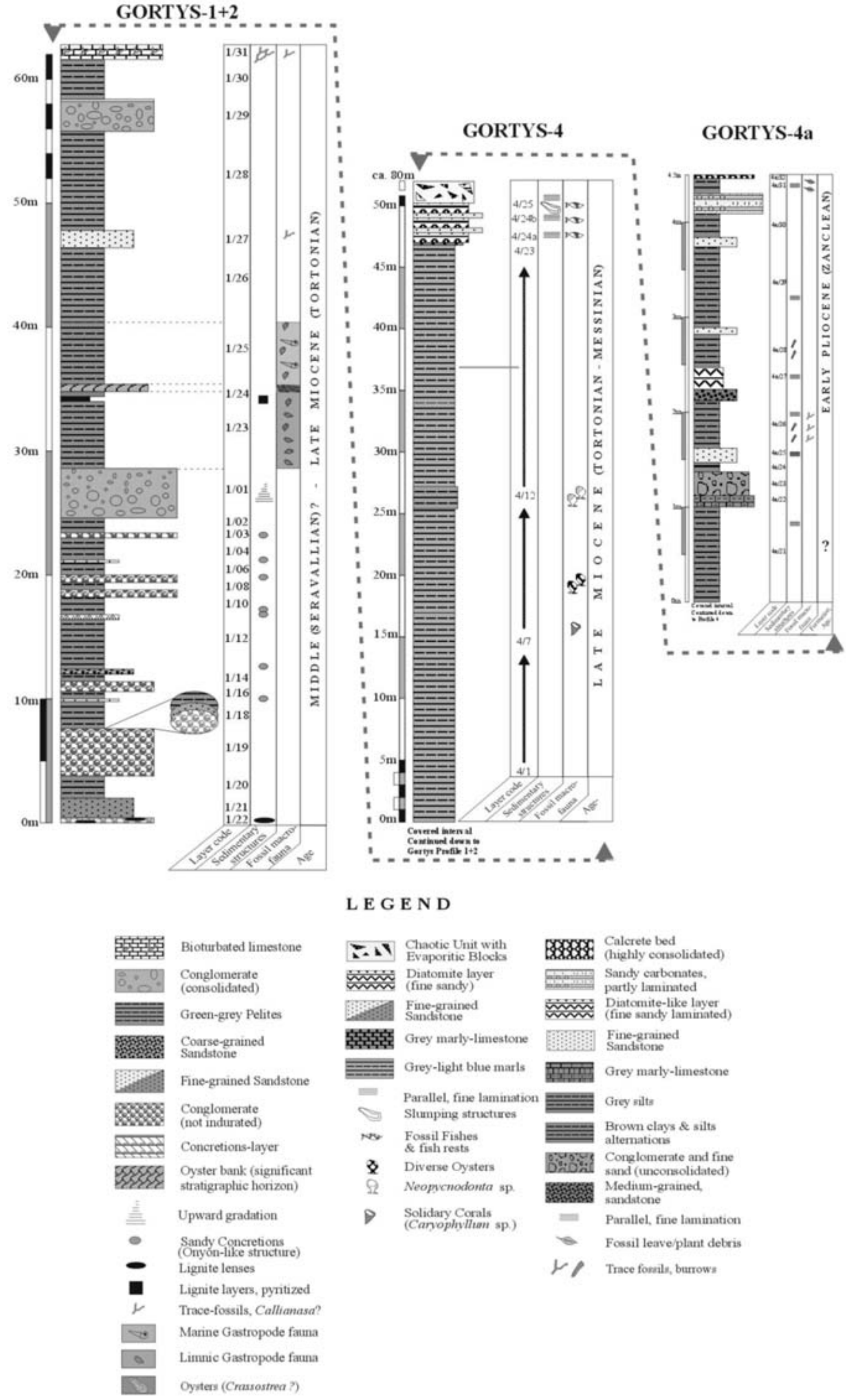

Fig. 2: Lithostratigraphy of the studied profiles; combined Gortys-1+2, Gortys-4 and Gortys-4a.

Theodoxus sp. and *Turritella tricincta*. Further upwards, the mudrocks dominate almost to the top. Exceptionally, three distinct horizons are to be observed; a fine-grained sandstone bank by the level of 46.0m (1.30m thick), a consolidated conglomerate by the level of 55.70m (2.0m thick) and a bioturbated limestone bearing traces of *Callianasa* sp. by the level of 62.0m, which closes the succession to the top.

4.1.2 Profile Gortys-4

A covered part of section exists between Gortys-1+2 and Gortys-4 Profiles. It seems that full-marine sedimentation (facies c) was developed again by the base of Gortys-4 Profile, mostly represented by grey to light blue marls of 48.0m in thickness. Fossil solidary corals (like *Caryophyllum* sp.), rich levels in *Neopycnodonta* sp. and some levels with diverse Oysters macroscopically prove this facies (Fig. 2). By the top of the profile the lithology shifts to sands and finely to laminated sandy Diatomites. Small fossil fishes (1-5cm) and fish-bone-rests are also observed. The profile closes at the top with a chaotic unit of ca. 28.0m, where evaporitic blocks of various sizes are incorporated (facies d, Messinian Salinity Crisis, MSC).

4.1.3 Profile Gortys-4a

Profile Gortys-4a measures 4.5m in thickness and it is situated ca. 150m to the west, over the main profile Gortys-4. It was sampled in order to complete the sedimentary record of the North Gortys subbasin area. It mainly consists of brown laminated silts and sands in alternation, bearing frequently plant debris and closes at the top with sandy carbonates and a calcrete bed (Fig. 2). A rich calcareous nannofossil flora gave evidence for the marine character of deposition (facies e).

4.2 Biostratigraphy

4.2.1 Profile Gortys-4

Calcareous nannofossils

Sixteen samples (s.1 to s.25) were biostratigraphically investigated from profile Gortys-4 (Table 1). The calcareous nannofossils assemblage recovered is very rich, well diversified and it is composed of at least 51 different species in total. In general preservation of fossil nannoplankton is very well to moderate. Secondary calcite overgrowth of several discoasterids is not the rule.

Ceratolithus cf. *primus*, although rare, is present from the basal sample (s.1). This is also apparent for *Discoaster berggrenii*/*Discoaster quinqueramus* intergrade. *D. berggrenii* FO (First occurrence) marks the base of CN9 Zone (*Discoaster quinqueramus*, Tab. 1) i.e. the base of CN9a subzone of Okada & Bukry (1980). Since both taxa occur at the base of Gortys-4 profile and considering that the *Amaurolithus primus* FO defines the base of CN9b (Okada & Bukry, 1980), it is obvious an assignment of the basal samples association to the CN9b subzone (co. Frydas & Bellas, 2009). In the absence of *A. delicatus*, this is partly equivalent with the upper part of the NN11a subzone of Martini & Müller (1986). Additionally, occurrences although rare of *Helicosphaera stalis* are in good agreement with this placement, which belongs to the *A. primus* Zone of Theodoridis (1984). Subsequently, samples association 1 to 18 is placed within the CN9b subzone of upper Tortonian age (Late Miocene). The LO (Lowest Occurrence) datum of *A. primus* (=LO of *Amaurolithus* spp.) was laid down to 7.424 Ma (Raffi et al., 2006; Tab. 3) and it was given an A (first) degree of reliability. Consequently, the Tortonian/Messinian boundary was also dated at 7.424 Ma for the Eastern Mediterranean, although generally it is dated at 7.246 Ma (Lourens et al., 2004).

Table 1. Calcareous nannofossil biostratigraphy of the Late Miocene profile Gortys-4. FoV= One Field of View in the light microscope (LM), under a magnification of 768x.

Profile Gortys-4, Messara Graben, south-central Crete																→ topwards
Discoaster quinqueramus Zone (NN11, CN9)																***Biozone (Codation)***
LATE MIOCENE (TORTONIAN) ╫→ MESSINIAN																***Series, Stage***
1	2	4	6	8	10	12	14	16	18	19	20	22	23	24	25	***←Studied samples Nr***
+= Present, R= Rare (1-4/50FoV), R/F= <1/FoV, F= Few (1-2/FoV), F/C= 3-9/FoV, C= Common (10-20/FoV), A= Abundant (21-50/FoV), VA= Very Abundant (>51/FoV)																***Calcareous nannofossils***
						+		+			R	R				*Nicklithus (A.) amplificus*
										R	R					*A. delicatus*
R	C	C	R	+	R	R/F	R	R	R	R	R	R	+	+	R	*Calcidiscus leptoporus*
	F	F	R	R	F/C	F	F	F/C	F	F	F	F	C	F/C	F/C	*Ca. macintyrei*
+	R	+			R			+	+	+		R	R	R	+	*Ceratolithus cf. primus (birefr.)*
															R	*C. rugosus*
								R			R					*C. tricorniculatus*
R	R	F	R	R/F	C	C	F	R	R/F	R/F	R	R/F	R/F	+	+	*Coccolithus pelagicus*
						R		+		R	R/F	+	R			*Cryptococcolithus takay.*
R	R	F	F/C	F/C	C	C	F	F	R/F	F	R	R	R/F	R	R/F	*Dictyococcites antarct.*
	R/F	R	R		C		A	VA	VA	A	C	C/A	VA	C	C/A	*Dic. productus*
+	+	R						+	+			R		+		*Discoaster adamanteus*
R	+		R		R/F		R	F	+	F	F	R	R	R	+	*D. berggrenii-quinquer.*
R	+		+					R	+	R	F	+				*D. brouweri*
	+				+		+	+	R	R	+	R/F	R			*D. challengeri*
							R	+	+				R			*D. pansus*
R	+		R		R/F	+		R	R	R	F	R/F	+	R		*D. pentaradiatus*
							+			+						*D. prepentaradiatus*
	R							R	R	+	R	R	R			*D. variabilis*
R/F	F	F	R	R	C	C	C	R	C	F/C	R/F	C	F/C	F	R	*Discoaster sp. (6-arms)*
R	R	+	+						R	R		+				*Discoasphaera tubifera*
A	A	C	C	C	C	A	C	C	C	C/A	C	A	C	C	C	*Geminilithella jafari*
R	F	F	F	F	R/F	F	R/F	R/F	F	F	F	F	F	R/F	R	*G. rotula*
+					R					R		+				*Hayaster perplexus*
F	F/C	C	C	F/C	C	C	C	C	C	C	F/C	C	C	F/C	C	*Helicosphaera carteri*
R	R	R	+	+	R	+		+	+		+	R				*H. intermedia-euphratis*
					R											*H. orientalis*
R	R					+	+	+			+	R	R			*H. pacifica*
+	+	R	R	R	R	R	+	+	+		+					*H. stalis stalis H. st. ovata*
						+							+			*Lithostromation perdurum*
R	R	R/F	R	R	R/F	R	R	R	R	R	R	R/F	R/F	R	+	*Pontosphaera spp.*
							+				+					*Reticulofenestra minutula*
+			R			R/F	R/F		R	+		R/F	R/F	+		*R. pseudoumbilica (>7μm)*
										R	R	R/F	R/F			*R. rotaria*
R	F	F	R	R	F	F	R/F	R	R/F	R/F	R/F	F	R/F	R/F	F	*Rhabdosphaera spp.*
+	+				F	R	R/F	+	R/F	R	R/F	F	F		R	*Scapholithus fossilis*
R	R	+	R		+	R	+	+	+	+	+	R	R	+		*Scyphosphaera spp.*
F/C	F	C	R	F	F	R	F	F	R/F	F	F	F/C	F/C	C	A	*Sphenolithus abies*
R									+				+			*Sph. verensis*
+	R	R/F	R		R	R		+	R						+	*Syracosphaera sp.*
	R						+			+	R	+	R	+		*Triquetrorhabdulus rug.*

Moving upwards, an occurrence of *A. delicatus* is recorded at the level of s.19 together with the FO of *Reticulofenestra rotaria*. The same pattern was also observed in the Pissouri section in Cyprus (Morigi et al., 2007). Both species are considered indicative of slightly predate the Tortonian/ Messinian (T/M) stages boundary. Although the LO biohorizon of *A. delicatus*, considered not reliable for open oceanic correlations by Raffi et al. (2006), it is very useful for marginal Seas like the Mediterranean. This bioevent, indeed, is recognized as the closest event to the *Globorotalia miotumida* datum and subsequently a good approximation for the T/M boundary (Morigi et al., 2007 and references therein). Based on the appearance of the former species the calcareous nannofossil assemblage of s.19 and upwards can be placed in the NN11b subzone of Martini & Müller (1986). Individuals of *D. berggrenii*/*D. quinqueramus* intergrade are consistently present along the studied section almost to the top.

The appearance and rapid extinction of *Nicklithus* (former *Amaurolithus) amplificus* bounds an interval within the CN9b subzone defined as CN9bB, with a C degree of reliability (Raffi & Flores, 1995; Raffi et al., 2006). In our record, this stratigraphic interval is found between s.20 and s.22. Following Raffi & Flores (1995) emended by Fornaciari (2000), it is therefore suggested an assignment of the s.19 assemblage (in the absence of *N. amplificus*) to the CN9bA subzone, while according to Martini & Müller (1986) it already belongs to the NN11b subzone. The nannofossils association of s.23 and s.24 is placed to the next younger in age subzone CN9bC due to absence of *N.* (*A.) amplificus* (Raffi & Flores, 1995 emend. by Fornaciari, 2000). However, *R. rotaria* is still present in s.23, making also possible an assignment of samples assemblage interval 19 to 23 to the homonymous Zone of Theodoridis (1984), which is partly equivalent with the NN11b subzone.

Ceratolithus rugosus occurrence only in the uppermost s.25 could place this assemblage in the CN10b subzone of Okada & Bukry (1980). Fornaciari (2000) did not utilize this species due to its rarity and Raffi et al. (2006) suggested a very low degree of reliability (D) to this event (considering its Lowest Occurrence). Therefore this event appears to be unreliable.

Summarizing, the samples interval between 1 and 25 of the Gortys-4 studied profile, is placed to the Late Miocene and specifically, the s. 1-18 to the Tortonian (CN9b, NN11a) and the s. 19-24 to the Messinian (CN9bA to CN9bC, NN11b), while s.25 could be a matter of debate (see below).

Siliceous component of GORTYS-4

Pennate diatom taxa like *Grammatophora* sp., *Rhizosolenia* sp. and Actiniscidians are included in the siliceous association of s.24b, but their preservation is rather moderate. The Silicoflagellate *Distephanus speculum* and centrate Diatoms like *Coscinodiscus* sp. are incorporated in the uppermost part of Gortys-4 (s.25), situated directly below the chaotic Evaporites. Additionally, Sponge spicules (s.25) like Oxeas, Triods etc. are common and present great variability.

Occurrence of *Ds. speculum* is biostratigraphically significant being indicative of the almost homonymous biozone *Distephanus speculum speculum* of the Late Miocene (Frydas, 1996). The recorded association can be correlated with a similar one from NW Crete (Messinian assemblage), Kastelli/Kissamou Neogene Basin (Keupp & Bellas in collab. Frydas & Bartholdy, 2000).

4.2.2 Profile Gortys-4a (supplement to Gortys-4)

Despite the relative reduced thickness of the studied profile, its stratigraphical importance is major, since it contributes to the completion of the Gortys subbasin evolution in course of Early Pliocene (postdate the MSC). Seven samples were biostratigraphically investigated. The calcareous nannofossils recovered are well diversified (41 identified species), but they occur in relatively low frequencies and rather inconsistently. In a biostratigraphic context, this is a very complicated profile. Following bioevents were identified along the studied profile moving from the base to the top (s.26b to s.32, Table 2):

Table 2. Calcareous nannofossil biostratigraphy of the early Pliocene profile Gortys-4a

Profile Gortys-4a, Messara Graben, south-central Crete							→ topwards
(NN14/15-NN16, CN10-CN11a- ?b)							**Biozone (Codation)**
EARLY PLIOCENE (ZANCLEAN)							**Series, Stage**
26b	**27b**	**28b**	**29**	**30**	**31a**	**32**	**←Studied samples Nr**
Abbreviations like in previous Table (+, R, F, C, A)							**Calcareous nannofossils**
	+						*Amaurolithus delicatus*
+		R	+	R			*Amaurolithus sp.*
R			C	C	R	C	*Calcidiscus leptoporus*
F/C	F	C		+			*Ca. macintyrei*
			+	+		R	*Ceratolithus cf. primus*
+		+	+				*C. tricorniculatus*
+	+		R	R		+	*Coccolithus pelagicus*
R		+	+	+			*Dictyococcites antarcticus*
C	F/C	C	C	F	F	F	*Dic. productus*
				R		+	*Discoaster asymmetricus*
+							*D. berggrenii-quinqueramus*
R	F	+	+				*D. brouweri*
	+		R	+			*D. challengeri*
	R/F						*D. intercalaris*
			R	F			*D. mendomobensis*
		R					*D. pansus*
	R		C	F/C		+	*D. pentaradiatus*
+	R			+			*D. surculus*
R	F	+		+			*D. variabilis*
C	F	F	R/F	R/F		+	*Discoaster sp. (6-arms)*
+		+				+	*Discoasphaera tubifera*
A	A	F/C	F			R	*Geminilithella jafari*
F	F	F	F	F	C	C/A	*G. rotula*
					F	C/A	*Geminilithella sp. (med.)*
			+				*Hayaster perplexus*
C	C	C	F	F	F/C	C	*Helicosphaera carteri*
			R				*H. intermedia-euphratis*
	R			R			*Lithostromation perdur.*
+	R/F	R	+			R	*Pontosphaera spp.*
+			+				*Reticulofenestra pseudoumb. μm)*
F/C	F/C	F	F	R	R/F	F	*Rhabdosphaera spp.*
R	+		+	+		+	*Scapholithus fossilis*
	R/F	+	+	R	+	F	*Scyphosphaera spp.*
C	C	C	C	C	F	F	*Sphenolithus abies*
			R	F			*Sph. neoabies*
+	R/F	F	F/C	F			*Sph. verensis*
R/F	F	F	F	R		R/F	*Syracosphaera spp.*
+							*Triquetrorhabdulus rugosus*

D. berggrenii/*D. quinqueramus* intergrade is absent, out of a simple presence in the basal s.26b. This excludes the nannofossils NN11 (CN9) Zone and in this context, the recorded association is indicative of a younger zone. *Triquetrorhabdulus rugosus* has also its only and Highest Occurrence (HO) in basal s.26b. This event marks the CN10a/CN10b subzones boundary (Okada & Bukry, 1980) with a given astronomical age estimation of 5.279 Ma from ODP data (Lourens et al., 2004; Raffi et al., 2006).

Ceratolithus tricorniculatus with a HO at s.29 has been commonly utilized as to define various zonal boundaries like 1) the CN10/CN11 (Okada & Bukry, 1980) and/or 2) the biostratigraphically equivalent MNN12/MNN13 in the Mediterranean (Rio et al., 1990; Fornaciari et al., 1996) and/or 3) the NN14/NN15 of Martini & Müller (1986).

Amaurolithus sp. disappears higher at the level of s.30. Usually, the HO of *Amaurolithus primus* was used to define the CN10/CN11 zones boundary (Okada & Bukry, 1980; Raffi et al., 2006). An age estimation of 4.50 Ma from ODP Leg 138 data is given for this event by Lourens et al. (2004).

Usually the extinction of sphenoliths (HO of *Sphenolithus* spp.) is used to define the early Pliocene (Zanclean)/mid Pliocene (Piacenzian) boundary (CN12aA/CN12aB subzones boundary) and it is approximated with an age of 3.7 Ma for the eastern Mediterranean (Lourens et al., 1996) or 3.65 Ma (Raffi et al., 2006: degree of bioevent reliability C). The HO of *Reticulofenestra pseudoumbilica* approximates this boundary as well (extinction at 3.839 Ma for E. Mediterranean in Raffi et al., 2006: zonal boundary CN11b-CN12aA, degree of reliability A). In our record, the HO of *R. pseudoumbilica* (although very scarcely present) is found at s.29, while the sphenoliths distribution pattern shows consistent occurrence to the top of the section, pointing clear to a still Zanclean age of the uppermost Gortys-4a assemblage (CN11a to ?CN11b subzone).

Summarizing, the nannofossil association of the basal sample 26b can be placed in the CN10a subzone due to the presence of *T. rugosus*. The next association (samples 27b to 29) belongs to the subzone CN10b. This is suggested by the presence of *A. tricorniculatus*, *R. pseudoumbilica* and *Sph. abies*, *Sph. neoabies* and *Sph. verensis*. *Discoaster asymmetricus* is found scarce and rare (s. 30 & 32), while FCO (First Common Occurrence) of *D. asymmetricus* marks the CN11a/CN11b boundary (Okada & Bukry, 1980; Rio et al., 1990; Fornaciari et al., 1996; degree of reliability B, with an age of 4.120 Ma in E. Mediterranean, Raffi et al., 2006). In the next samples (31a & 32), the disappearance of *A. tricorniculatus*, *Sph. neoabies* and *Sph. verensis*, the reduce in frequency of *Sph. abies*, the very scarce occurrences of *D. asymmetricus* in conjunction with the bioevent of *Discoaster pentaradiatus* PE (introduced by Fornaciari, 2000) in the absence of *Discoaster tamalis* (FO in the CN11b subzone) and *Pseudoemiliania lacunosa* (FO within the CN11b), are all indicative of the subzones interval CN10c to CN11a.

Summarizing, all the available data indicate a lower Pliocene age (Zanclean) for the Gortys-4a profile and place its deposits (together with those of Kourtes) among the youngest in the Messara area.

5. Concluding remarks

In order to improve our knowledge of the late Cenozoic geological history of central Crete, we studied four Neogene outcrops north of Gortys ancient city ruins in the Messara plain (Gortys subbasin). Due to lithostratigraphical similarities, two of them (Gortys-1 and -2) which represent the older strata, were combined as one (Gortys-1+2) and are interpreted as fresh-water (fluvial) to lagoon deposits. The other two studied Profiles (Gortys-4 and -4a), which represent the depositional continuation of the previous, represent a marine development of the subbasin towards the top, interrupted by the MSC (recorded as a chaotic evaporites unit at the upper part of Gortys-4). For the latter two profiles was applied calcareous and siliceous nannofossils biostratigraphy.

A Late Miocene age is given to the deposits of Profile Gortys-4. The calcareous nannofossils assemblages characterize the *Discoaster quinqueramus* Zone (NN11, CN9) and specifically, the samples assemblage s.1 to s.18 (lower part of the profile) suggest an assignment to the CN9b (NN11a or *Amaurolithus primus*) subzones of Tortonian (sensu Okada & Bukry, 1980; Martini & Müller, 1986; Theodoridis, 1984), while samples assemblages s.19 to s.24 assigned to the CN9bA to CN9bC [sensu Raffi & Flores (1995) emend. by Fornaciari (2000)] (or NN11b or *Reticulofenestra rotaria*) subzones of lower Messinian (Martini & Müller, 1986; Theodoridis, 1984). Key species include biohorizons and correspondent reliability degrees (Raffi et al., 2006) of *A. primus, A. delicatus, D. berggrenii/D. quinqueramus, H. stalis, R. rotaria* and *N. amplificus*.

Additionally, occurrence of the silicoflagellate species *Distephanus speculum* clearly points out to a Late Miocene age for the uppermost sample assemblage of Profile Gortys-4 (s.25). This fact together with development of the chaotic evaporites above s. 25, proves the Late Miocene age of the section sediments. Large similarities were detected in litho- and bio-stratigraphy context between Gortys-4 and Pissouri section in Cyprus (co. Morigi et al., 2007).

Considering the calcareous nannofossil assemblage of profile Gortys-4a, last record of *T. rugosus* (HO) is found in basal s.26b. This event marks the CN10a/CN10b subzones boundary (Okada & Bukry, 1980) with a given astronomical age estimation of 5.279 Ma (Lourens et al., 2004; Raffi et al., 2006). Since *D. asymmetricus* FCO is estimated with an age of 4.120 Ma in E. Mediterranean and this event has not been detected in the studied samples of profile Gortys-4a, it means that the uppermost layers of the profile are surely younger in age than this estimation. Subsequently, the calcareous nannofossil assemblage of Gortys-4a characterizes the uppermost CN10a to CN11a subzones (Zanclean, early Pliocene) and covers an interval of approximately 1.159 my of deposition. Key species include absence of *D. berggrenii/D. quinqueramus* and biohorizons of *T. rugosus, A. delicatus*, *D. asymmetricus*, *Sphenolithus* spp.

Concluding, the Gortys subbasin development commenced with a thick succession of fluvial deposits (Gortys-1+2) possibly in the course of Seravallian to lower Tortonian (based on the fact that they underlie and subsequently predate the Tortonian age marine strata of Gortys-4), then sedimentation turned to lagoonal and after an azoic silty interval started the pure marine transgression in the subbasin during upper Tortonian, while deepening of it continued in the lower Messinian (Gortys-4). Evaporites predominantly of chaotic structure close this succession to the top, pointing to the well known desiccation (MSC) of the Mediterranean (top of Gortys-4). After a covered interval, strata of profile Gortys-4a record a renewal of transgression (lower Pliocene) in the course of Zanclean. It is suggested that the Gortys subbasin area should have been uplifted in Piacenzian (middle Pliocene) and remain exposed since then.

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UPPER CRETACEOUS (MAASTRICHTIAN) LANDVERTEBRATE DIVERSITY IN ALBA DISTRICT (ROMANIA)

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Abstract

In Romania, Maastrichtian (Late Cretaceous) dwarf dinosaur remains were first reported from the Haţeg basin by the Baron Franz Nopcsa, at the end of 19th century. Later, the same expanded his research to others areas of Transylvania, adding new localities with comparable Maastrichtian vertebrate assemblages in Alba and Sălaj Counties. Following Nopcsa, both these regions and topics have not been studied for a long time. In the last decade, new field works succeeded in finding rich and diverse Maastrichtian terrestrial vertebrate fauna in Alba County restricted to a distinct Late Cretaceous sedimentary area (Metaliferi). For these studies, the Şard Formation is of main interest. In this formation, the Maastrichtian is developed in fluvial system environments which are documented by flood plain overbank and channel fill deposits. Besides fishes, amphibians, birds and mammals, the fossils embrace mainly various dinosaurs such as sauropods, hadrosaurs, ornithopods, ankylosaurs, various small-sized theropods, as well as other reptiles as turtles and crocodilians. Often, the remains are fragmentary and dislocated. Besides the Haţeg basin, the Metaliferi area is the second important region documenting the Maastrichtian terrestrial biota in Romania.

Key words: *Romania, Transylvania, Late Cretaceous, dinosaurs, land vertebrates.*

1. Introduction

Maastrichtian dinosaur localities are scarce in Europe (northern Spain, southern France, and Romania). In Romania, the first Maastrichtian dwarf dinosaurs had been reported since over a century ago by Baron Franz Nopcsa, in the Haţeg basin. The same continued his survey also to other areas from Transylvania as in Alba and Sălaj counties where he found comparable Maastrichtian vertebrates (Nopcsa, 1905). Later, other studies underlined the remarkable abundance (Grigorescu, 1992; Grigorescu et al., 1999) and diversity of these assemblages (Codrea et al., 2002a; Smith et al., 2002).

Nopcsa assumed the presence of Maastrichtian deposits rather southwestern Transylvania at Vurpăr and Lancrăm (Nopcsa, 1905; 1909), where he found mainly ornithopod remains. Except few contributions (e.g. Grigorescu, 1987) pointing out mainly the low potential of Alba Maastrichtian localities, the area has hardly been studied for several decades after Nopcsa. In '90, new works carried out in Alba County by palaeontologists of "Babeş-Bolyai University", succeeded in adding new localities with Maastrichtian terrestrial vertebrates to those already known before (Codrea et al., 2001, 2002b, 2009). These finds enlarged the knowledge on this biota considerably by recording new taxa

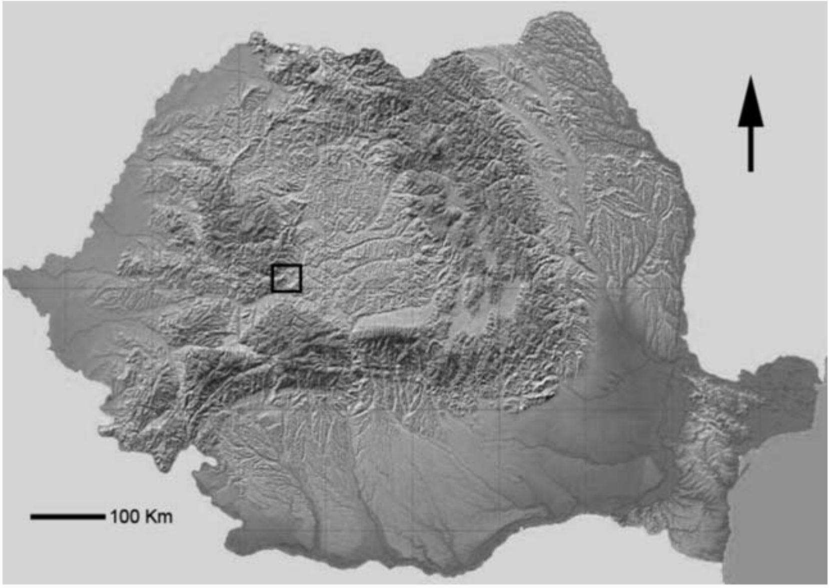

Fig. 1: Location of the Maastrichtian Metaliferi sedimentary area in Romania.

for this region. Codrea and Dica (2005) outlined a distinct sedimentary area in Alba County with Late Cretaceous formations named Metaliferi area (Fig. 1). The Alba continental formations are probably coeval with the Sânpetru Formation of the Haţeg basin. The paleomagnetic studies evidenced that the Sânpetru Formation is Lower Maastrichtian (Panaiotu & Panaiotu, 2002, 2009). However, palynological data (Antonescu, 1973; Antonescu et al., 1983) indicate that the samples collected in the Pâclişa Valley (south Alba Iulia) would be Late Maastrichtian age, according to the *Pseudopapillopollis praesubhercynicus* GOCZAN, GROOT, KRUTZCH, PACLTOVA, 1967 assemblage. Obviously, more data are needed for a refined stratigraphy of the area.

2. Geological setting

Located in southwestern Transylvania, in the Metaliferi sedimentary area Upper Cretaceous-Lower Miocene formations (Codrea et al., 2003; Codrea & Dica, 2005) marine and continental environments are inerbeded.

A Maastrichtian continental sequence can be observed between the Bozeş and Ighiu formations. It begins with the Vurpăr Formation (deltaic sequence, interrupted by several short marine ingressions) and Şard Formation (fluvial red beds, with flood plain red silty clay and conglomerate and arenitic channel fills (Codrea et al., 2001, 2009). Mainly the last bears relatively numerous vertebrate fossils. In both formations, the bases and tops are obvious well-defined due to the turnover of environments which are reflected in their lithologies. The first one is dominated by yellowish sand and sandstones, the second by red beds.

While the base of the Şard Formation is doubtless Maastrichtian, the age of the top is less clear: the sedimentation may have lasted into the Paleogene but currently there is no evidence. It may therefore also be presumed that the whole sequence could be exclusively of Maastrichtian age. Its clastic input probably originated from two source areas: one at the Apuseni Mountains, and a second at the South Carpathians. The detrital inputs from these two sources interfered toward the centre of the sedimentary basin.

The first type of lithoclasts originates from magmatic acid and basic rocks, Upper Jurassic limestones, jaspers, Cretaceous sandstones, metamorphic rocks, which are reworked in conglomerates and arenites. It can be observed in a series of red beds outcrops between Vurpăr-Pâclişa-Şard-Bărăbanţ, deposited over the folded nappes of the Apuseni Transylvanids (Săndulescu, 1984). In the Vurpăr and Stăuinii Valley, the vertebrate fossils occur mainly in the basal part of this succession, but are extremely scarce toward its top. The entire sequence suggests a braided fluvial system with channels fills of sand and gravel, internal bars and overbank accumulations with red silt and pedogenetic levels. Here and there, as at Oarda de Jos, the fluvial system developed pond-like deposits with tendencies of forming small lakes in part represented by grey-blackish silt clay (Codrea et al., 2001).

The second source area discharged mainly metamorphic and pegmatitic clasts, filling numerous channels. Such red beds are exposed at Petreşti, Râpa Roşie and Râpa Lancrămului (near Sebeş and Lancrăm). While the first locality was only found recently, the other exposures are notorious in Romania, being geological areas under protection (Toniuc et al., 1992). However, the geological age of these red beds is rather controversial. Until now, there was a general consensus for a Cenozoic age (e.g. Grigorescu, 1987, Codrea & Dica, 2005 etc). The evidence was the existence of nummulite limestone pebbles and boulders inside these deposits. In fact, these Paleogene limestones -which can be found in Râpa Roşie-, originate from reworked rocks of the transgressing marine Middle Miocene (Badenian) that overlies the red beds. They are simply rolling down the scarp and remain trapped in the red mud after heavy rainfalls. Therefore, the nummulite limestone does not belong to this formation. The fossils reported from these deposits are exclusively those of Late Cretaceous reptiles (Koch, 1894, 1900; Grigorescu, 1987; Jianu et al., 1997; Codrea & Vremir, 1997; Codrea et al., 2008), being apparently reworked: the bones are white and broken the tips eroded, indicating transportation. However, these features are only valid for the fossils collected from the basal sequence of the red beds in Râpa Roşie but not in its upper part. In fact, the upward fining tendency in this locality has already been before (Grigorescu et al. 1990), but this sedimentary trend remained devoid of explanation. Recently, a cervical vertebra of a huge azhdarchid pterosaur was found in the upper portion of the Râpa Roşie red beds sequence (Vremir et al., 2009). The bone does not show any marks of reworking. Anyhow, such a fragile bone could never be ever reworked without breaking into pieces. Besides this vertebra, other reptile bones found in the same section are devoid of reworking marks, too. Considering this, the red beds from Râpa Roşie should be reassessed to the Maastrichtian, Şard Formation, too.

3. The Maastrichtian biodiversity

In all outcrops the vertebrate remains are not very rich. The bones of the large size reptiles are frequently broken and the fragments scattered. However, occasionally, parts of skeletons in anatomical connection occur, as in Vurpăr (Codrea et al., 2009) or Sebeş-Glod, thus documenting the autochthonous status of the fossils. The majority of the red beds outcrops (Vurpăr, Stăuinii Valley, Râpa Roşie, Râpa Lancrămului, Petreşti) yielded white or coloured bones with cracks on their surfaces, proving long weathering before burial. On the opposite, in localities (Oarda de Jos; Codrea et al., 2001, 2009) with pond sedimentation, the fossilisation is completely different, with black or grey coloured bones. In these environments, the bones frequently originated from the preys of crocodile (frequent bite-marks on numerous crocodile bones; Delfino et al., 2008). The burial of the bones into the mud was faster there.

The macrovertebrate remains were collected by annual monitoring of the localities over a decade. The survey has led to a rich collection of various teeth and bones, originating from different vertebrate taxa.

The majority belongs to reptiles, but other groups are well represented too. The fossils are housed in the "Babeş-Bolyai" University Cluj-Napoca, Department of Geology - Palaeontology. Besides macrovertebrates, microvertebrates are also present in the Maastrichtian fossil record for the Metaliferi area.

Reptiles

Dinosaurs

The dinosaur teeth and bones are sometimes fairly well preserved. The faunal assemblage includes titanosaurids, a hadrosaur, ornithopods, an ankylosaur, and theropods.

The sauropod titanosaurs are well documented at Sebeş, Oarda de Jos and Lancrăm, but are missing in other places, as Vurpăr. Samples include femora, humeri, tibia, fibulae and mostly caudal vertebrae. The skulls are unknown, probably due to taphonomic reasons. The limb bones are usually well preserved, as the tibia illustrated in Fig. 2a.

The single notorious basal hadrosaur known from Romania, *Telmatosaurus transsylvanicus* is attested by one scapula, several tibiae (more or less well preserved) and femora. The most important outcrops where it is well represented are Lancrăm, where 7 pieces have been found and Oarda de Jos, with 2 pieces only.

Besides the hadrosaur, the other ornithopod dinosaurs belong to *Zalmoxes*. These fossils are very frequent in Vurpăr. The samples include cranial and limb bones as fibulae, humeri, tibiae, as well as numerous dorsal and caudal vertebrae. Some fair preserved isolated teeth have been collected in Vurpăr (Fig. 2d).

The nodosaurid ankylosaur (the only genus reported from the Maastrichtian in Romania is *Strutiosaurus*) is documented by a large number of dorsal and caudal vertebrae, fragments of femora and numerous osteoderms (Fig. 2b).

Remains of Theropod dinosaurs are scarce. They consist only of isolated teeth which seem to evidence a rather large diversity, assigned to Velociraptorinae or Theropoda *incertae sedis* (Fig. 2g).

The dinosaur teeth and bones are sometimes accompanied by eggshell fragments. These fragments are extremely numerous in Oarda de Jos and are referring to four types (Monique Vianey-Liaud, Montpellier, *written communication* 2008) including ?Pseudogeckoolithus and Megaloolithidae, pointing to similarities with the eggshells reported from the Haţeg basin (Grigorescu et al., 1990, 1994; Codrea et al., 2002a; Smith et al., 2002; Csiki et al., 2008).

Crocodilians

Crocodilian remains are numerous in Oarda de Jos, being represented by many isolated teeth and skull fragments. The best-preserved and most complete skull ever discovered originates from Oarda. It belongs to the eusuchian *Allodaposuchus precedens* (Delfino et al., 2008). The isolated teeth are either highly conical, with small smooth mesial and distal carinae, belonging to *Allodaposuchus precedens* (Fig. 2c) or short, broad triangular and labio-lingually compressed, probably belonging to *Doratodon*.

Turtles

There are several fragments from plastron and carapaces, vertebrae and leg bones, the majority originating from Oarda. Most of the material collected belongs to a Dortokid species (Vremir & Codrea, 2009; Lapparent et al., 2009). The remains of the species *Kallokibotion bajazidi* are less abundant (Codrea & Vremir, 1997; Vremir, 2004; Vremir & Codrea, 2009; Lapparent et al., 2009).

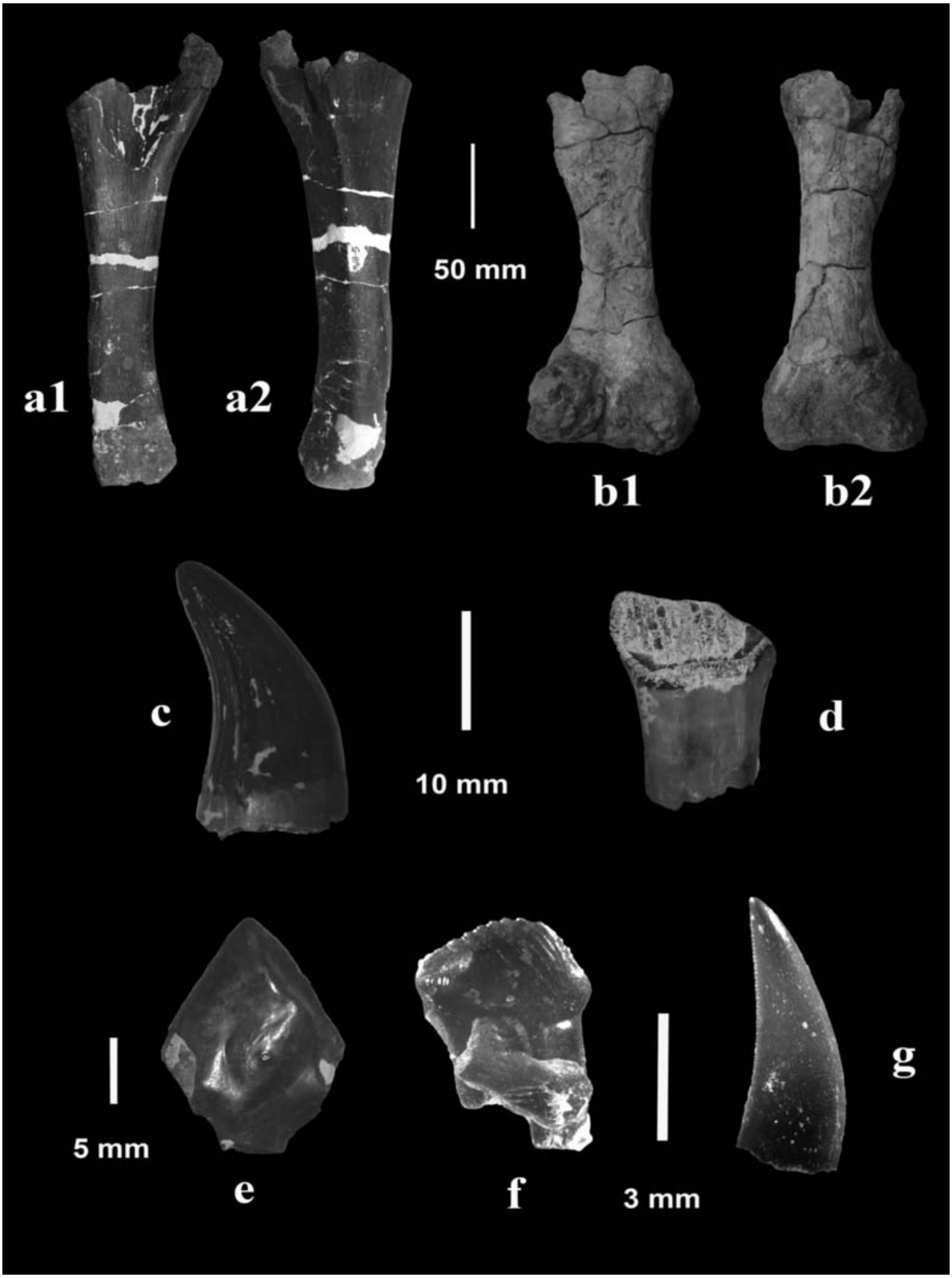

Fig. 2: Maastrichtian vertebrates from Alba County: (a1, a2) Titanosauria, right tibia (UBB OdB-5), posterior and anterior views; (b1, b2) *Struthiosaurus transilvanicus*, right femur (UBB VP-26), posterior and anterior views; (c) *Allodaposuchus precedens*, tooth; (d) *Zalmoxes* sp., isolated tooth (UBB VP-71), lingual view; (e) Lepisosteidae fish scale, Oarda de Jos, external view; (f) Multituberculate tooth: Kogaionidae indet., p4, lateral view; (g) Theropoda *incertae sedis*, tooth, lateral view.

Other vertebrates

Fish

The sample includes around 100 teeth, many vertebrae and scales (Fig. 2e). According to teeth and scale morphologies they mainly belong to the Lepisosteidae.

Amphibians

Numerous maxillary fragments with various numbers of teeth are preserved, distal ends of humeri, ulnae, frontals and vertebrae: axis, atlas and sacral refer to the Albanerpetontidae (Allocaudata). Frog remains include limb elements such as urostylae, fused tibiofibulae and radi-ulnae.

Lizards

Fossils such as jaws and dentitions prove the presence of several lizard species. One of them exposes slightly tricuspid and cylindrical teeth. A well-preserved frontal belongs to the same group.

Mammals

Like in the Haţeg basin, the only mammal remains collected from this area are those of Kogaionidae multituberculates (more than 30 isolated upper and lower teeth document this group; Fig. 2f). They were collected by screen-washing about 1.8 ton of sediments. The Eutherians remain unknown from this biota.

4. Conclusions

The dinosaur assemblage of the Metaliferi area is similar with to the notorious ones reported from different localities of the Haţeg Basin. Outlining an inland area, the dinosaurs from Alba County supplement the knowledge of the environments and the paleogeography of the Late Cretaceous in Transylvania, where these taxa evolved from (Nopcsa, 1914; Codrea et al., 2009). Preliminary studies on microvertebrates add new data about the Maastrichtian terrestrial ecosystem, increasing the systematic biodiversity. They may yield additional details for reconstructing the Maastrichtian climates and biota in Transylvania.

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COMPARING LIVING AND HOLOCENE COCCOLITHOPHORE ASSEMBLAGES IN THE AEGEAN MARINE ENVIRONMENTS

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Abstract

Detailed quantitative analyses of coccolithophores performed on the shallow deposits of the south-eastern Aegean region (core NS-14, 505 m depth), evidenced that the distribution of calcare-ous nannoplankton assemblages during the last 13 ka BP reflects paleoenvironmental changes which are directly related to parameters such as temperature, salinity, productivity and nutrient flux in the water column. Analysis enabled the separation of the assemblages in four groups. Group A consists of Emiliania huxleyi and the subtropical species Syracosphaera spp. and Rhabdosphaera clavigera, Group B is composed of Helicospaera spp. and Florisphaera profunda, typical species for high productivity conditions in the middle-lower photic zone, Group C consists of Gephyrocapsa oceanica and Braarudosphaera bigelowii, that characterise low salinity conditions and Group D includes Umbilicosphaera spp. and Calcidiscus spp. which are described as relatively eutrophic species. The Holocene assemblages differ distinctly from the living coccolithophore communities in the coastal ecosystems of the Aegean Sea, where only Group A coccolithophores are thriving in the seasonally controlled marine environment.

Key words: *coccolithophores, living communities, fossil assemblages, Holocene, Aegean Sea.*

1. Introduction

Coccolithophores/calcareous nannoplankton constitute a significant component of the marine phytoplankton in modern oceans that can provide sensitive indicators of environmental conditions because it directly depends on surface water temperature, salinity, nutrient contents, and the availability of sunlight (e.g. Giraudeau et al., 1993; Winter et al., 1994). Consequently, changes in fossil coccolithophore assemblages, recorded by the study of marine sediments, are a successful palaeontological tool for the reconstruction of the paleoclimatic and paleoceanographic conditions in the geological past (e.g. Negri and Giunta, 2001; Principato et al., 2006; Giunta et al., 2003, Triantaphyllou et al., 2009a). In the Mediterranean Sea waters, the living coccolithophores present a high number of species (e.g. Kleijne, 1993; Cros, 2001; Knappertsbusch, 1993; Triantaphyllou et al., 2002, 2004; Malinverno et al., 2003; Dimiza et al., 2008a) with a strong seasonal variability and regional patchiness. The oligotrophic character of the Mediterranean Sea, as well as the high seasonality in sea surface temperatures, solar radiation, nutrient concentrations and in the circulation of surface water masses affect the content, the species abundance and the productivity of living coccolithophores in general. In addition, the region is ideal for reconstructions of past climatic changes due to its unique physical and geographic configuration, as it displays complicate sea-bed morphology and numerous island complexes. The short- and long- time

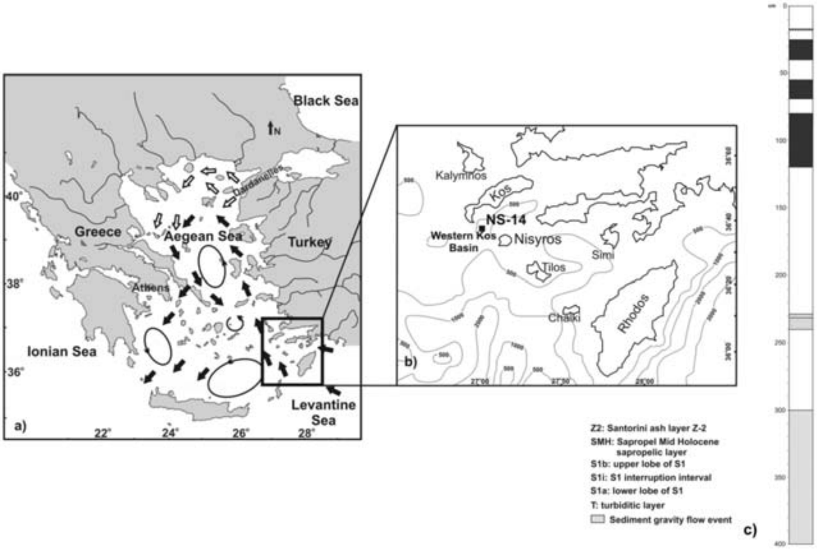

Fig. 1: a Location of the study area in the SE Aegean Sea and principal circulation patterns of the surface waters. b Location of core NS-14. c Core NS-14 stratigraphy (after Triantaphyllou et al., 2007, 2009a, b).

scale climatic and oceanographic events of the Late Glacial – Holocene, as recorded in the sediment record, resulted in the response of coccolithophores and was therefore recorded in fossil assemblages. We attempt herein to determine the changes in calcareous nannoplankton assemblages of the southeastern Aegean region (core NS-14) during the last 13 ka BP. Diversity indices and multivariate analyses were used in order to evaluate the impact of environmental changes on fossil coccolithophore assemblages using the ecological preferences of several taxa. Moreover, a comparison of the fossil coccolithophore assemblages with the living coccolithophore communities in the Aegean Sea is provided.

2. Materials and previous studies

The NS-14 gravity core, 400 cm long was recovered during the R/V Aegeo-Cruise 1998, in western Kos Basin (SE Aegean Sea), from a water depth of 505 m, at 36° 38´ 55´´ N and 27° 00´ 28´´ E (Fig. 1a, b). The western Kos Basin lying between Kos and Nisyros islands represents the easternmost edge of the volcanic arc that characterizes the recent Aegean Sea. The prominent tectonic features of the area are dominated by the active Kos fault zone, resulting to the complexity of the bottom morphology and the existence of five separate submarine basins including the western Kos basin. The depth of the basin does not exceed 510 m (Papanikolaou and Nomikou, 2001).

The dominant lithology of the sediment core is grey hemipelagic mud (Fig. 1c). The most recent Z2 Santorini tephra layer is positioned at a depth of 17 cm. A first dark layer, defined as the mid-Holocene sapropel-like layer (Sapropel Mid Holocene -SMH; Triantaphyllou et al., 2009b). Sapropel S1 is recognised from 55 to 120 cm and is distinctively divided in two units (S1a, S1b) by a lighter grey coloured interval from 69-80 cm. A turbiditic layer (T) is located between 231 and 240 cm. Grey clay with pebbles prevail from 300 cm to the bottom, representing a gravity flow event (Triantaphyllou et al., 2009a, b).

The age model for core NS-14 has been taken from Triantaphyllou et al. (2009b). According to the age model the base of S1a is considered to have an age of 10 ka cal BP whereas the top of S1a corresponds to 7.9 ka cal BP. The top of S1 interruption is calibrated at 7.3 ka cal BP and the top of S1b has an age of 6.4 ka cal BP.

3. Methodology

A total of 156 samples were collected for coccolithophore analysis every 2 cm in the hemipelagic mud and every 1 cm in the sapropel intervals from the upper 300 cm of the NS-14 gravity core. Sample preparation followed standard smear slide techniques. Analyses were performed using a Leica DMSP optical polarising light microscope at 1250x magnification by counting at least 300 specimens per sample. Additional counts of 15 fields of view (Negri and Giunta, 2001) were performed for the species lesser occurrence such as *Helicosphaera* spp., *Rhabdosphaera clavigera*, *Syracosphaera* spp. The rare species *Braarudosphaera bigelowii* was counted in a fixed area of 150 fields of view. All results were converted in relative abundances of selected species in order to avoid dilution effects such as the input of terrigenous matter (Flores et al., 1997).

The ecological measures were calculated using the Past.exe 1.23 software package (Hammer et al., 2001), including Dominance (D) and Shannon–Wiener (H′) diversity indices. The dominance index (Simpson, 1949) was calculated to express the abundance of the most common taxa as a fraction of the total number of individuals, whereas Shannon Wiener index measures heterogeneity evaluation, which means the distribution of individuals in the different taxa (Magurran, 1988).

Multivariate statistical analyses [R-mode Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA)] were performed using SPSS (version 10.1) statistical software. Analyses applied to 10 taxa with sufficient occurrence and higher abundance. HCA was used to determine species associations and to assess the ecological affinity among different groups. PCA was carried out in order to evaluate the factors that interpreted the impact of environmental changes on fossil coccolithophore assemblages.

4. Results

R-mode HCA on nannoflora of the core NS-14 allowed us to discriminate four groups of coccolithophore taxa (Fig. 2). In Group A *Emiliania huxleyi* is the most abundant species. Associated taxa include *Rhabdosphaera clavigera* and *Syracosphaera* spp. (mainly *S. pulchra*). Group B is dominated by *Florisphaera profunda* and *Helicospaera* spp. (mainly *H. carteri*). The Group C consists of *Gephyrocapsa oceanica* and *Braarudosphaera bigelowii* and Group D is composed of *Umbilicosphaera* spp. and *Calcidiscus* spp.

In addition, R-mode PCA allows an interpretation of the complex patterns of nannofossil changes on the Holocene deposits of the southeastern Aegean region. The first and second components of PCA account for 29% and 25% of the variance respectively. The first component is positively loaded mainly by *E. huxleyi* with negative loadings for *F. profunda*, while the second component is positively loaded mainly by *Umbilicosphaera* spp. and *G. oceanica* (Table 1).

The cumulative plots of the four coccolithophore Groups are shown in figure 3. They are plotted with the pattern of diversity indices and score plots of two components of PCA. Group A characterizes the lower part of core (> 10.5 ka cal BP). Above this, its relative abundance gradual decreases with minimum frequencies (exceeds 40 %) between 76-72 ka cal BP. Group A increases again from ~4.5 ka cal BP towards the core top. At the mid-section of the core, between 10.5 and 6.7 ka cal BP,

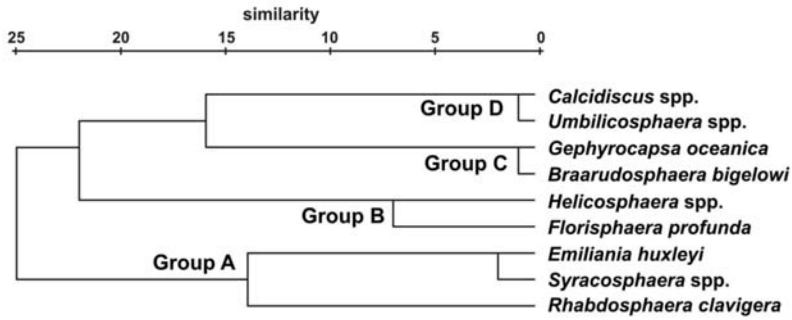

Fig. 2: HCA (centroid linkage method; distance metric is 1-Pearson correlation coefficient) based on the relative abundance of the coccolithophore species.

Group B alternates with Group A and presents maximum frequencies (up to 60 %) between 7.6 and 7.2 ka cal BP. The presence of Group C is distinct in the upper part of core after 8 ka cal BP, while Group D occurs mainly between 6.5 and 4.8 ka cal BP with an abrupt increase at ~ 6.5 ka cal BP.

The components singled out by the PCA may be referred to Groups of the HCA. The component 1 score plot shows similar graphic trend with Group A and opposite with Group 2 (Fig. 3). The component 2 score plot present short fluctuations and mainly negative values at the lower part of core

Table1. Component Matrix

	component 1	*component 2*
Braarudosphaera bigelowii	0,090	0,661
Calcidiscus spp.	0,124	0,651
Emiliania huxleyi	0,947	0,033
Florisphaera profunda	-0,939	-0,115
Gephyrocapsa oceanica	0,146	0,700
Helicosphaera spp.	-0,407	0,472
Rhabdosphaera clavigera	0,313	-0,026
Syracosphaera spp.	0,658	0,076
Umbilicosphaera spp.	-0,245	0,819

(> 8 ka cal BP), while significantly more positive values are observed between 6.5 and 4.8 ka cal BP. A general increase in Shannon–Wiener index across the core is observed, with three abrupt drops between 7.5 and 7.2 ka cal BP, at 5.5 ka cal BP, and from 3.8 ka cal BP to towards the core top (Fig. 3). On the contrary, Dominance index exhibits abrupt raises between 7.7 and 7.2 ka cal BP, 6.6-6.2 ka cal BP and 5.8-5.3 ka cal BP and 3.6-3.3 ka cal BP. In general, the Dominance index presents a relative opposite trend in the respect to the Shannon–Wiener index and positive correlation with the Group A (r =0.67), therefore a rising of Group A corresponding to increase in dominance.

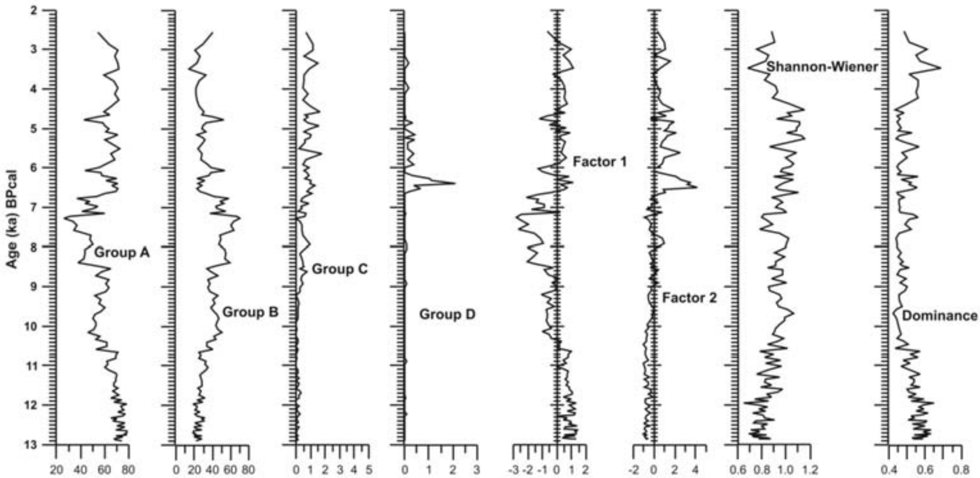

Fig. 3: Cumulative plots of the four coccolithophore Groups, score plots of two components of PCA and pattern of diversity indices.

5. Holocene coccolithophore assemblages: Paleoecological groups

In order to interpret the quantitative results, we discuss the ecological behaviour of coccolithophore species and paleoecological meaning for each of the four groups of the HCA. Syntheses of ecological data on coccolithophores show that certain associations of species characterize different environmental conditions.

Group A consists of the subtropical species *Syracosphaera* spp. *R. clavigera* and the opportunistic *E. huxleyi*. *E. huxleyi* is by far the most abundant of the coccolithophores on a global basis and has a wide ecological distribution. In the Mediterranean Sea waters, this species prevails throughout the year in the living coccolithophore assemblages (Knappertsbusch, 1993; Kleijne, 1993; Cros, 2001; Triantaphyllou et al., 2002, 2004; Malinverno et al., 2003), and predominates during winter in the Aegean Sea (Dimiza et al., 2008a). *R. clavigera* is warm water species of the upper water column (Roth and Coulbourn, 1982; Brand, 1994; Haidar and Thierstein, 2001; Malinverno et al., 2003). This species is abundant in the Mediterranean Sea waters (Kleijne, 1993; Malinverno et al., 2003; Dimiza et al., 2008a). *R. clavigera* is considered oligotrophic species (Jordan and Winter, 2000; Haidar and Thierstein, 2001) and according to Brand (1994), grows well at low nutrient levels and does not increase its growth rate in response to elevate nutrient concentrations. *Syracosphaera* is the most diverse living coccolithophore genus (Jordan and Chamberlein, 1997). Young (1994) included Rhabdosphaeraceae along with Syracosphaeraceae and holococcolithophores in the "miscellaneous" group of species; this group does not have an obviously distinctive biogeography, but tends to be more important in intermediate environments than in the extreme eutrophic or oligotrophic conditions, showing a tendency towards weak K-selection/efficiency maximizing (Brand, 1994; Young, 1994; Baumann et al., 2005). In the eastern Mediterranean Sea waters, *Syracosphaera* is a significant component of coccolithophore nannoflora and is represented mainly by *S. pulchra*, *S. histrica*, *S. molischii*, *S. ossa*, and *S. halldalii* (Dimiza et al., 2008a). In this study, the genus *Syracosphaera* is represented mainly by *S. pulchra*, a typical species of tropical-subtropical oligotrophic environments (Roth and Coulbourn, 1982; Findlay and Giraudeau, 2000; Haidar and Thierstein, 2001; Ziveri et al., 2004).

Group B is composed of *H. carteri* and *F. profunda* typical species for high productivity conditions in the middle-lower photic zone. *F. profunda* is included in the floriform coccolithophores which live below the thermocline under low light and temperature conditions (Young, 1994; Winter et al., 1994; Takahashi and Okada, 2000; Malinverno et al., 2003; Dimiza et al., 2008b). This species has proven to be a very reliable proxy to locate the nutricline-thermocline level in tropical and subtropical environments (Molfino and McIntyre, 1990) and is important in paleoenvironmental reconstructions (Castradori, 1993; Beaufort et al., 1997; Di Stefano and Incarbona, 2004). In recent Eastern Mediterranean - as it has been confirmed by sediment trap data - the relative abundance of *F. profunda* is more intense during the low coccolithophore productivity interval when max sea surface temperature is occurring (Triantaphyllou et al., 2004) pointing to a deeper nutricline according to the model of Molfino and McIntyre (1990) and supporting Ahagon et al. (1993) who recognized a close relationship between the increase of *F. profunda* and increased water transparency. *Helicosphaera* spp. is known to preferentially high productivity waters in the middle photic zone (Ziveri et al., 2004; Crudeli et al., 2006). In this study, the genus *Helicosphaera* is represented mainly by *H. carteri*, a species with preference in warm waters (Brand, 1994; Baumann et al., 2005) and moderately elevated nutrient levels (Findlay and Giraudeau, 2000; Andruleit and Rogalla, 2002; Ziveri et al., 2004). According to Cros (2001) in the western Mediterranean Sea waters, this species lives close to the chlorophyll maximum.

Group C consists of *G. oceanica* and *B. bigelowi* that characterise low salinity conditions. *G. oceanica* prefers warm, high-nutrient, less saline environments (Roth and Coulbourn, 1982; Klejine, 1993; Knappertsbusch, 1993; Jordan and Winter, 2000; Takahashi and Okada, 2000; Andruleit and Rogalla, 2002; Di Stefano and Incarbona, 2004), such as upwelling areas or continental shelves (Giraudeau, 1992; Young, 1994). *B. bigelowii* is known to preferentially low salinity saline surface waters (Müller, 1979; Negri and Giunta, 2001; Giunta et al., 2003).

Group D includes *Umbilicosphaera* spp. and *Calcidiscus* spp. which are described as relatively eutrophic species. *Umbilicosphaera* spp. are warm water taxa (Flores et al., 1999; Takahashi and Okada, 2000) with a preferential in high-nutrient environments (Roth and Coulbourn, 1982; Young, 1994; Andruleit and Rogalla, 2002) and is consistent with the nutrient redistribution in the surface waters (Principato et al., 2006). According to Shipe et al. (2002), it presents positive correlation with decline of salinity. *Calcidiscus* spp. is considered by several authors as being characteristic of tropical to subtropical oligotrophic warm waters (Klejine, 1993; Winter et al., 1994; Flores et al., 1999; Baumann et al., 2004). However, some ecological preference for cold eutrophic environments have been inferred (Giraudeau, 1992; Young, 1994; Flores et al., 1997, Hiramatsu and De Deckker, 1997; Andruleit and Rogalla, 2002).

6. Comparison between living and Holocene assemblages

According to the results of the HCA, it was possible to identify the succession of four distinct groups, in the Aegean coccolithophore assemblages during the last 13 ka: Group A (subtropical species- *R. clavigera* and *Syracosphaera* spp. and the opportunistic *E. huxleyi*), Group B (high productivity species-*F. profunda* and *Helicosphaera* spp.), Group C (low salinity species-*G. oceanica* and *B. bigelowii*) and Group D (relative eutrophic species-*Calcidiscus* spp. and *Umbilicosphaera* spp.). By applying the PCA, two important statistical factors interpreted the impact of environmental changes on calcareous nannoplankton distribution. The first component represents productivity variation, while the second component reflects high nutrient and low salinity conditions. Moreover, the Shannon diversity shows an opposite trend with regard to the Dominance index. The positive correlation

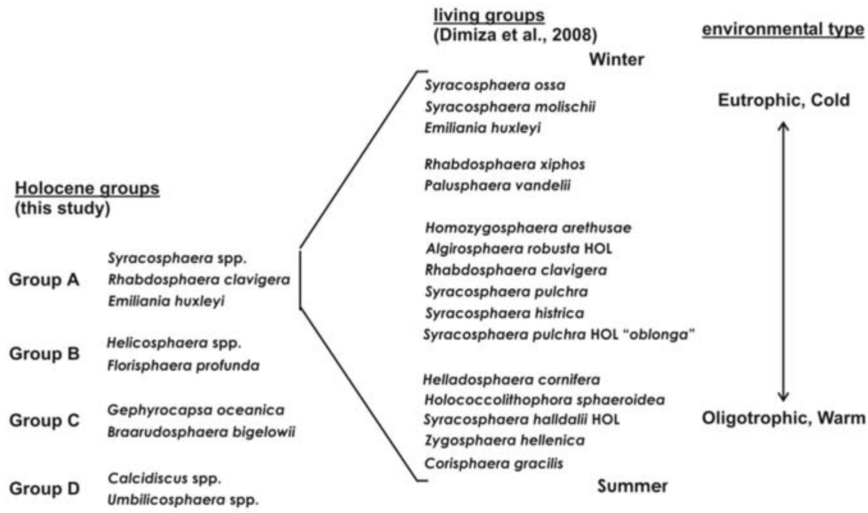

Fig. 4: Correlation between Holocene and living coccolithophore assemblages.

between dominance and Group A is interpreted with predominance of r-selected species *E. huxleyi* of Group A in eutrophic conditions (Young, 1994). Consequently, the fluctuation in the environmental conditions of the Holocene, in the eastern Mediterranean region, which is directly related to parameters such as temperature, salinity, productivity and nutrient flux in the water column, is ideally reflected in the coccolithophore assemblages.

In the study of living coccolithophore communities from the coastal ecosystems of Andros Island, Dimiza et al. (2008a) identified four distinct recent coccolithophore groups in the upper water column: *Emiliania huxleyi* group (late autumn-early spring), *Palusphaera vandelii* group (spring), *Rhabdosphaera clavigera* group (summer), *Helladosphaera cornifera* group (early autumn), suggesting that variability in coccolithophore composition in the Aegean Sea is controlled by the oligotrophic and warm summer and eutrophic and cold winter seasonal cycle. As the Aegean region today appears to be one of the most oligotrophic areas in the world, the research on extant coccolithophores from the coastal ecosystems provided detailed results concerning the expansion of the species of subtropical-oligotrophic environments.

Comparing the determined Holocene and living coccolithophore groups it becomes obvious that the latter are exclusively dominated by the subtropical species *R. clavigera* and *Syracosphaera* spp. and the opportunistic *E. huxleyi*, which correspond to the paleoecological Group A (Fig. 4). In particular the living ecological groups that were identified are based on *E. huxleyi* and various species of families Rhabdosphaeraceae, Syracosphaeraceae and Calyptrosphaeraceae. The latter include holococcoliths that are rarely preserved in sediments and are therefore not easily included in paleontological assemblages.

The species composition of fossil assemblages is influenced from sedimentological and preservational processes. Recent detailed study of sinking planktonic assemblages and Holocene samples (Andruleit et al. 2004; Baumann et al., 2005; Young et al., 2005) indicates that the majority of the morphological diversity is dissolved in the upper water column. In surface waters, delicate forms (species of several different groups of coccolithophores, including the Rhabdosphaeraceae and almost all holococcolithophores) present low preservation potential and preferential destroyed (Roth and Coulbourn, 1982; Andruleit, 1997). Only the species with robust structure (as *Calcidiscus* spp. and *Umbilicosphaera* spp.) or high cell densities (such as *E. huxleyi*) have a higher preservation potential. In the lower photic zone, species such as *F. profunda* have slight advantages because of less destruction by biological breakdown and a shorter transport distance (Andruleit, 1997; Andruleit et al., 2004). As a result, the fossil assemblages cannot precisely represent the living community from which they are derived. However, despite the loss in species diversity of fossil assemblages, the coccolithophore record has a much higher preservation capability than many other proxies (Samtleben et al., 1995; Beaufort et al., 1997; Balch et al., 2000; Andruleit et al., 2004) and therefore is one of the most reliable groups for paleoenvironmental reconstructions.

7. Conclusions

An interesting application concerns the use of knowledge from the study of living communities in the explanation and documentation of fossilized records. One important parameter of the ecological research on living coccolithophore communities from the coastal ecosystems of Andros Island lies in the seasonal separation of the subtropical species. This distinction led to the differentiation of coccolithophore communities, as a response to short-time scale seasonal fluctuations in temperature and nutrient content in the upper photic zone. More specifically, a fluctuation of species in eutrophic and oligotrophic environments was observed, in the context of seasonality (cool-warm period), a parameter that cannot be easily specified in fossil assemblages.

The present study identifies four distinct calcareous nannoplankton groups from NS-14 sediment core, suggesting that variability in coccolithophore composition is controlled by changes in temperature, salinity, productivity and nutrient flux in the water column. The paleoecological groups are used as a basis for discussion of the relation of Holocene assemblages with living communities in the coastal marine ecosystems of the Aegean Sea. In the comparison it becomes obvious that the living ecological groups are exclusively correlated with the Holocene paleoecological Group A that indicates a seasonally controlled marine environment. The ample development of Group A before 10Ka and towards the recent times should mainly be interpreted through the existence of seasonality. So in the particular period, the warm season would be characterized by oligotrophic conditions in the photic zone, with high occurrence of representatives of the Rabdosphaeraceae and Syracosphaeraceae, while water mixture during the cool period allowed the increase of *E. huxleyi*. However, the wide variety of species composition in living communities is not preserved in the fossil assemblages. This is most probably due to dissolution effects in the water column and the state of preservation in the sediment.

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BENTHIC FORAMINIFERA ASSOCIATED WITH THE ZOOXANTHELLATE CORAL *CLADOCORA* IN THE PLEISTOCENE OF THE KOS ISLAND (AEGEAN SEA, GREECE): SEA LEVEL CHANGES AND PALAEOENVIRONMENTAL CONDITIONS

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Abstract

A Pleistocene section, cropping out in the northern Kos Island has been selected for study. The main lithology (clayey sands, sandy marls) of the section is interrupted by a prominent Cladocora *bank which allows a proper extraction of its faunal contents and identification at species level. The evaluation of benthic foraminiferal assemblages from this bank helps to determine the range of the environmental controls in sedimentation. The foraminiferal assemblage is related to a relatively high supply of organic material and rather strong current intensities in water depth of the coral growth. We suggest that the fossil reef of* Cladocora *grew in coastal waters characterised by a marked seasonality, with periodical inputs of terrigenous sediments, moderate turbidity and higher temperature than today. Such results, although preliminary, suggest that* Cladocora *together with benthic foraminifera could be reference species for future work on changing Mediterranean climate and sea level.*

Key words: *benthic foraminifera, palaeoenvironment, Pleistocene, coral bank, SE Greece.*

1. Introduction

The Mediterranean Sea is an interesting place to study global change because it is land-locked and acts like a miniature ocean, which reacts faster to environmental changes than the open ocean (Béthoux et al., 1990). Under this respect, the study of Mediterranean faunas can be used to model predictions on how this semi-enclosed basin responds to global climatic and environmental change.

One important tool for monitor these environmental and climatic changes is the distribution and abundance of benthic foraminifera in paralic and shallow marine environments. It is well documented that benthic foraminifera are very sensitive to variations in depth, salinity and substrate texture (Murray, 1991). Consequently, benthic foraminiferal assemblages preserved in the sedimentary record provide a useful palaeoecological indicator, because some taxa tolerate extreme conditions but react very quickly to environmental changes (e.g. Jorissen 1987, 1988; Murray 1991).

Cladocora coral is endemic and present throughout the whole Mediterranean (Zibrowius, 1980; Peirano et al., 1998). Large fossil *Cladocora* formations were found as old as Late Pliocene, when this coral formed true reefs both in the Eastern and Western Mediterranean Sea (Aguirre and Jiménez, 1998; Dornbos and Wilson, 1999). Large fossil banks of *Cladocora* are also known from the Early

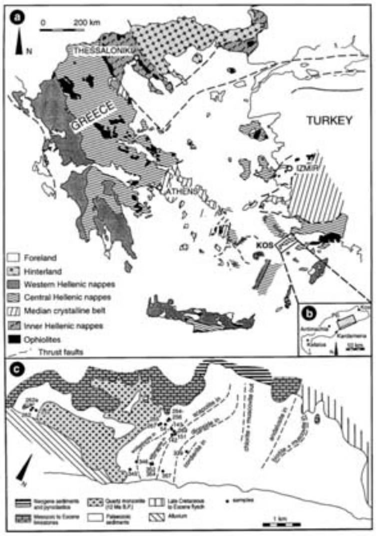

Fig. 1: (a) Geological sketch map of the Hellenic – Tauric orogenic belt in southeastern Europe and Turkey, modified after Jacobschagen (1986) and Kalt et al. (1998), showing the main tectonic units and the location of the Kos Island. (b), (c), location and geological features of the Dicheo Massif, including mineral isograds in the Palaeozoic sediments, resulting from contact metamorphism of the quartz monzonite (Altherr et al. 1976, Kalt et al. 1998).

Pleistocene (Bernasconi et al., 1997), from the Middle and Late Pleistocene and from the Holocene (for a review, see Peirano et al., 1998). The bathymetric distributions of these corals range from 5 to 40 m depth and they are well adapted to turbid coastal environments with high sedimentation rates (Zibrowius, 1974; Peirano et al., 2005).

The aim of the present study is to document the benthic foraminiferal faunal composition of a well exposed *Cladocora caespitosa* bank of Pleistocene age on the eastern Mediterranean island of Kos. The evaluation of benthic foraminiferal assemblages from this coral bank will help to characterize the range of the environmental controls in sedimentation.

2. Geological setting

The island of Kos off the Turkish coast in the Eastern Aegean Sea (Fig. 1) forms part of the Hellenic-Tauric system, a complex mountain belt extending from southeastern Europe to Turkey. The Hellenic arc results from the collision of the Apulian microcontinent with the crystalline complexes of northeastern Greece during Mesozoic to Cenozoic times. It displays a pronounced southwest vergent nappe character. Apart from minor Palaeozoic units, the nappes consist of Mesozoic to Cenozoic sediments and magmatic rocks, including ophiolites. Some of these nappes have been subject to different degrees of metamorphism during collision (Jacobshagen 1986). Metamorphism and thrusting took place during several events between Jurassic and Miocene times (Altherr et al. 1994, Seidel et al. 1977, 1982).

The geological units on the island of Kos form part of the Central Hellenic nappes (Fig. 1, Jacobshagen 1986). The oldest units form the Dicheo Massif in the central part of the island towards the south coast (Fig. 1b and c). They consist of Permocarboniferous marls, impure limestones and sandstones, phyllites and rare mafic intercalations (Altherr et al. 1976, Gralla 1982) that have been subject to post-Permocarboniferous regional metamorphism at very low grades. At 12 Ma, this series was partly contact metamorphosed by the intrusion of a large quartz monzonite (Altherr et al. 1982, Henjes-Kunst et al. 1988). Subsequent to intrusion and exhumation Permocarboniferous metasediments and Miocene quartz monzonite were tectonically overridden by Cretaceous to Eocene limestones that crop out mainly north and west of the pluton (Fig. 1c). After tectonic emplacement of these limestones, the area west of the Dicheo Massif was covered by Pliocene and Pleistocene sediments and mostly Quaternary volcanics (Keller 1969; Dürr and Jacobshagen 1986). To the east, the Dicheo Massif is tectonically bordered by a flysch sequence of Late Cretaceous to Tertiary age (Dürr and Jacobshagen 1986).

The Neogene sedimentary cover of Kos consists of Lower Miocene molassic sediments on western Kos unconformably overlying the Mesozoic carbonates (Papanikolaou and Nomikou 1998), and north of the Dicheos window ranges from middle Miocene to Pleistocene shallow marine to terrestrial deposits (Böger et al. 1974, Altherr et al. 1976, Willmann 1983). It dips southward as a result of north-dipping normal faults that separate the sediments from the pre- Neogene basement (Böger et al. 1974).

The island of Kos is dominantly non-volcanic but contains Miocene to Pleistocene volcanic centres. The Kamari caldera is of mid-Pleistocene age and contains the 1.0–0.55 million-year-old, post-caldera Zini lava dome. The widespread Kos Plateau Tuff (160,000 years ago), which blankets much of the western half of Kos, originated from a submarine source between Kos and Nisyros islands and resulted in the formation of a large caldera. The caldera dimensions are uncertain, but may extend as much as 20 kilometres from Kefalos Bay in southwestern Kos Island to Nisyros Island. Several solfatara fields are found on Kos Island, including Vromotopos at Kefalos Isthmus on the western side of the island and a group of thermal areas at the eastern side of Kos. Thermal activity consists of weak hydrogen sulfide emission, sulfur deposits, and two hot springs along the southeastern coast.

Bardintzeff et al. (1989) grouped the Kos volcanism into two eruptive episodes which have occurred during the Tertiary and Quaternary eras. A Miocene (10.4–7.5 Ma) subduction-related early episode which produced a welded ignimbrite formation exposed throughout the whole island, and a more recent (~2.7 Ma) episode which is related to the present subduction of the African plate beneath the Aegean micro-plate, associated with eruptive products which can be observed only in the central and western parts of Kos.

3. Material and Methods

3.1 The coral-bearing unit

The sediment samples used in this investigation were collected from the basal part of a section cropping out along Mastichari Bay, north Kos Island, located under the Kos ignimbrite which is dated to 145000 ± 5000 years BP and represents an important volcano-stratigraphic time-marker in the Eastern Mediterranean. Foraminiferal faunas were examined in one representative sample recovered from the studied succession (Fig. 2).

The relevant outcrop exposes a deepening – upwards succession with littoral sands at the base giving way to nearshore silts and sands with a very rich marine macrofauna assemblage including *Cladocora caespitosa* corals (sample K13 in Fig. 2). According to Peirano et al. (2004), the assemblage is typical of temperate-warm, shallow sea and of mixed carbonate-terrigenous, infralittoral environment.

3.2 Micropalaeontological analysis

In the laboratory, foraminifera were separated from the sediments by washing them through a 125 μm sieve. Identification of benthic foraminiferal species relies upon original descriptions and several key papers (Jorissen 1988, Albani and Serandrei Barbero 1990, Cimerman and Langer 1991, Sgarrella and Moncharmont Zei 1993, Fiorini and Vaiani 2001).

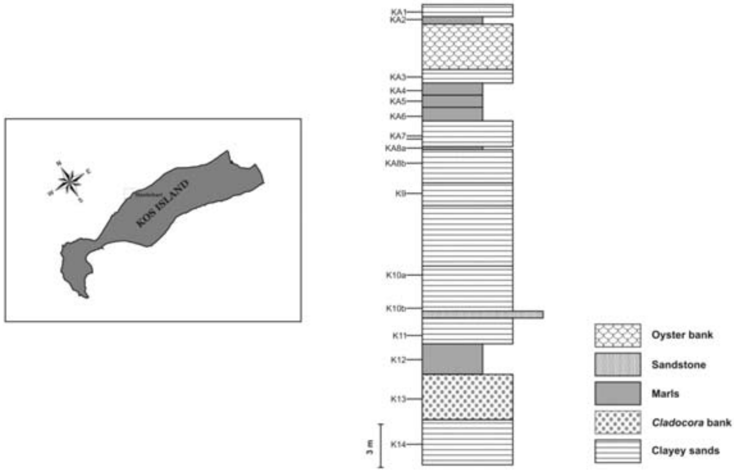

Fig. 2: Lithostratigraphical column of the studied section, showing the studied Cladocora bank.

Benthic foraminiferal assemblage diversity (Fisher alpha-diversity) was determined by plotting the total number of individuals against the total number of species in a Fisher alpha-a diversity base-graph. Species richness diversity was determined for the sample, categorized as very low (1–7 species), low (8–25), medium (26–50), or high (51–79).

Ecological interpretation of species and environmental significance of microfaunal associations are inferred from comparison with modern benthic communities (Jorissen 1987, Murray 1991, Van der Zwaan and Jorissen 1991, Barmawidjaja et al. 1992, Yassini and Jones 1995, Debenay et al. 2000, Donnici and Serandrei Barbero 2002) and similar microfaunal assemblages recorded within late Quaternary coastal successions of the Mediterranean.

Planktonic foraminifera are treated as a separate group; their proportional abundance (in % of the foraminiferal assemblages) was calculated.

4. Results-Discussion

A total of 287 specimens belonging to 20 species have been identified in the studied sample on which it was possible to perform a quantitative analysis. Only well-preserved tests (without breakages or abrasions) that did not show any sign of reworking and/or transportation were counted and, as a consequence, considered in the statistical analysis. However, most of the individuals do not show signs of re-deposition.

Benthic foraminifera are large- to medium-sized and usually well preserved; only a few specimens are fragmented. Furthermore, the presence of a relatively large amount (6%) of highly-reworked planktonic foraminifera was noticed.

The low number of taxa (20) of benthic foraminifera in this "microenvironment' suggests 'drastic' ecological conditions for the benthic microfauna. Since planktonic remains are restricted to low percentage values we conclude that the deviation from the norm of palaeoenvironmental conditions is affecting the preservation of biogenic material and limiting the establishment of the benthic population.

The foraminiferal assemblage is moderately diversified (Shannon index: 2.218 and Fisher-alpha index: 4.891), consisting of *Ammonia beccarii* group (27.87%), *Haynesina depressula* (16.72%), *Cibicides lobatulus* group (11.85%) and *Neoconorbina terquemi* (14.63%).

The high abundance values of *A. beccarii* are indicative of a shallow-marine environment with sandy bottom (Sgarrella and Moncharmont Zei 1993). Jorissen (1988) found that this species is very abundant in the Adriatic along a belt parallel to the Italian coast at a water depth of less than 20 m. The highest abundance is found between 15 and 20 m water-depth in samples with intermediate percentages of organic matter in which at least some sand fraction is present. A strict interpretation based on the known modern distribution of *A. beccarii* would confine the species to upper shoreface environments (Hayward et al. 2004).

The high occurrence of *H. depressula* indicates increasing salinity together with pH > 6.0 and less stressful environmental conditions.

Cibicides locatulus group together with *Neoconorbina terquemi* represent species with strong positive correlation with sandy substrates and a negative one with organic matter. They are epiphytic species, preferring the presence of vegetation.

The moderate frequency values of *Cancris oblongus* indicate tolerance to mesotrophic - eutrophic conditions.

Cladocora caespitosa colonies occupy a wide ecological range, from hard to soft substrates and from low- to high-turbulence water (Zibrowius 1980; Schiller 1993a). The abundance of *Cladocora* fragments with the in situ colonies reinforces the indication by foraminiferal assemblage for preservation in moderate-energy shallow environment.

5. Conclusions

The micropalaeontological analysis allows us to describe the microenvironments, considering ecological conditions as well as preservation and/or sedimentary features.

The microfaunal assemblage is indicative of a marine environment characterised by moderate water energy. The absence of turbulent deposition and the presence of vegetation, as this is illustrated by the high frequency numbers of epiphytal species, usually set a depth limit of approximately 5–20 m although these plants may sporadically also reach down to 45 m deep (Langer 1993). The foraminiferal assemblage supports and extends these conclusions. *Haynesina* and *Ammonia* favour a water depth of 0–50 m (Murray 1991, 2006).

In conclusion, the foraminifera suggest an infralittoral environment with a water depth of between 20 and 50 m. This interpretation is supported by the low abundance of planktonic foraminifera and medium diversity of benthic foraminifera. The diversity of the latter group increases with water depth, and a low-diversity benthic foraminifer fauna is generally typical for marginal marine environments (Sen Gupta 1999, Murray 1991, 2006).

The assemblage is indicative of an infralittoral environment with vegetation cover as suggested by the presence of epiphytic species. Species adapted to live in coarser substrates are also abundant. The presence of *Haynesina depressula* suggests relatively high concentrations of organic matter.

6. Acknowledgments

The authors wish to thank the two reviewers for their suggestions on the manuscript.

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MIOCENE SCLERACTINIAN CORALS OF GAVDOS ISLAND, SOUTHERN GREECE: IMPLICATIONS FOR TECTONIC CONTROL AND SEA-LEVEL CHANGES

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Abstract

Low-diversity scleractinian patch reefs that have been developed, during Early to Middle Tortonian, in Gavdos island are studied, aiming in a better understanding of the time and space relationships of the reef development and the associated basin fill evolution. Gavdos island consists part of a tectonically active setting constituting the southernmost extension of the Hellenic arc (Eastern Mediterranean). A representative Tortonian section (Bo section), located in the northwest part of the island, which hosts a mass occurrence of hermatypic corals, is studied. Scleractinian samples were collected from the upper 12 m of the section, which is characterized by interchanges of marly limestone and compact marls.

The reefs are represented by the coral species Heliastraea oligophylla, Porites maicientensis, Thegioastraea roasendai and Porites collegniana. The microfacies analysis showed that the medium-to-thin-bedded carbonates of the limestone-marl alternations comprise patch reefs (boundstones-framestones, SMF 16, sensu Wilson, 1975, FZ 7-8, sensu Flügel 1982) consisted of screractinian corals. Corals are associated with corallinacean algae. Patch reefs are associated by bioclastic packstones-floatstones, characterized by benthic foraminifera, calcareous algae, spines of echinoids, gastropods and molluscs. Reefs are laterally associated by a bioclastic limestone rich in planktonic forams, associated by detrital material (fragments of quartz, feldspars, quartzites and cherts). The studied reef facies have been dolomitized and cemented in the meteoric realm. In places pseudomorphs after evaporites have been observed, tending to occlude cavities resulted after dissolution. The depositional environment corresponds to a moderate to high-energy inner platform setting, experiencing open-ocean influences. The pattern of coralgal reef development during Miocene, in the tectonically controlled Gavdos island, represents a complex interaction of tectonic activity and global sea-level changes.

Key words: *Tortonian reef, scleractinian corals, microfacies analysis, palaeoenvironment.*

1. Introduction

As palaeoclimatology has become a central topic of carbonate sedimentology, palaeoecology is particularly significant for climate research because the carbonate secreting biotas are very sensitive archives of climate. In this context, the taxonomic composition and internal structure of corals and coralline algae provides a powerful tool for palaeoecological reconstructions. Furthermore, combined analysis of microfacies and coral features provides a useful tool for palaeoenvironmental studies.

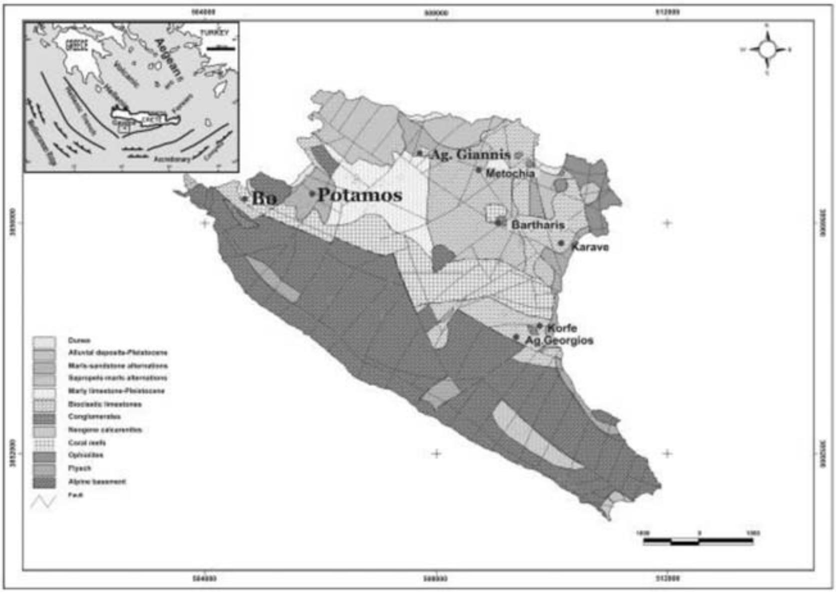

Fig. 1: Simplified geological map of Gavdos island (after Tsaparas, 2005, modified).

During the Oligocene and the Miocene, shallow-water carbonates of the Eastern Mediterranean region were rich in scleractinian corals thriving within various depositional settings, including different reef types. Their diversity patterns, although related to a complex interplay between a suite of environmental factors, are considered to be strongly controlled by climate variability and changes in sea-surface water temperature.

The aim of this paper is the documentation of the distribution of the scleractinian coral assemblages in Tortonian and the depositional environment recognition. Field observations revealing the lithofacies associations arrangement, are combined with detailed micropaleontological and microfacies analyses.

2. Geological setting

The island of Gavdos is located in the Eastern Mediterranean and constitutes the southernmost extension of the Hellenic arc (Fig. 1).

During the Serravallian, the island of Gavdos consisted of emerged sediments, of the Pre-Neogene basement. Field observations together with micropalaeontological analysis (Anastasakis et al. 1995) showed that at the end of Serravallian, the island was probably affected by drastic subsidence which resulted in the transformation of the central-west part of the island into a single shelf characterized by hemipelagic sedimentation. During the Early Tortonian, differentiated fault activity broke up this shelf into individual sub-basins forming separate palaeogeographic spaces (Tsaparas 2005).

Early Tortonian was characterized by the development of a WNW-ESE coral reef barrier which acted as a structural limit restricting water exchanges between these sub-basins (Fig. 2, Tsaparas and Dermitzakis 2005). Therefore, Bo shelf (NNW of Gavdos island), which is characterized by the presence of a rich scleractinian fauna (Tsaparas and Marcopoulou-Diakantoni 2005) indicates a

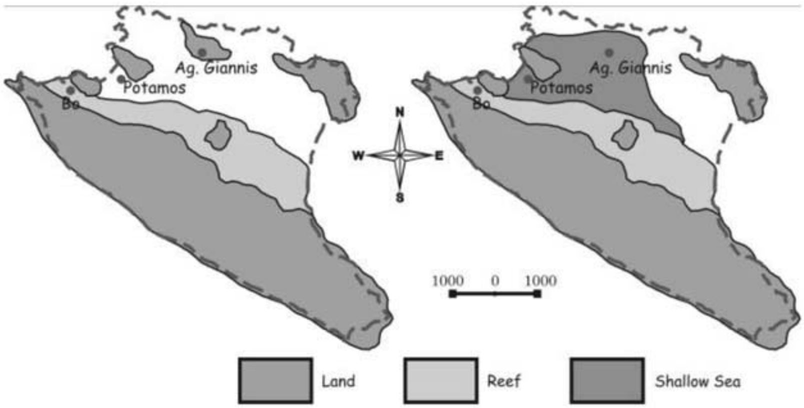

Fig. 2: Palaeogeographical reconstruction of Gavdos Island during Early and late Early Tortonian (after Tsaparas 2005 and Tsaparas and Dermitzakis 2005).

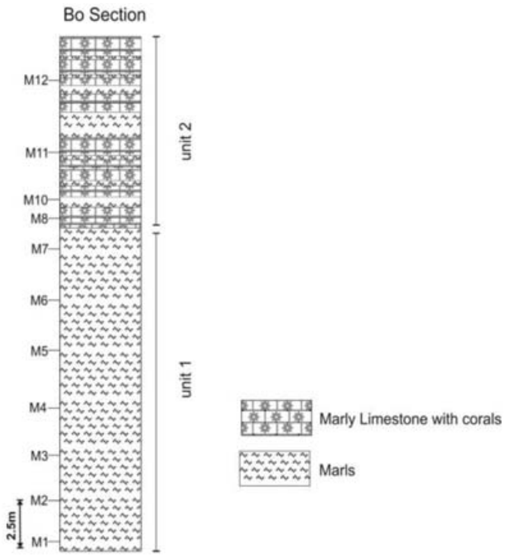

Fig. 3: Lithostratigraphical column of the studied section (after Tsaparas 2005).

warm and a rather oligotrophic environment whereas the time-equivalent Potamos shelf hosts species inhabiting brackish water lagoons or shelves (Drinia 2009).

This study is restricted in one representative Tortonian section (Bo section), located in the northwest part of the island, which hosts a mass occurrence of hermatypic corals. The section is 25 m thick and its sediments are arranged into two different types of lithofacies associations, constituting a shallowing-upward sequence (Fig. 3).

The basal part is composed of a marl succession. These marls are well bedded, variably lithified and consist almost entirely of carbonate with abundant foraminifera (Antonarakou et al. 2007, Drinia 2009). Approximately half way up the section, the dominantly fine-grained deposits change from blue marls to rhythmic bioclastic limestone-marl alternations. This transition takes place over a few

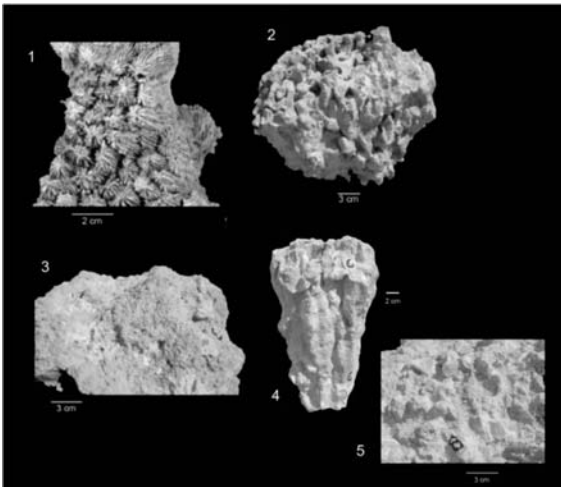

Fig. 4: 1. *Thegioastraea roasendai* (MICHELOTTI), 2. *Porites collegniana* (MICHELOTTI), 3. *Heliastraea oligophylla* (REUSS), 4, 5. *Porites mancietensis* CHEVALIER (photos originate from Tsaparas & Marcopoulou-Diakantoni 2005, 1=Table III,1, 2=Table II,5, 3=Table I,3, 4=Table II,1, 5=Table II,2).

tens of centimetres passing from bluish marl with abundant planktonic foraminifera to marl with macrofossils and then into hard bioclastic limestone. The marl succession in the studied section is 14 m thick and has been dated using planktonic foraminifera as being of early Late Miocene (early Tortonian) age, being characterized by the co-existence of the benthic foraminifera *Uvigerina* spp. and *Cancris auricula* which indicate a rather deep, mesotrophic to eutrophic environment (Drinia 2009). On the contrary, the upper part of the succession (12 to 25 m) is dominated by a group of plano-convex benthic foraminiferal species which appear to have a low tolerance for salinity deviations. Scleractinian samples were collected from the upper 12 m of the record, which is characterized by interchanges of marly limestone and compact marls.

3. Material and Methods

A detailed microfacies analysis has been performed. Analysis of matrix and grains, textural features, fossil content, petrographic and energy index classification, facies zone, standard microfacies zone and model, formation, origin, correlation and interpretation criteria, as determined from thin sections study, is attempted (Dunham 1962, Folk 1962, Plumley et al. 1962, Selley 1970, Wilson 1975). The present study focuses on the study of the early and late diagenetic cement patterns. X-ray analysis was performed, as well.

4. Results

4.1 Microfacies Analysis

The microfacies analysis showed that the medium-to-thin-bedded carbonates of the limestone-marl alternations comprise patch reefs (boundstones-framestones, SMF 16, *sensu* Wilson 1975, FZ 7-8, *sensu* Flügel 1982) consisted of scleractinian corals.

A mass occurrence of hermatypic corals, with dominant *Heliastraea oligophylla, Porites maicietensis, Thegioastraea roasendal* and *Porites collegniana* (Fig. 4) characterize the studied carbon-

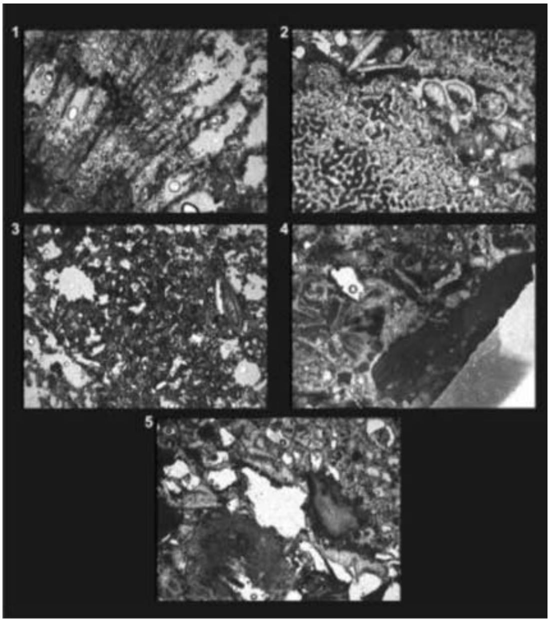

Fig. 5: 1. Patch reefs consisted of scleractinid corals (boundstones: framestones/ bafflestones, SMF 7, sensu Wilson, 1975, FZ 7-8, sensu Flügel 1982). Due to meteoric diagenesis intraskeletal porosity is reduced by cement growth (dog-teeth and blocky cement) (1,6X), 2. Boundstones consisted of scleractinid corals, associated by bioclastic packstones with spines of echinoids, gastropods and molluscs. Bioclasts are dissolved and filled by blocky calcite (1,6X), 3. Bioclastic limestone rich in planktonic forams, benthic foraminifera and detrital material (fragments of quartz, feldspars, quartzites and cherts) (1,6X), 4. Boundstone with corallinacae algae and bryozoans (1,6X), 5. Boundstones intensively affected by meteoric diagenesis. Intraskeletal porosity is reduced by cement growth (blocky cement) (1,6X).

ate interlayers representing laterally distributed reefal build-ups, indicative of highly variable environmental conditions, related to higher temperatures and salinities and sea-level change.

Corals are associated with corallinacean algae, which surround the corals. Bryozoans are neither abundant, nor diverse in the sampled coral facies. Most are encrusting and only some of them can be considered as accessory framework builders.

Patch reefs are associated by a coarse grained packstone-floatstone, characterized by spines of echinoids, calcareous algae, and fragments of corallinacean algae, gastropods and molluscs (Fig. 5). Reef facies is laterally associated by a wackestone-packstone with planktonic forams, in places rich in detrital material (fragments of quartz, feldspars, quartzites and cherts).

4.2 Diagenesis

The reef facies has undergone diagenesis in the meteoric realm (Fig. 5e), including dolomitization and dissolution of aragonite /high-Mg calcite that constituted the scleractinid corals, as well the bioclasts. Intraskeletal porosity is reduced by cement growth. The resulting pores have been filled firstly by a thin halo of dog-teeth cement, open spaces either remaining empty or filled by bladed and/or blocky cement. Meniscus cement occurs, as well. In places, spaces resulted after dissolution have been filled by cement reminding pseudomorphs after evaporites. Marine cement has not been detected.

4.3 Depositional Environment

The depositional environment corresponds to a moderate to high-energy inner platform setting, possibly of ramp type (inner-mid ramp), experiencing open-ocean influences, in which patch reefs have been developed, forming a WNW-ESE coral reef barrier which acted as a structural limit restricting water exchanges between sub-basins.

5. Discussion

The low diversity of scleractinid corals in the studied reefs, together with the presence of high-tolerance species as *Porites* is characteristic of Mediterranean Miocene reefs, particularly in the middle to late Miocene (Chevalier 1961, Rouchy et al. 1986, Flecker et al. 1995) and suggests that the environment was under stress conditions.

The relatively sharp transition from the lower succession that consists entirely of deeper-water, lower energy, planktonic-foraminiferal rich marls, to shallow-water, high-energy reefs, implies that a major relative sea level fall took place.

According to Le Pichon and Angelier (1979), Meulenkamp and Hilgen (1986), extensional tectonics controlled the evolution of the southwestern part of the Aegean region along the Tortonian. Relative sea level fluctuations related to extensional tectonics could have been the main cause giving way to the sequential evolution. Tectonic pulses increases and created accommodation space drowning the coral patch-reefs and favoring marl sedimentation. Nevertheless, the general trend of the studied succession was shallowing upwards, with the shallowest facies in the upper part.

6. Conclusions

The study of the coral patch reefs from one Tortonian section of Gavdos island shed light on the palaeoenvironmental conditions, paying special attention to the palaeoecology of the corals. The main conclusions can be summarized as follows:

(a) Depositional structures, benthic organisms and the carbonate microfacies indicate restricted to open-marine, moderate energy inner platform setting.

(b) The low diversity of corals in these reefs, together with the presence of high tolerance species as *Porites* suggests that the environment was under stress conditions.

(c) The relatively sharp transition from the lower succession that consists almost entirely of deeper-water, lower energy, planktonic-foraminiferal rich marls, to shallow-water, high-energy reefs, implies that a relative sea level fall took place.

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PRELIMINARY DATA FROM THE FIRST RECORD OF THE EARLY TOARCIAN OCEANIC ANOXIC EVENT IN THE SEDIMENTS OF THE PINDOS ZONE (GREECE)

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Abstract

The Early Toarcian Oceanic Anoxic Event (ca 183 Ma) coincides with high palaeotemperatures, regional anoxia to euxinia, marine transgression, mass extinction and high rates of organic-carbon burial in a global context. Most of the detailed studies of this event have investigated deposits formed in the epicontinental seas of northern Europe, although coeval organic-rich shales are known locally in the Tethyan region. However, the global or regional character of this event is still under debate.

In this study we present, for the first time, a high-resolution geochemical record of the Early Toarcian Oceanic Anoxic event in pelagic sediments (Kastelli Pelites) formed in a long-lived Mesozoic deep-sea basin, corresponding to the western passive margin of the Pindos Ocean of western Greece.

Our data record both the positive excursion in total organic carbon (TOC) and the characteristic negative excursion in $\delta^{13}C_{carb}$. The $\delta^{13}C_{carb}$ values are very stable in the bottom of the section (~2‰), whereas higher in the section the values drop down to ~ -5‰. Following this negative excursion, the carbonate carbon-isotope ratios return to background values. The TOC excursion is modest, rising from a background of 0.05% to ~ 2% and then returning to a background of 0.04%.

Because both relative enrichment in TOC and the negative carbon-isotope excursion that characterize the Toarcian OAE are recorded in some of the deepest marine sediments of the Tethyan region, the global significance of the event is reinforced.

***Key words:** Toarcian, Oceanic Anoxic Event, Pindos Zone.*

1. Introduction

The early Toarcian (ca 183 Ma) coincides with high palaeotemperatures (Bailey et al. 2003), regional anoxia to euxinia, marine transgression, mass extinction (Little and Benton 1995) and high rates of organic-carbon burial, attributed to a so-called Oceanic Anoxic Event (Schlanger and Jenkyns 1976; Jenkyns 1988; Karakitsios 1995; Rigakis and Karakitsios 1998; Jenkyns et al. 2001). The geochemical characteristics of the early Toarcian OAE (or T-OAE) are a relative maximum in total organic carbon (TOC) and a broad, locally subdued positive carbon-isotope excursion punctuated by an abrupt negative excursion, recorded in marine organic matter, marine pelagic and shallow-water carbonate and terrestrial organic material (Jenkyns and Clayton, 1986, 1997; Hesselbo et

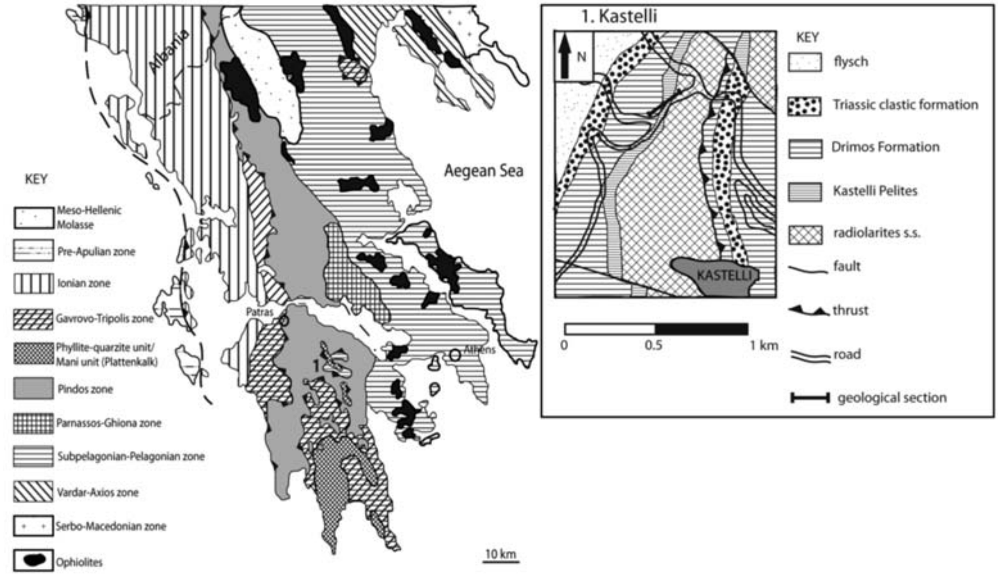

Fig. 1: (left): Simplified geological map showing the main tectono-stratigraphic zones of the Hellenides; (right): Geological map illustrating the general position of the Kastelli section.

al. 2000; Jenkyns et al. 2001; Jenkyns, 2003, 2010; Kemp et al. 2005; Hesselbo et al. 2007; Woodfine et al., 2008). Most of the detailed studies of this event have investigated deposits formed in the epicontinental seas of northern Europe (e.g. Hesselbo et al. 2000; Kemp et al. 2005), although coeval organic-rich shales are known locally in the Tethyan region (Jenkyns et al., 1985; Jenkyns and Clayton, 1986; Jenkyns, 1988; Sabatino et al. 2009). However, the global or regional character of this event is still under debate (van der Schootbrugge et al. 2005; Hesselbo et al. 2007; Suan et al. 2008).

In this study we present, for the first time, a high-resolution geochemical record of the Early Toarcian Oceanic Anoxic event in pelagic sediments formed in a long-lived Mesozoic deep-sea basin, corresponding to the western passive margin of the Pindos Ocean of western Greece. We undertook Total Organic Carbon (TOC) and stable carbon-isotopic analyses in the Kastelli section from the Pindos Zone (North Peloponnesus).

2. Geological setting

The study area is located to the Pindos Zone (Western Greece) which belongs to the external Hellenides (Fig. 1). The sediments of the Pindos Zone originate from an elongate remnant ocean basin that formed in mid-Triassic times along the north-east passive margin of Apulia between the extensive Gavrovo–Tripolis platform in the present west and the Pelagonian continental block in the east (Degnan and Robertson 1998). The Pindos Zone of Western Greece is exceptional because it was deformed into a regular series of thrust sheets during its emplacement, with a minimum of disruption. The present-day westward-vergent fold and thrust sheets have not been affected by major backthrusting or out-of-sequence thrusting. The sedimentary successions of the Pindos Zone comprise deep-water carbonate, siliciclastic and siliceous rocks, ranging in age from Late Triassic to Eocene (Fleury 1980). Degnan and Robertson (1998) describe the series as follows: the oldest sediments (Carnian) comprise disrupted siliciclastic turbidites (with plant remains), largely derived from a

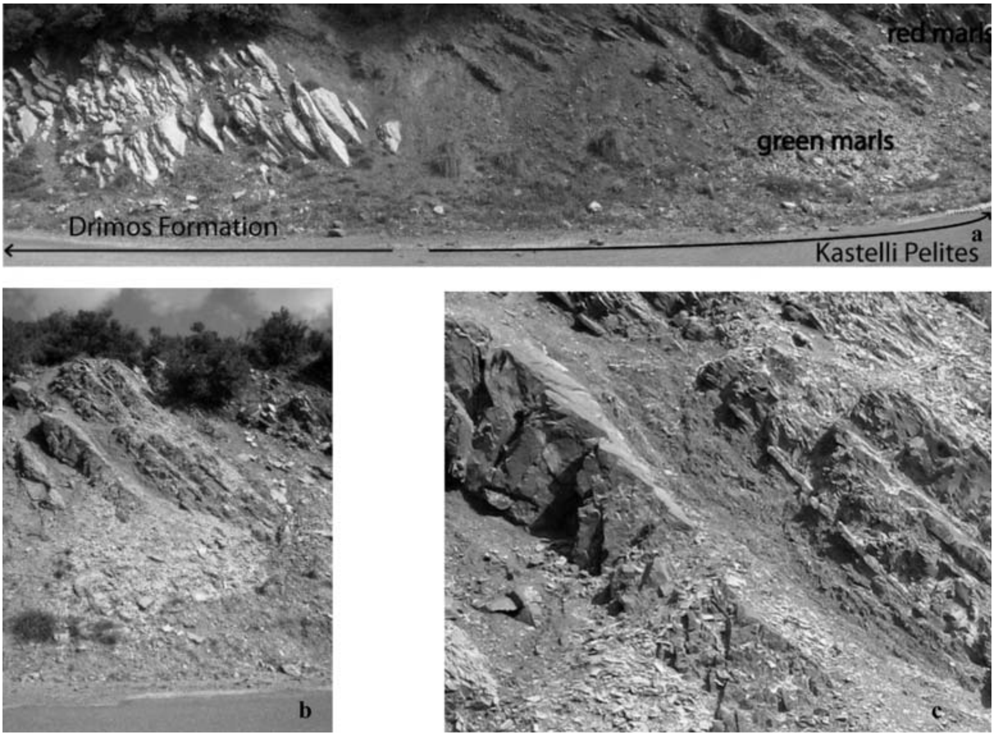

Fig. 2: (a): view of the whole section (b): green marls at the base of the Kastelli Pelites formation (c): detail of the green marls.

metamorphic source to the west and deposited on young oceanic basement. From the Norian to the end-Maastrichtian, variable thicknesses of hemipelagic–pelagic carbonates, marls and proximal carbonate debris flows accumulated in westerly areas, while mainly pelagic carbonate and more distal calciturbidites were deposited further east. This pattern was interrupted by an extended period of siliceous, radiolarian-dominated sedimentation (radiolarites) during the Aalenian to Tithonian stages of the Jurassic. From the Maastrichtian onwards, progressive closure of the Pindos oceanic basin is recorded by a gradual change in sediment composition (late Maastrichtian “couches de passage”) from dominantly carbonate deposition to siliciclastic sediment (flysch) derived from the north and east. During the Eocene, complete closure of the Pindos Ocean resulted in the detachment of its deep-sea sedimentary cover from its oceanic basement as an accretionary prism and emplacement westwards onto the adjacent carbonate platform, ending up as a series of thin-skinned thrust sheets.

In the Kastelli section (Fig. 1 and 2), from bottom to top, the following are observed:

- Drimos Formation, which in the upper part comprises mainly limestones attaining some 60 m in thickness. The observed faunas in this upper part, containing only some reworked algae and Foraminifera (e.g. *Thaumatoporella sp*. and Textulariida respectively), do not allow determination of a precise age.

- Kastelli Pelites, comprising sediments of about 35 m thick. The first 5 m consists of a succession of thin-layered (5-10 cm) marly limestones alternating with marls, followed by a succession of 10 m of mainly green organic carbon-rich clays, marly limestones and rare chert intercalations. The section continues with about 10 m of red marls and some intercalations of marly limestones, followed by 5 m of red-green marly limestones and marls. In thin-sections of the marly limestones, badly preserved Foraminifera are observed. The succession ends with 5 m of marly limestones and red marls, cherty at top. These cherts indicate a passage into the stratigraphically overlying radiolarites *s.s.*

There are very few data concerning the age of Kastelli Pelites. Lyberis et al. (1980) attributed the formation to the Upper Pliensbachian–Toarcian, comparing the palynological associations observed in the Greek mainland with those of the Vicentinian Alps, Italy. Nevertheless, the only precise data are referred to by Fleury (1980) and de Wever and Origlia-Devos (1982), who suggested an Aalenian age for the top of the Kastelli Pelites. Fleury's (1980) data are based on the presence of *Meyendorffina* (*Lucasella*) *Cayeuxi* (Lucas) in a limestone layer at the top of Kastelli Pelites (in the Karpenission region, central Greece); and de Wever and Origlia-Devos's (1982) data are based on foraminiferal faunas from the Peloponessus. Based on general biostratigraphic and diagnostic chemostratigraphic signatures described in an earlier (Jenkyns 1988) and the present work, we suggest that the Kastelli Pelites are correlative with other biostratigraphically well-dated Lower Toarcian black shales in Greece (e.g. Ionian Zone) and were formed during the Oceanic Anoxic Event. This interpretation would place most or all of the Kastelli Pelites in the *tenuicostatum* and the overlying *falciferum*/*levisoni*/*serpentinum* and possibly *bifrons* Zones (c.f. Jenkyns et al., 2002; Hesselbo et al., 2007).

3. Methods

A set of 191 bulk sediments was collected from the Kastelli section. The collected samples were powdered and analysed for weight percent total organic carbon using a Strohlein Coulomat 702 analyser (details in Jenkyns, 1988) and for carbonate carbon isotopes using a VG Isogas Prism II mass spectrometer (details in Jenkyns et al., 1994). All the above analyses were undertaken in the Department of Earth Sciences in the University of Oxford.

4. Conclusions–Results

In the Kastelli section, the TOC percentage is very low (Figure 3). The background values of TOC fluctuate around 0.10–0.20 wt% and cover most parts of the section. After the lowest 7.5 m, TOC values begin to rise gradually for 1.5 m, until the maximum value of 1.79 wt% is attained. After this positive excursion, values return to background values until the end of the studied section.

In the same figure the carbon-isotope values in carbonate are reported. The bulk carbonate carbon-isotope values record a small positive followed by a negative excursion in the lowest metre of the section: $\delta^{13}C_{carb}$ values climb up to 3.32‰ and drop down to 0.64‰. A similar excursion, but with a larger range of values, has been reported in Peniche, Portugal and Yorkshire, northeast England (Hesselbo et al. 2007; Littler et al. 2010) at the Pliensbachian–Toarcian boundary, and this age assignment is adopted for the Kastelli section. Above the stage boundary, values are stable around 2‰. The background values continue up to the next 7.50 m of the section, where $\delta^{13}C_{carb}$ begins to fall irregularly, reaching a minimum of -5‰. The negative excursion persists over the next 5 m. Following that, values begin to recover and indicate a broad positive excursion up to 3.83‰, as seen in many other European sections whose biostratigraphy is well constrained (Jenkyns and Clayton, 1986, 1997; Jenkyns, 2003; Sabatino et al., 2009).

Comparing the TOC and carbon-isotope curves, the polarity between them is noteworthy. Such a stratigraphical coincidence between the negative carbon-isotope excursion and TOC maximum has

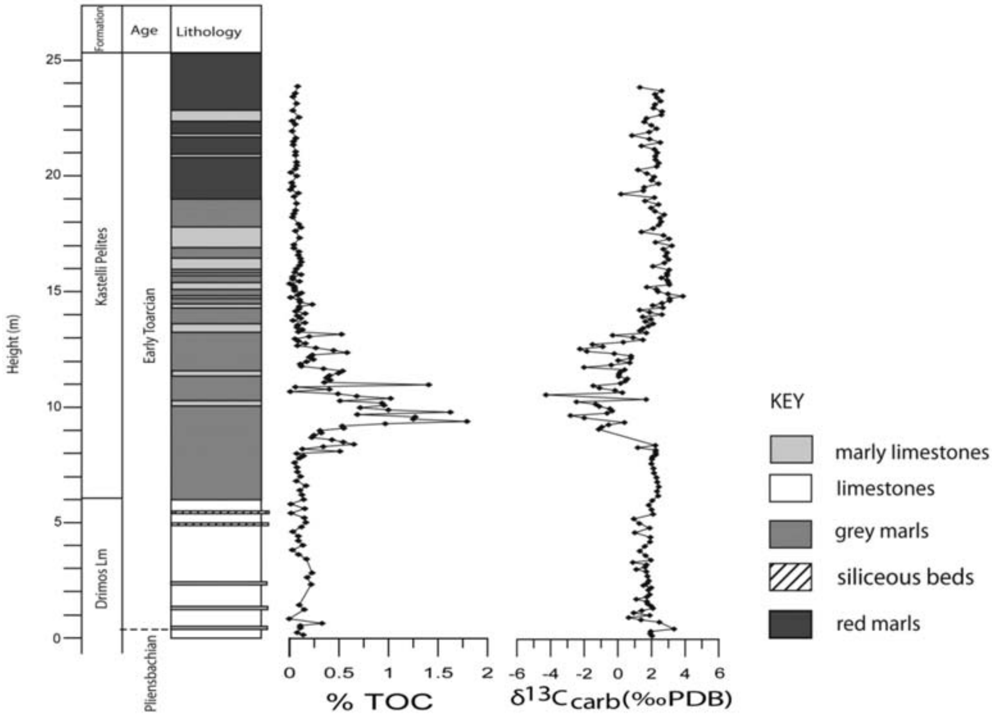

Fig. 3: Lithological column, bulk TOC and stable carbon carbonate-isotope profile for the Kastelli section.

also been observed in Lower Toarcian black shales in northern Europe (Jenkyns and Clayton 1997; Jenkyns et al. 2002). The TOC values are, however, very low compared with other coeval Toarcian sections from northern Europe, where values reach up to 15%. This difference probably relates to relatively elevated organic productivity, enhanced watermass stratification, more frequent and prolonged euxinic conditions and lesser water depths in the more boreal epicontinental seaway (Jenkyns et al. 2002; Sabatino et al. 2009; Jenkyns, 2010).

Even though this research is preliminary, the record of the Toarcian OAE from these deep-marine sediments reinforces the global character of this event. Further studies of this section and comparison with coeval horizons of the Ionian Zone (lower Posidonia beds) are in progress. Integration of these results will shed further light on the causes and effects of the early Toarcian Oceanic Anoxic Event.

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PRELIMINARY STUDY ON THE SLUMP STRUCTURES OF THE EARLY OLIGOCENE SEDIMENTS OF THE PRE-APULIAN ZONE (ANTIPAXOS ISLAND, NORTH-WESTERN GREECE)

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Abstract

A spectacular slump is observed in the Alpine sediments of the Antipaxos Island (Pre-Apulian zone, Western Greece). It can be followed in a zone of about 2000 m, in the eastern coast of the island. The slumped unit exposure length extends for more than 200 m, and is directly overlain and underlain by undeformed strata. The slump has an average thickness of 15 m and is composed, as the surrounding undeformed units, of calcareous mudstones and fine-grained calcareous sandstones. Synsedimentary folds that very often are transformed to contorted beds affect slump sediments. Fold and contorted bed axes present a NNW-SSE direction, coinciding with the general direction of the Pre-Apulian zone. Slump and overlain/underlain undeformed sediments originate from the flux of clastic mainly pelagic/neritic biogenic particles, emanating from turbidity currents. More than 50 samples have been collected and analyzed for calcareous nannofossil content. All samples were featured by the contemporaneous presence of abundant nannofossil flora implying the biostratigraphic correlation with the NP23 nannofossil biozone. The biostratigraphic assignment places the slump and the surrounding sediments to the Early Oligocene. As the Pre-Apulian zone corresponds to the slope between the Apulian Platform and the Ionian Basin, the presence of the slump is directly related to the same age sloping and tectonic mobility of this domain. The Antipaxos turbidites sediments are well integrated to the flysch deposition of the external Hellenide foreland basin system.

Key words: *synsedimentary mass flow, Early Oligocene, synsedimentary folds, contorted beds, debris flow, slope, forebulge, foreland basin system.*

1. Introduction

This paper concerns the spectacular slump horizon observed in Paxi and especially in Antipaxos Island. The mass flows described here correspond to a broad zone, 10 to 15 m thick, of synsedimentary folds and contorted beds which are rarely accompanied by debris flows. This zone is clearly framed on bottom and top by sub-horizontal undeformed beds, implying the close relationship with synsedimentary deformation and redeposition mostly of cohesive material. The Antipaxos slump is confined to distinct stratigraphic horizons and indicates that it is related to major events (e.g. earthquakes; tectonic instability; quite important dip slope, etc.) which may cause synsedimentary deformation structures and cohesive mass flows contemporaneously.

2. Geological setting

Antipaxos Island belongs to the Pre-Apulian zone. This zone corresponds to the most external domain of the Hellenic fold-and-thrust belt (Fig. 1). It has traditionally been considered as a relatively

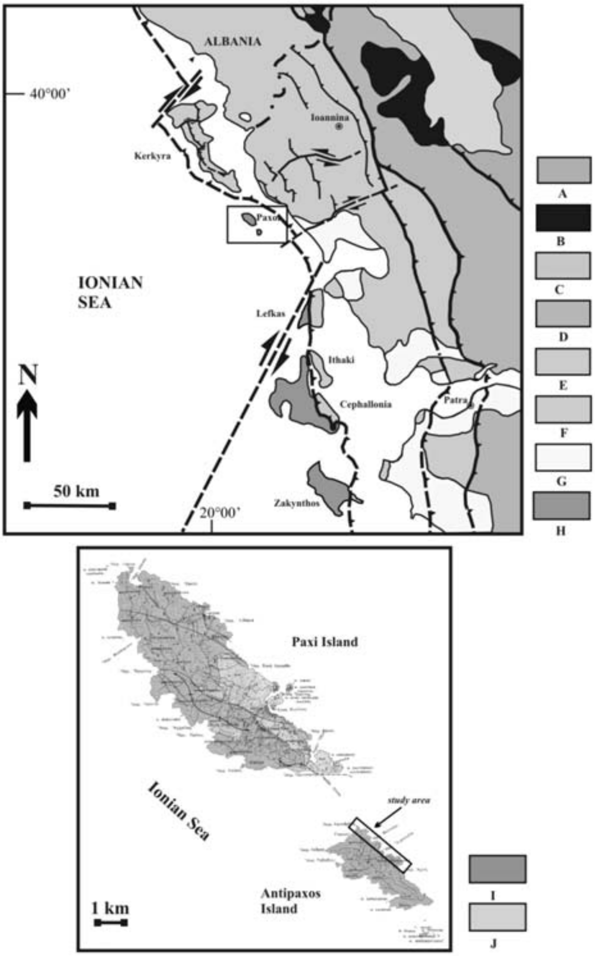

Fig. 1: On top, simplified geologic map of Western Greece (Karakitsios & Rigakis 2007). A. Pelagonian domain; B. Ophiolites; C. Mesohellenic molasse; D. Pindos zone; E. Gavrovo-Tripolis zone; F. Ionian zone; G. Neogene – Quaternany (post-Alpine sediments); H. Preapulian zone. On bottom, geological map of Paxi and Antipaxos Islands (adapted from Perry et al. 1960). I. Early Eocene - Early Miocene; J. Late Cretaceous - Middle Eocene.

uniform, Mesozoic – Cenozoic carbonate domain, transitional between the Apulian platform and the Ionian basin. Its general setting is complex as a result of intense tectonic deformation, including phases of extension, collision and flexural subsidence, with undetermined amounts of shortening and block rotation (Accordi et al., 1998). Outcropping successions differ in stratigraphic completeness, sedimentary development and faunal/floral content.

The depositional sequence in the Pre-Apulian zone (Fig. 2) begins with Triassic limestones containing intercalations of black shales and anhydrites. The oldest of these beds, according to borehole data (ESSO Hel., 1960), are dated as Toarcian to Bajocian. The stratigraphically lowest outcrops, located in Lefkas Island, comprise Lower Jurassic dolomites and Middle Jurassic cherts and bituminous shales (Bornovas, 1964; BP, 1971). The Upper Jurassic succession consists of white chalky limestones with dolomite intercalations, accompanied by rare cherts and organic-carbon rich black shales, containing

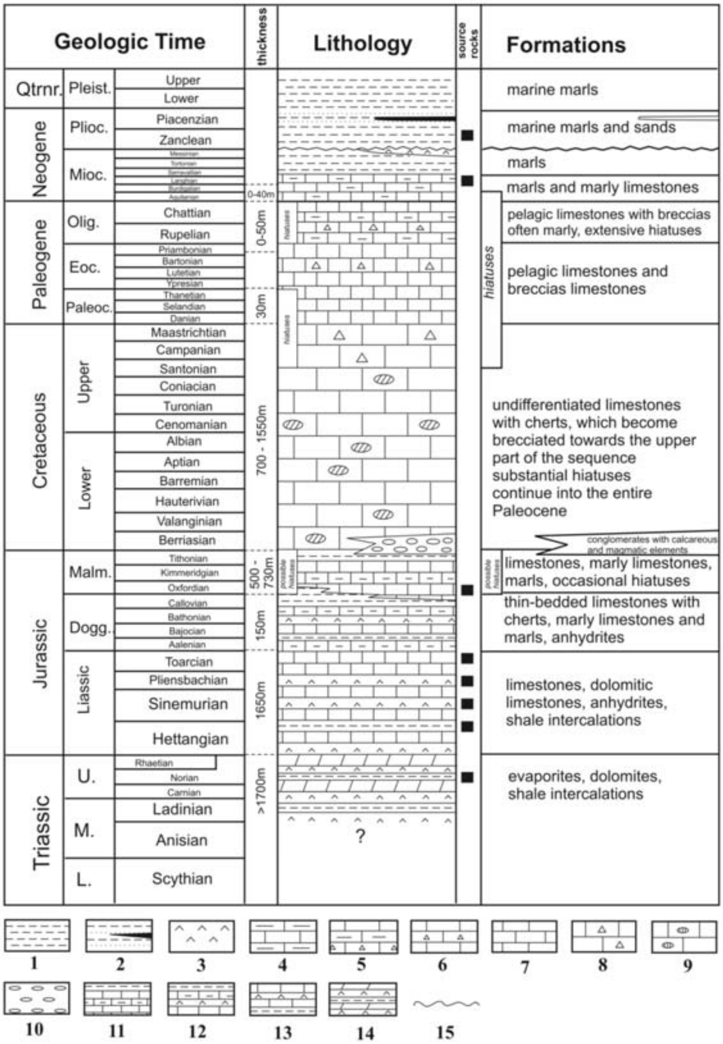

Fig. 2: Synthetic lithostratigraphic column of the Preapulian zone (Karakitsios & Rigakis 2007).
1: marine marls; 2: marine marls and sand (in black: lignite intercalations); 3: evaporites; 4: limestones often marly; 5: pelagic limestones or marly limestones with breccia intervals; 6: mixed pelagic-neritic limestones sometimes with breccias; 7: pelagic limestones; 8: mixed pelagic-neritic calcareous sediments with rudist fragments; 9: pelagic limestones with nodules and rare cherty intercalations; 10: conglomerates with calcareous and magmatic elements; 11: pelagic limestones, often marly; 12: limestones, shales and basal anhydrites; 13: limestones and dolomitic limestones, anhydrites and shale intercalations; 14: evaporites with shale intercalations, 15: unconformity.

planktonic species (Calpionellidae) together with benthic foraminifera and algal species. Borehole data from Zakynthos Island indicates the presence in the basal Cretaceous of conglomerates derived from carbonate and magmatic rocks. Lower Cretaceous limestones and dolomites crop out only on Cephallonia Island, and their facies is less pelagic than age-equivalent Ionian facies. The depositional environment throughout the Cenomanian-Turonian interval is indicated by the presence of rudist fragments, benthic foraminifera and algal species. During the Campanian-Maastrichtian, however, the platy limestones gradually become chalky with thin argillaceous layers. They contain, especially towards the top of this formation, planktonic foraminifera such as Globotruncanidae, in addition to rudist fragments. This co-existence indicates the presence of intra-platform basins characterizing the slope between the Apulian Platform and the Ionian Basin. Paleocene micritic limestones with planktic foraminifera were described by BP (1971) in the Pre-Apulian zone. Mirkou (1974) noted that these Paleocene units sometimes rest on Santonian or Maastrichtian limestones, and that neritic-facies microbreccias and brecciated limestones that occur at their base. This indicates intense tectonic activity which resulted in the differentiation of the Pre-Apulian zone into relatively deep-water and relatively shallow (sometimes emergent) areas, which provided the breccias material. The Lower Eocene comprises pelagic limestones with marl intercalations. The Upper Eocene consists of massive limestones with algae, bryozoans, corals, echinoids and large foraminifera. Oligocene sediments were deposited in small basins (tectonic grabens) between larger or smaller emergent areas, which were locally eroded, reflecting tectonic instability which continued throughout the Oligocene. During the Oligocene-Aquitanian, the diversification of foraminiferal assemblages suggests the presence of subsiding foreland basins. Finally, in the late Early Miocene, progressive deepening occurred, flooding the former carbonate slope (or carbonate ramp: Accordi et al., 1998).

The thickness of the Pre-Apulian series, in both outcrop and borehole data show that it is increasing from north to south (ESSO Hel., 1960). This observation translates the different position of the Ionian Islands in the transitional slope, represented by this zone, between the Apulian platform to the southwest and the Ionian basin to the northeast. So that, Paxi and Antipaxos Islands to the North, presenting a more basinal character, are closer to the Ionian basin, while the eastern half of the Zakynthos Island, with a more neritic character, is closer to the Apulian platform. In fact, the western part of Zakynthos already belongs to the Apulian platform, as it is composed by late Cretaceous neritic limestone with rudists.

Accordi et al. (1998) investigated the structural control on carbonate deposition and distinguished six tectono-sedimentary sectors within the Pre-Apulian zone, which was studied in the Paliki peninsula of Cephallonia Island. The boundaries of these sectors were identified by lithologic and stratigraphic discontinuities. The relationship between the different sectors is somewhat hypothetical, although, according to the above authors, they probably correspond to a number of tectonically obliterated areas of unknown extent. A general trend can be hypothesized for the study area, passing from a Late Cretaceous rimmed platform to a Paleocene homoclinal carbonate ramp. In the Paleocene, local tectonic subsidence together with eustatic sea-level changes and biological controls on the carbonate “factory” resulted in a deposition of a range of shallow-water to slope deposits, punctuated by episodes of emergence. Furthermore, the presence of a hiatus representing the greater part of the Eocene can be demonstrated in the same area.

Structures developed in the Pre-Apulian zone (mainly on the islands of Cephallonia and Zakynthos) may be accommodated within a simple model of continued foreland-directed migration of Hellenide (Alpine) thrusting during the Late Neogene and Quaternary (Accordi et al. 1998, Karakitsios & Rigakis 2007). Initial activity on the Ionian thrust can be dated as Early Pliocene, and the main thrusts (and some of the backthrusts) observed in the Pre-Apulian zone (e.g. on Cephallonia and Zakynthos Islands) are of late Pliocene and Pleistocene ages (Hug, 1969; Nikolaou, 1986; Underhill, 1989). Although, a foreland-propagating fold and thrust system in the northern external Hellenides segmented the former continental margin basin in Zakynthos and permitted diapiric intrusion of Triassic gypsum along thrust ramps, resulting in the development of coeval extentional basins, with increasing rates of subsidence from the Pliocene to Quaternary (Zelilidis et al. 1998).

Antipaxos Island is characterized by 80-90-meter-thick outcrops of a thin-bedded pelagic marly limestones succession, often microbecciated. The only geological studies concerning Paxos and Antipaxos Islands are the geological reports made by Esso Hellenic (Perry et al. 1960), AGIP (Rizzini & Balduzzi 1983) and Hellenic Petroleum geologists (Stylianou et al. 1986). The geological mapping of the Paxos sheet was accomplished by Perry et al. (1960). In this map (Fig. 1) the age range attributed to all of the Paxos Island outcrops is the Late Eocene-Early Miocene.

3. Slump description - Sedimentology

The slump horizon is clearly framed both on bottom (Fig. 3g) and top (Fig. 3a, f) by sub-horizontal undeformed beds. The thickness of the Early Oligocene slump horizon is 10 to 15 m (Fig. 3), its visible length is more than 200 m, forming a NW-SE direction zone which follows for about 2 km to the eastern coast of the island. The slump horizon is characterised by synsedimentary folds (Fig. 3) often transformed in contorted beds (Fig. 3b, c, e). The axes of synsedinendary folds and rotated beds present an NNW-SSE direction, parallel to extension of the Pre-Apulian zone and in general that of the external Hellenides. In some cases debris flows with big elements are observed (Fig. 3d). Load structures are present in the substrate unlithified plastic beds as the result of big contortions formed by slumped material (Fig. 3e). Stratigraphic gaps are implied in cases where the undeformed beds framing the slump are in direct contact, because the missing strata have been removed as slump. In general, stratigraphic successions characterised by broad and thick slumps, are expected to present secondary unconformities due to the removal of slumped beds. This case is necessary to be tested by a further detailed stratigraphic and sedimentological study. Slump horizons are characterised by downward sliding as a single mass, usually accompanied with backward rotation relative to the slope along which movement took place. The viscosity contrast of marl-limestone alternation caused development of slumping structures during gravitational redeposition. The most pronounced deformation within the slumped units occurred in semi-liquid muds (injection of marls into the cores of slump folds proves poor lithification prior to deformation). Early lithified beds were deformed in a ductile or brittle-ductile mode. In this case rare reverse faults with eastward divergence are observed.

The slump horizon is composed of the same lithofacies as the surrounding undeformed units. The dominant lithology corresponds to pelagic marly limestone often microbecciated, organized in a thin-bedded succession. According to the sedimentological investigations these sediments originate from the flux of clastic mainly pelagic/neritic biogenic particles, emanating from turbidity currents. Bioclasts range in age from the Late Cretaceous to the Early Eocene. Neritic clasts clearly demonstrate the deposition of benthic material derived from the eroded Apulian platform, which was transported by turbidity currents.

Turbidites are represented by sharp-based graded beds with a foraminiferal packstone lower part passing up into foram-wackestone/mudstone (Fig. 4). The formed sediments present a well-stratified facies of platy-marly limestones.

4. The age of the slump involved strata

Over than fifty samples recovered from the most clayey beds of the slump horizon and its undeformed base, have been studied for calcareous nannofossil biostratigraphic analysis, in order to date the Pre-Apulian calcareous sequences exposed on Antipaxos Island. Smear slides for calcareous nannofossil analysis have been prepared following the standard preparation technique of Perch Nielsen (1985). To obtain accurate biostratigraphic estimations, up to 100 fields of view have been investigated per slide, counting at least 500 specimens, with a Leica DMLSP optical polarising light

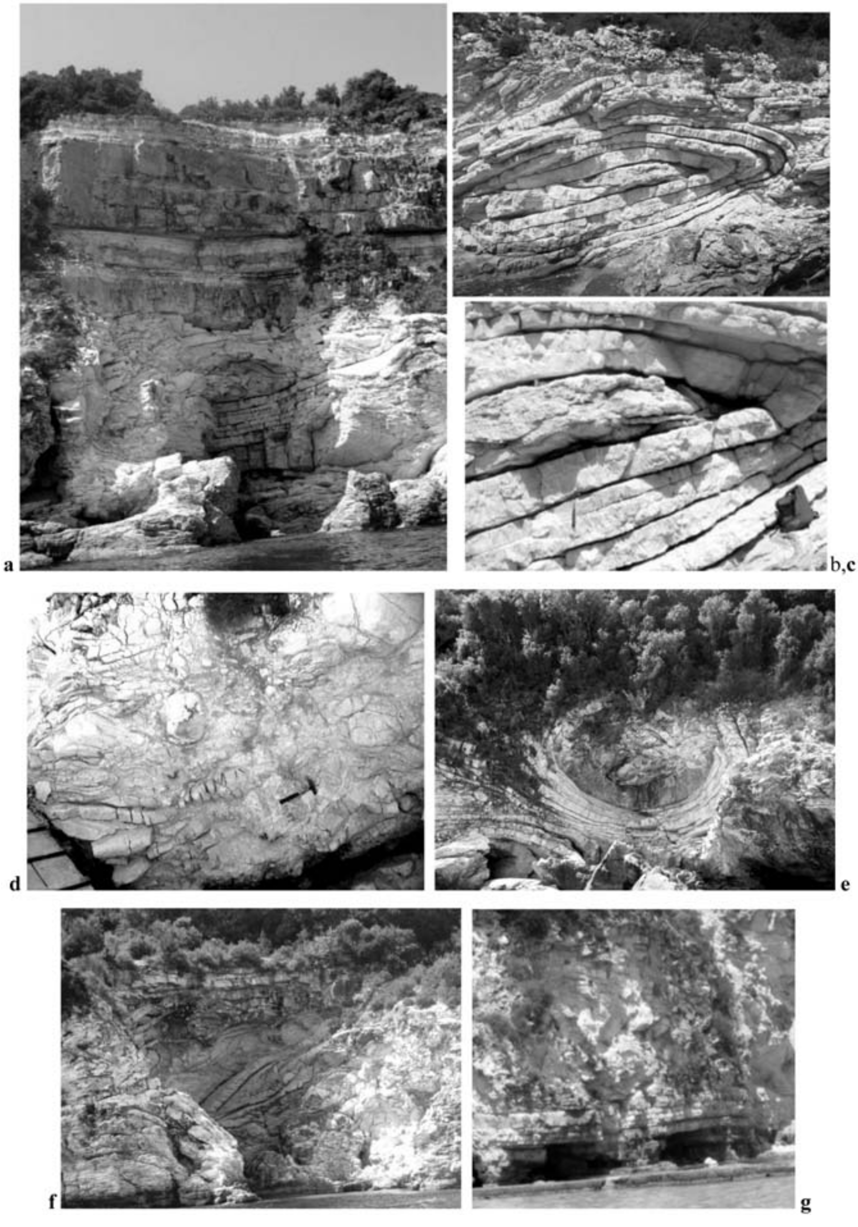

Fig. 3: Slump horizon as seen in outcrop. Slump framed on top (a,f) and bottom (g) by undeformed beds; Contortion (b) and detail (c); Debris flows with big elements (d); Load structures which were developed in the substrate unlithified plastic beds when the slumped material formed big contortions (e).

microscope at 1250x. Nannofossil state of preservation was overall very good and abundances were high. Semiquantitative abundances of the taxa encountered were recorded as follows: A, abundant: more than one specimen every field of view; C, common: 1 specimen/10 fields of view; R, rare: 1 specimen/ 50 fields of view; P, present: 1 specimen/ >100 fields of view; RW, reworked specimens.

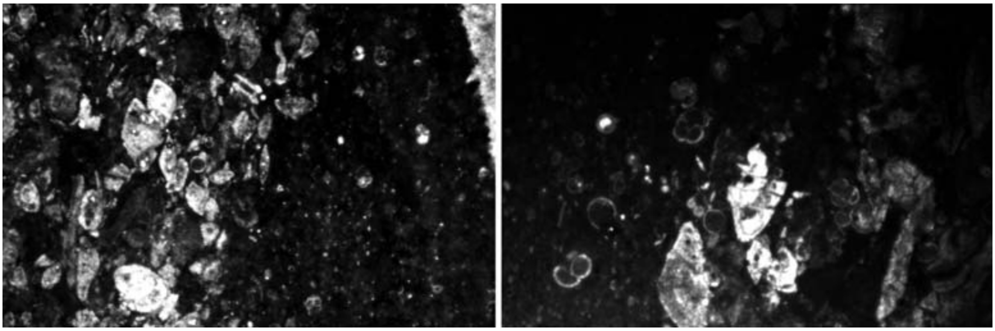

Fig. 4: Pelagic/neritic biogenic particles, emanating from turbidity currents. Bioclasts range in age from the Late Cretaceous to the Early Eocene.

The taxonomy of the determined calcareous nannofossil species has been based on Aubry (1984, 1988, 1989, 1990); Perch-Nielsen (1985). The nannofossil and biostratigraphic results are based on the biozonal schemes of Martini (1971), as they have been incorporated in the magnetobiochronologic framework of Berggren et al. (1995) and revised by Luterbacher et al. (2004). Numerical ages of biozone boundaries are given according to Luterbacher et al. (2004).

All the studied samples were featured by the contemporaneous presence of abundant *Cyclicargolithus floridanus* and Reticulofenestra bisecta, common *Sphenolithus predistentus*, rare *Sphenolithus distentus* and rather small forms of *Cyclicargolithus abisectus*, implying the biostratigraphic correlation with the NP23 nannofossil biozone. This biozone is bracketed by the bioevents of the highest occurrence (HO) of *Ericsonia formosa* at its base and the lowest occurrence (LO) of *Sphenolithus ciperoensis* at its top (Martini, 1971). It spans between 32.4-30.1 Ma, pointing to Early Oligocene age.

5. Discussion and Conclusions

Sub-aquatic slumps are structures in which sedimentary beds are deformed and the upstream part is torn away in detached lump (the form is not always recognizable) and extended (Reading 1986). The escarpment produced on the upstream part may then be subject to submarine erosion and then covered by gap with younger sediments. This gap represents the age interval of the slumped stratigraphic unit plus the age of the eroded sediment trance. The downstream part is characterized by intense deformation of the beds in synsedimentary folds, contortions and reverse faults, as the slippage generates compression. Minor earthquakes may prompt the formation of slumps on the slope, or the slope's lack of stiffness to resist an excess sedimentary load. Certain geological series of the past include impressive sequences that witness to active synsedimentary tectonics (Bally 1983). Any type of sediment can slump. In certain cases, the slump fold heads are dissociated and the less cohesive material then participates in other types of gravity-driven deposits (e.g. debris-flow; Strachan 2008). In the literature the causes triggering the slump movement are attributed to (Chamley 1990): earthquakes; tectonic uplift or depression; quite important dip slope; fast deposition that causes load excess; various nature of sediments which present different degree of consolidation or load excess, e.g. sands of higher density upstream, clays of lesser density downstream; high water content in the sediments (water saturated); rapid biochemical organic matter degradation with gas production in the sediment; substrate deformation due to evaporite mass rising. In our case the only certain factors are the dip slope and tectonic instability of the Ple-Apulian zone.

It has so far been generally accepted that the Pre-Apulian zone lacks typical flysch sediments. However, the observed progressive passage from the Ionian typical flysch to the more calcareous, age-equivalent, facies in the Pre-Apulian zone (BP, 1971) indicates that Oligocene Pre-Apulian sediments correspond to an atypical distal flysch unit (Karakitsios & Rigakis 2007). The partial or complete absence of this unit from some areas is due to the fact that these areas corresponded to the most external part of the forebulge depozone in the Hellenide foreland basin system (*sensu* De-Celles & Giles 1996), which has possibly been eroded (Karakitsios & Rigakis 2007). The observed Early Oligocene marly limestone turbidite sediments in Antipaxos Island are coeval to the typical Ionian flysch, whose thickness in the external western part of the Ionian zone is reduced and more calcareous, due to its paleogeographic position in the outer foredeep depozone (*sensu* Mutti et al. 2003). The Antipaxos turbidites composed by pelagic/neritic clasts favour the paleogeographic position of this domain east of the forebulge depozone corresponding to the western marginal part of the Apulian platform whose erosion supplies the turbidite material deposited in the Pre-Apulian slop. Consequently, the Antipaxos turbidites sediments are well integrated to the flysch deposition of the external Hellenide foreland basin system.

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TEXTURE VERSUS DISTANCE OF TRAVEL OF GRAVELS ON A STREAM BED: A CASE STUDY FROM FOUR STREAMS IN NW PELOPONNESE, GREECE

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Abstract

This study concerns the change of lithology, grain size and roundness of gravels with distance downstream in lowland area from four streams which are Krathis, Kerinitis, Meganitis and Finikas. Four types of gravelly clast lithology were collected: limestone, chert, sandstone and conglomerate. In Krathis stream, the absence of variability in lithologic content is due to a short travel. The variability of the arithmetic mean depends on the width of stream channel. The roundness either remains constant or becomes better downstream because of selective transport. In Kerinitis stream, the variability or the invariability in the lithologic content is due to partly or local sample variation, partly to influx of new material, and partly to effects of increase or decrease of other types. The arithmetic mean and roundness either remain constant or are decreased downstream due to the contamination and the short travel. In Meganitis Stream, the lithologic content shows variability, the arithmetic mean absence of downstream fining gravel and the roundness variability or invariability because of the contamination and gravel mining. In Finikas Stream, the lithological content, the arithmetic mean and the roundness show either variability or invariability because of the gravel mining.

Key word: *Lithology, grain size, roundness, gravels, streams, NW Peloponnese.*

1. Introduction

It has long been established that parameters such as particle size, shape and roundness change progressively downstream in coarse grain alluvial deposits as a consequence of the sorting, mechanical abrasion and chemical weathering in sediment transport. Previous investigators have attributed downstream fining to both selective sorting and abrasion. Downstream trends in fining can be interrupted or overridden by lateral inputs of coarse sediments from tributary channels and hillslope processes. The downstream changes in the lithology of stream gravels depend on the resistances of various rock types to abrasion and breakage. Krumbein (1942) and Plumley (1948) concluded that the roundness increases as a logarithmic function of distance. Moreover, the rounding does increase with distance, most rapidly at first and then more slowly (Pettijohn, 1973). There seems to be a limiting roundness, in part related to the lithology of the materials- lower, for example, for chert than for quartz or limestone. Previous studies of changes in fluvial size distribution and roundness in a downstream direction are completely limited in Greece (Kontopoulos & Panagos, 1979; Karkanas & Kontopoulos, 2004).

The aim of this work is to test and reason the downstream change of size and roundness in braided stream gravels in northwestern Peloponnese.

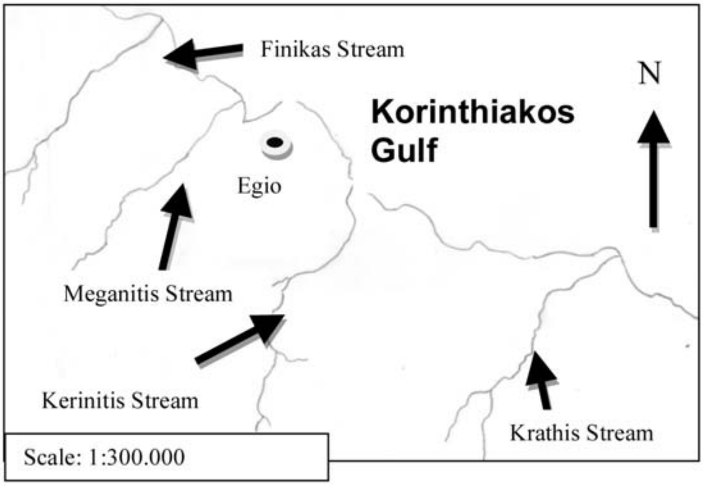

Fig. 1: Simplified sketch which shows the streambeds of study streams.

2. Study area

Four sampling areas were chosen (Fig. 1). These are the streambeds of Krathis, Kerinitis, Meganitis, and Finikas streams. These are the main channels of fan deltas which were established on southwest coast of Korinthiakos Gulf. The mean value of Kerinitis streambed steepness is about 1.9 degree in its distal part while in the other three streams is about 2 degree. The stream source areas consist of limestone and flysh of Pindos zone and Pliocene and Pleistocene fine-grained sediments while the bedrock of Tripolis zone is one additional source area for Krathis stream.

3. Methods

Sample sites were chosen in order to give an overview of the downstream clast changes (Figs. 2, 3, 4, 5). Field sampling of clasts was made following Bunt and Abt (2001) using sampling frame and a tape measure stretched from bank to bank. Each clast was identified to rock type and the following parameters were measured: (1) b axis and (2) roundness after Krumbein (1942).The statistical validity of the downstream changes in arithmetic mean (b) and roundness were tested using multiple comparisons in one-way analysis of variance and Dunkan'test at a 0.1% significance level. Levene's test for the homogeneity of variances was used. The statistical validity of the downstream changes in lithology was tested using X^2 method. The studied relative resistances to abrasion and breakage of the rock types were calculated on basis of the chert ratio.

4. Results

4.1 Krathis Stream

The percentage of all lithologies shows insignificant changes downstream (Table 1, Fig. 6).

The arithmetic mean of limestone pebbles decreases significantly from sample site 2 to sample site 4 while the arithmetic mean of sandstone and conglomerate pebbles shows insignificant changes downstream. The arithmetic mean of chert pebbles decreases significantly only from site 3 to site 4. (Table 2, Fig. 7). The roundness value of chert and sandstone pebbles shows insignificant changes

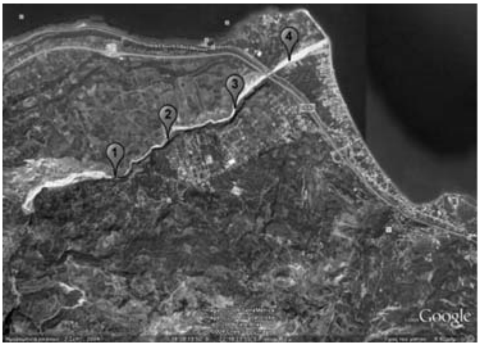

Fig. 2: Map of Krathis stream with paddles showing the sampling sites.

Fig. 3: Sampling map of Kerinitis stream. The paddles show the sample stations. The pushpins show two bridges respecti-vely.

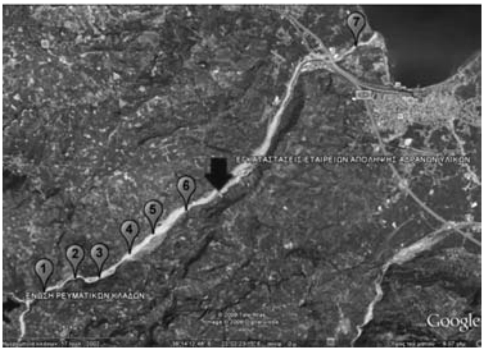

Fig. 4: Sampling map of Meganitis stream. The paddles show the sample stations. The black arrow shows a zone of aggregate quarry. The black concave arrow shows the joining of a tributary with the main channel.

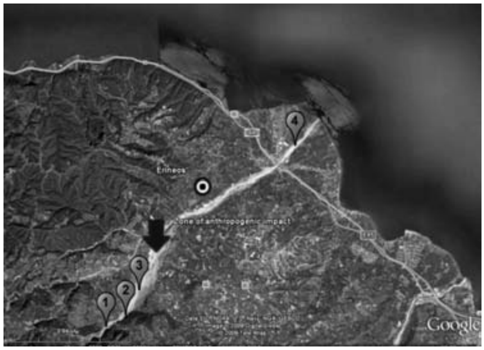

Fig. 5: Sampling map of Finikas stream. The paddles show the sample stations. The black arrow shows a zone of aggre-gate quarry.

among the sample sites. The roundness value of limestone pebbles becomes significantly better only from site 3 to site 4. The conglomerate pebbles become significantly better from site 2 to site 3 (Table 3, Fig. 8), also.

Table 1. Percentage lithological composition of pebbles at the sample sites in the Krathis stream.

Krathis Sample sites	Limestone grains %	Chert grains %	Sandstone grains %	Conglomerate grains %
Σ1	73,88	10,45	8,21	7,46
Σ2	75	12,5	6,73	5,77
Σ3	79,56	12,71	4,42	3,31
Σ4	76,37	11,54	6,6	5,49

Table 2. The values of the arithmetic mean all lithologies at the sample si-tes in the Krathis stream.

Krathis Sample sites	Limestone grains Arithmetic mean (mm)	Chert grains Arith-metic mean (mm)	Sandstone grains Arithmetic mean (mm)	Conglomerate grains Arithmetic mean (mm)
Σ1	65,48	50,29	52,09	164,3
Σ2	62,91	55,69	73,57	108,33
Σ3	55,92	62,22	57,75	99,33
Σ4	41,17	29,1	43,67	48,11

Table 3. The roundness values of all lithologies at the sample sites in the Krathis stream.

Krathis Sample sites	Limestone grains Roundness value	Chert grains Roundness value	Sandstones grains Roundness value	Conglome-rate grains Roundness value
Σ1	0,42	0,25	0,42	0,27
Σ2	0,39	0,27	0,55	0,25
Σ3	0,42	0,28	0,5	0,42
Σ4	0,47	0,23	0,47	0,41

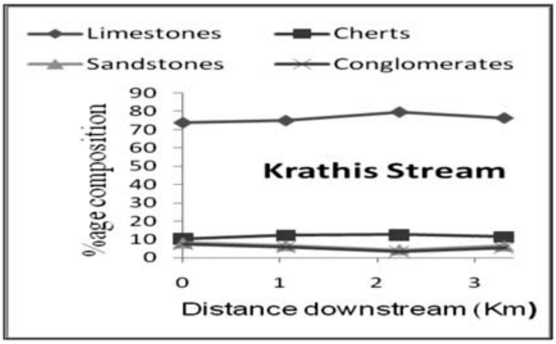

Fig. 6: Rock type vs downstream distance, Krathis stream.

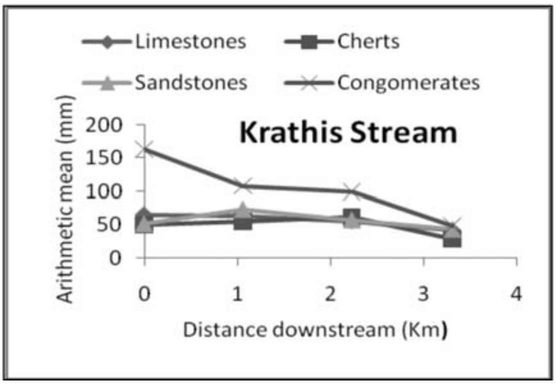

Fig. 7: Downstream changes in particle size of different lithologies, Krathis Stream.

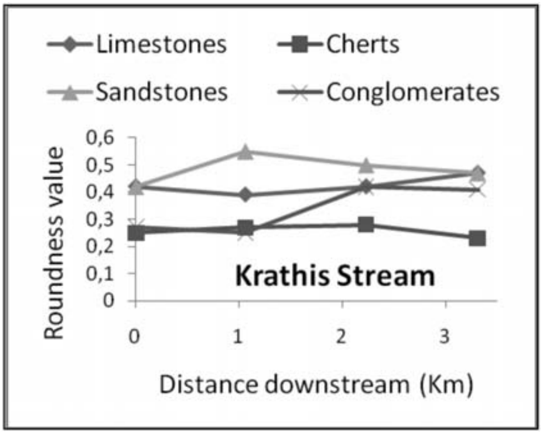

Fig. 8: Rock type roundness vs. distance downstream, Krathis Stream.

4.2 Kerinitis Stream

The total lithological assemblages show significant differences among the sample localities. These differentiations are the result of decrease of percentage of limestone pebbles and the increase respectively of sandstone pebbles from site 2 to site 3 (Table 4, Fig. 9). The arithmetic mean of limestone and chert pebbles is decreased significant only from site 1 to site 2. Conversely the ari-thmetic mean of sandstone pebbles shows significant decrease downstream only from site 2 to site 3 (Table 5, Fig. 10).The roundness value of chert and sandstone pebbles shows insignificant changes among the sample sites. The roundness value of limestone pebbles becomes significant worse only between the site 1 and the site 2 and there is no significant change between the site 2 and the site 3 (Table 6, Fig. 11).

Table 4. Percentage lithological composition of pebble at the sample sites in the Kerinitis Stream.

Kerinitis Sample sites	Limestone grains %	Chert grains %	Sandstone grains %
Σ1	90,08	7,44	2,48
Σ2	87,41	8,39	4,2
Σ3	76	10,67	13,33

Table 5. The values of the arithmetic mean all lithogies at the sample sites in the Kerinitis Stream.

Kerinitis Sample Sites	Limestone grains Arithmetic mean(mm)	Chert grains Arithmetic mean(mm)	Sandstone grains Arithmetic Mean(mm)
Σ1	177,83	111,83	110
Σ2	115,66	47,33	111,67
Σ3	99,31	46,25	54,38

Table 6. The roundness values of all lithologies at the sample sites in the Kerinitis Stream.

Kerinitis Sample sites	Limestone grains Roundness value	Chert grains Roundness value	Sandstone grains Roundness value
Σ1	0,55	0,33	0,67
Σ2	0,52	0,3	0,76
Σ3	0,51	0,34	0,56

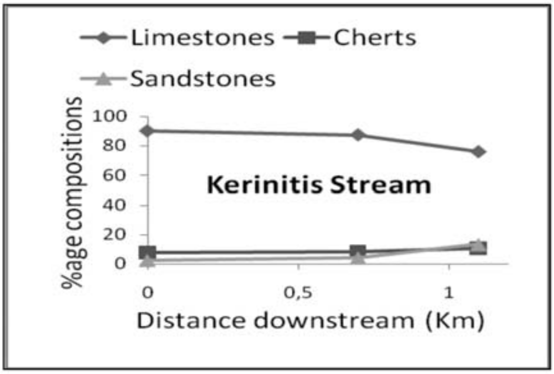

Fig. 9: Rock type vs. downstream distance, Kerinitis Stream.

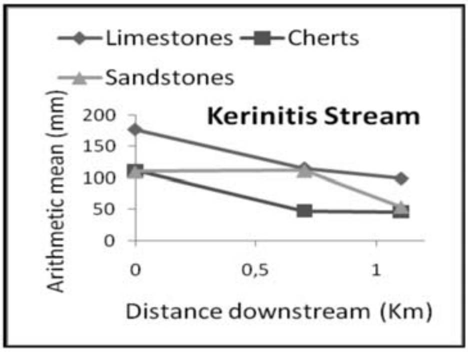

Fig. 10: Downstream changes in particle size of different lithologies, Kerinitis Stream.

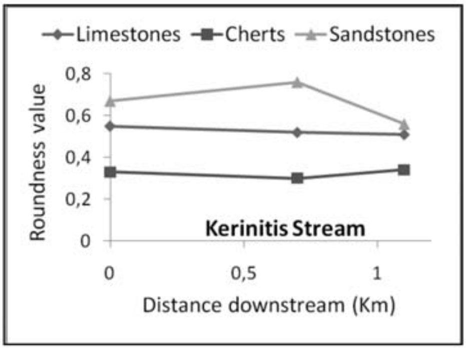

Fig. 11: Rock type roundness vs distance downstream, Kerinitis stream.

4.3 Meganitis Stream

The lithological assemblage shows significant differences among the sample localities (Table 7, Fig.12). This differentiation is the result of percentage lithological changes of limestone and sandstone pebbles. The percentage of limestone grains increases from site 1 to site 2 and then gradually decreases through site 3 to the site 4 while increases again from site 6 to site 7. The percentage of chert pebbles shows a weak decrease both from site 1 to site 2 and from site 6 to site 7. The percentage of sandstone pebbles shows a weak decrease from site 1 to site 2 and a significant decrease from site 6 to site 7. The arithmetic mean of limestones shows significant decrease in both from site 1 to site 2 and from site 6 to site 7. The arithmetic mean of chert pebbles does not show changes downstream. The arithmetic mean of sandstones pebbles shows significant decrease from site 5 to site 6 and then is increased significant from site 6 to site 7(Table 8, Fig. 13). The roundness value of limestone pebbles shows a discontinuous reduction from site 1 to site 6 and then becomes significantly better from site 6 to site 7. The roundness value of chert pebbles shows significant decrease from site 2 to site 3 and then remains constant up to the site 6. This value becomes significantly better from site 6 to site 7. The roundness value of sandstone pebbles shows insignificant changes from site 4 to site 7. This becomes significantly better at site 2 in relation to the other sites except the sites 3 and 1. The roundness value at site 3 shows that is better in relationship to that of side 6 (Table 9, Fig. 14).

Table 7. Percentage lithological composition of pebbles at the sample sites in the Meganitis stream.

Meganitis Sample sites	Limestone grains %	Chert grains %	Sandstone grains %
Σ1	63,64	11,57	24,79
Σ2	68,26	9,58	22,16
Σ3	68,58	8,05	23,37
Σ4	62,89	12,22	24,89
Σ5	61,21	14,23	24,56
Σ6	61,69	11,44	26,87
Σ7	77,87	8,3	13,83

Table 8. The values of the arithmetic mean all lithogies at the sample sites in the Meganitis stream.

Meganitis Sample sites	Limestone grains Arithmetic mean	Chert grains Arithmetic mean	Sandstone grains Arithmetic mean
Σ1	112,79	91,07	125,7
Σ2	81,75	73,94	107,16
Σ3	99,02	69,29	96,08
Σ4	100,67	59,3	110,95
Σ5	85,79	50,11	87,17
Σ6	105,51	47,41	121,66
Σ7	69,84	48,71	77,66

Table 9. The roundness values of all lithologies at the sample sites in the Meganitis stream.

Meganitis Sample sites	Limestone grains Roundness value	Chert grains Roundness value	Sandstone grains Roundness value
Σ1	0,46	0,45	0,56
Σ2	0,43	0,43	0,66
Σ3	0,42	0,26	0,58
Σ4	0,39	0,22	0,51
Σ5	0,38	0,2	0,51
Σ6	0,36	0,23	0,44
Σ7	0,49	0,51	0,51

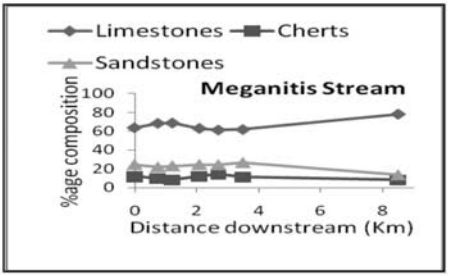

Fig. 12: Rock type vs downstream distance, Meganitis stream.

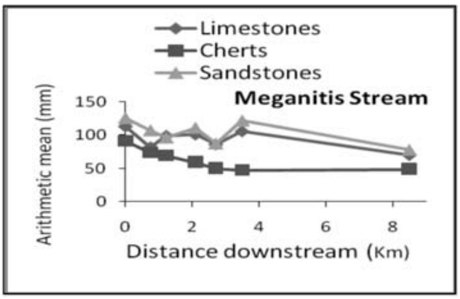

Fig. 13: Downstream changes in particle size of different lithologies, Meganitis stream.

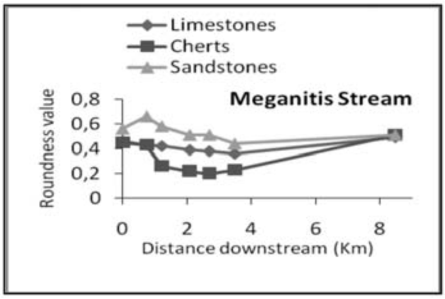

Fig. 14: Rock type roundness vs distance downstream, Meganitis stream.

4.4 Finikas Stream

The composition of lithological assemblage shows insignificant differences among the three first sample localities (Table 10, Fig.15). In the fourth sample site in relation to the other three sites, the percentage of limestone pebbles increases significant while the percentage of the other two lithologies is decreased significant. The arithmetic mean of limestone pebbles shows significant decrease downstream from site 2 to site 4 while there is no change from site 1 to site 2. The arithmetic mean of chert pebbles does not show significant change from the site 1 to site 3 while is decreased from site 3 to site 4. The arithmetic mean of sandstone pebbles does not show significant change from site 1 to site 3 while is decreased from site 3 to site 4 (Table 11, Fig. 16). The roundness value of limestone pebbles increases significant from site 1to site 4 through the sites 3and 4. The roundness value of chert and sandstone pebbles does not show significant change from site 1 to site 3 while increases significant from site 3 to site 4 (Table 12, Fig. 17).

Table 10. Percentage lithological composition of pebbles at the sample sites in the Finikas stream.

Finikas stream Sample sites	Limestone grains %	Chert grains %	Sandstone grains %
Σ1	67,2	14,29	18,52
Σ2	60,74	18,02	21,23
Σ3	65,23	15,22	19,54
Σ4	81,85	11,08	7,08

Table 11. The values of the arithmetic mean all lithologies at the sample sites in the Finikas stream.

Finikas stream Sample sites	Limestone grains Arithmetic mean(mm)	Chert grains Arithmetic mean(mm)	Sandstone grains Arithmetic mean(mm)
Σ1	157,94	94,56	142,07
Σ2	162,73	96,04	154,7
Σ3	135,15	122,51	165,78
Σ4	72,58	58,53	60,09

Table 12. The roundness values of all lithologies at the sample sites in the Finikas stream.

Finikas Stream Sample sites	Limestone grains Roundness value	Chert grains Roundness value	Sandstones grains Roundness value
Σ1	0,38	0,22	0,51
Σ2	0,45	0,24	0,54
Σ3	0,45	0,23	0,56
Σ4	0,52	0,31	0,75

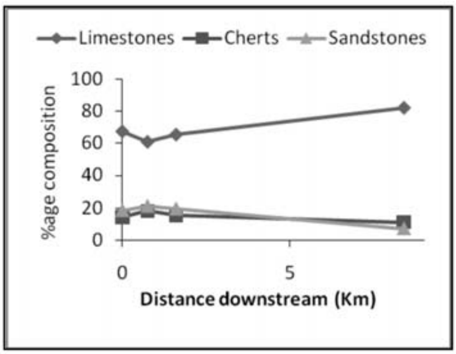

Fig. 15: Rock type vs distance downstream, Finikas stream.

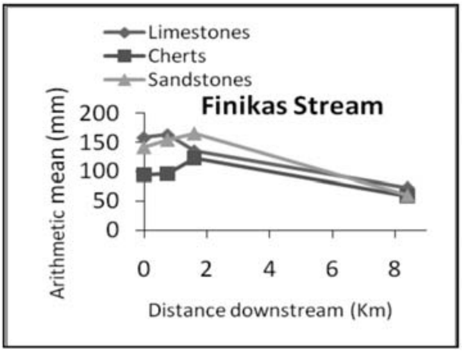

Fig. 16: Downstream changes in particle size of different lithologies, Finikas stream.

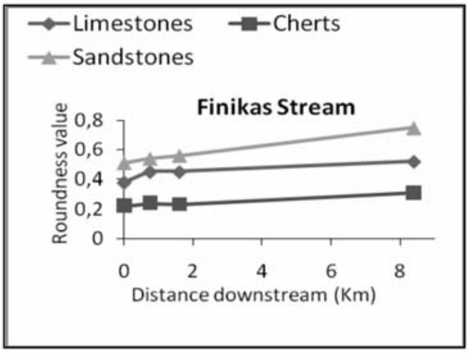

Fig. 17: Rock type roundness vs distance downstream, Finikas stream.

5. Conclusions-Discussion

There is absence of variability in lithologic content from one sample site to other, in the Krathis stream. This effect is due to the small total distance of sampling. The reduction of soft rock types as the limestone and sandstone pebbles by the abrasion and breakage is negligible in a short distance of stream transport. The arithmetic mean of the limestone pebbles is decreased from site 2 up to the site 4 while the arithmetic mean of the chert pebbles is decreased from site 3 up to the site 4. The arithmetic mean of sandstone and conglomerate pebbles does not change along the distance of sampling. The stream channel from site 2 up to the site 4 is wide while from site 1 up to the site 2 is very narrow (Fig. 2). The stream width appears to assert a local control on grain size; coarse particles are associated with narrow channel reaches, whereas smaller particles are associated with wide channel reaches (Rengers & Wohl, 2006). Wide sections, therefore, display downstream fining of sediment and can be explain the downstream fining of limestone and chert pebbles because of the selective transport. The roundness value of chert and sandstone pebbles does not change along the distance of sampling. In contrary, the roundness value of limestone pebbles increases from site 3 up to the site 4 while the roundness value of conglomerate pebbles also increases from site 2 up to the site 3. The increase of roundness downstream is due to the previously mentioned selective transport.

There is variability in the lithologic content in short distance of sampling, in the Kerinitis stream. The Chert ratio curves show irregularities which means that the proportion of chert does not increase with distance at the expense of all other rock types (Fig. 18). This is due partly to local sample variation, partly to influx of new material, and partly to effects of increase or decrease of other types, (Plumley, 1948). These three reasons justify the variability. The arithmetic mean either remains stable or is decreased between two successive sampling positions. This behaviour of the arithmetic means is due to the contamination by tributary stream between the site 1 and the site 2 and the sort distance of sampling. The roundness values of chert and sandstone pebbles remain unchanged along the distance of sampling. The roundness value of limestone pebbles shows a decrease from site 1 up to the site 2 and it remains stable from site 2 up to the site 3. The decrease in roundness with distance of transport is impossible unless if contamination or short travel of gravels exist along the distance of sampling. These facts happen as previously mentioned.

The lithologic content shows a variation along the distance of sampling, in the Meganitis stream.

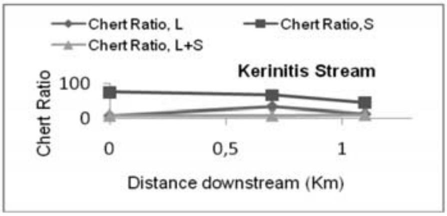

Fig. 18: Ratio of Chert to Chert plus each component: L, Limestone; S, Sandstone; L+S, Limestone plus Sandstone.

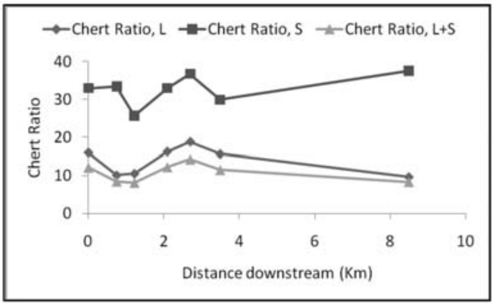

Fig. 19: Ratio of Chert to Chert plus each component: L, Limestone; S, Sandstone; L+S, Limestone plus Sandstone.

The Chert ratio curves show the absence of any action of the abrasion, breakage and weathering. (Fig. 19).

However, this lack of action is misleading. The contamination with new material among the sample stations and the anthropogenic impact obscure the operation of the abrasion, breakage and weathering. This contamination and gravel mining determine the lithologic variability (Fig. 4). Also, the selective transport and abrasion is obscured by contamination of new material and gravel mining. So, a downstream fining trend is not observed. The roundness fluctuates or remains constant. This absence of any systematic change is owed to the same reasons which interpret the lithological variability.

The lithologic content remains constant in the first three localities of sampling of Finikas stream while it changes from the third up to fourth station of sampling. The lack change in the lithological content along the first three sampling stations is interpreted by the small distance between them. The change in the lithological content from the third up to the fourth station of sampling is explained by the presence of aggregate quarry between them (Fig. 5). The arithmetic mean of limestone pebbles shows a downstream fining trend from site 2 up to the site 4 and remains constant from site 1 up to the site 2. The arithmetic mean of chert and sandstone pebbles remains constant from site 1 up to the site 3 and shows a decrease from site 3 up to the site 4. The previous mentioned changes of arithmetic mean of the three lithologies are due to the pebble mining. The roundness value of limestone pebbles increases from site 1 up to the site 4 through sites 2 and 3. In contrary, the roundness value of chert and sandstone pebbles remains constant from site1 up to the site 3 and increases only from site 3 up to the site 4. The roundness value trend of limestone pebbles could be the result of the selective transport. However, we must assume that the chert and sandstone pebbles show the same roundness trend as limestone pebbles. However this is not in effect. So, the gravel mining regulates the roundness behavior along the distance of sampling.

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SEDIMENTOLOGICAL AND GEOPHYSICAL OBSERVATIONS IN THE DELTA PLAIN OF SELINOUS RIVER, ANCIENT HELIKE, NORTHERN PELOPONNESUS GREECE

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Abstract

Fine and coarse grained lithofacies and depositional environments were distinguished in Selinous River delta plain, from sediment cores using an Eijkelkamp percussion corer with barrel windows. The sedimentary sequence of deltaic plain deposits of Selinous River mostly consists of fine lithofacies interbedded occasionally with conglomerate facies. Fine grained lithofacies based on sediment types, structure, color, as well as contact depths and bed characteristics were interpreted as floodplain, crevasse splay, back swamp / fresh water swamp, permanent shallow fresh water lake and ephemeral fresh water lake facies. The coarse grained lithofacies consists of pebble - conglomerates and were interpreted as paleochannels. The Time-Domain Electromagnetic technique, (TEM) was applied in order to define the spatial distribution of lenses of conglomerates, palaeochannels and fine grained sedimentary material to be recognised, at a depth up to 35m. Both the sedimentological and geophysical approaches, in combination with the available geological and geomorphological data of the area, can provide information about the evolution, existence and the geometry of paleochannels of the Selinous River flood plain, and the paleoenvironment of the area of the ancient Helike.

***Key words**: Selinous River, delta plain, depositional environments, TEM, ancient Helike.*

1. Introduction

On the southwest shore of the Gulf of Corinth, deposits from Selinous and Kerynites Rivers form a low delta plain. During the winter of 373 BC, according to historical sources the Helike city was destroyed by a strong earthquake tsunami and rapidly submerged (Katsanopoulou, 2005). The city was the capital of the "Achaean Dodecapolis". During the last fifty years many Greek and foreigner scientists tried to interpret the way of destruction and the locality of ancient Helike. The paleogeographic evolution of the delta plain may be the key to be recognized the mechanisms of the destruction and the geographical location of the city. In order to reconstruct the evolution of the Selinous and Kerynites delta plains, sedimentological and geophysical data were intergrated. Sedimentological data were obtained from the detailed description of several boreholes of the area (Koutsios, 2009) while geophysical data where based on the application of the Time-Domain Electromagnetic technique.

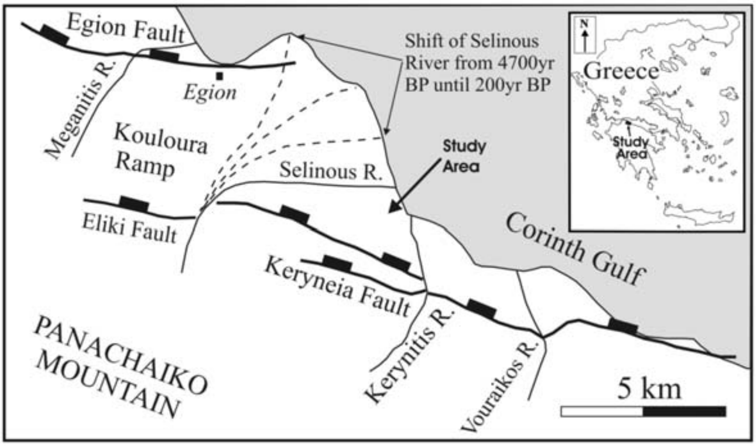

Fig. 1: Map showing the location of the study area, Selinous and Kerynitis Rivers, the major fault systems of the area (Koukouvelas & Doutsos 1996; Koukouvelas 1998) and the shift of Selinous river flow from a NNE to a ENE course (Kontopoulos & Avramidis 2003).

The Time-Domain ElectroMagnetic technique, (TEM) is a relatively recent method, as it has been used in environmental and hydrogeological studies (Soupios et al. 2009; Kalisperi 2009) in the last 15-20 years. An analytical presentation of the method can be found by McNeill (1994), and Nabighian and Macnae (1991), whereas a brief description of the method is provided. The TEM method makes use of a direct current transmitted into the transmitter loop lying on the ground. The current creates a primary, stationary magnetic field. The direct current is switched off which induces an eddy current system in the ground. Due to ohmic resistance of the subsurface, the current system will decay and further induce a secondary magnetic field that is measured in an induction coil (the receiver coil). The decay rate of the electromagnetic field depends on the resistivity distribution of the subsurface.

The main purpose of this study is to contribute in understanding of the paleogeographic evolution of the Selinous delta (Ancient Helike) plain during late Holocene times, examining its subsurface geology with sedimentological and geophysical approach. TEM method is used in this study, for a very detailed survey since the target (lenses of conglomerates, paleochannels and other depositional materials) is very shallow and has very limited size.

2. Geological setting

The study area is located between the Selinous and Kerynites Rivers in the north Peloponnesus, Greece. The largest part of the study area is characterized by the presence of five WNW-trending normal extensional faults dipping to the north (Koukouvelas & Doutsos 1996). Two of these, the Helike and Egion faults, are the northernmost that affect the south coast of the Gulf of Corinth (Fig. 1).

A thick sequence of fan delta sediments of the Selinous river that accumulated on the Heliki hanging wall block during the late Quaternary, evolved under the influence of long-term tectonic uplift and earthquake-related subsidence (Soter, 1998). Also, Pleistocene and modern fan deltas were deposited in the hangingwall basin of the Egion fault (Poulimenos, 1993).

Modern fan delta sediments are supplied from the Meganitis river and occur towards the central portion of the fault. Towards both ends of the Egion fault, progressive emergence of the hangingwall

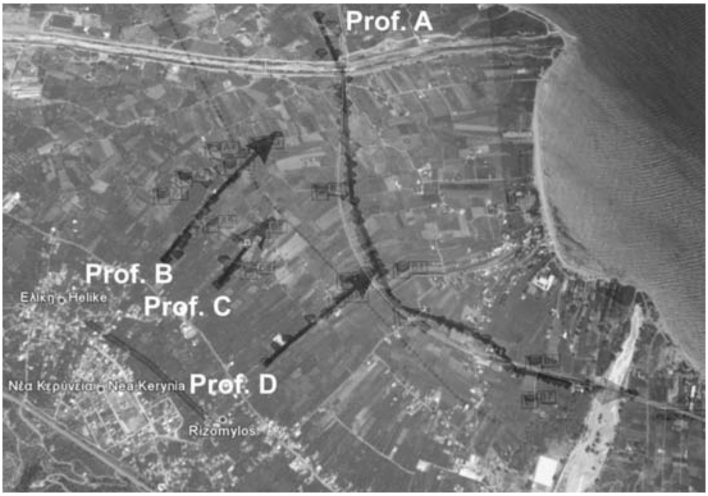

Fig. 2: Map showing, The Selinous and Kerynitis Rivers, the location of the boreholes (A1-A6 and B1-B10) and the geophysical profiles (A, B, C, & D). Note that, Profile A was acquired along the local railway.

basin is testified by the development the Meganitis and Selinous coastal alluvial plains (Koukouvelas, 1998). The Egion and Eiki faults are separated by the eastward – tilted Kouloura ramp (Fig. 1). The Kouloura ramp developed under competition between uplift of the Egion footwall and subsidence of the Heliki hangingwall areas (Koukouvelas, 1996). This ramp has induced the historical shift of the Selinous river flow from a NNE to a ENE course (Kontopoulos & Avramidis 2003).

3. Methods

Sediment cores A1-A6 and B1-B10 were obtained using an Eijkelkamp percussion corer with barrel windows (Fig. 2). Sediment types, structure, color, as well as contact depths and bed characteristics were recorded for each core in the field. The approximate percentage of shell fragments, plant remains, carbonate cemented grains concretions and terrigenous grains in the sand fraction were estimated visually. Radiocarbon dating was carried out in selected samples (shells and organic material) at Beta Analytic, Miami (Fig. 3).

In this work, an innovative application of TEM technique (Missiaen et al. 2008) was attempted, using single loop 12.5x12.5m for very shallow-depth (less than 30 meters) paleogeographical mapping in the broader area of Heliki village (Northern Peloponnesus), Greece was conducted. In total, one hundred ninety-five (195) TEM soundings were acquired in one hundred twenty-one (121) different locations (Fig. 2). The study area is located into the flood plain of Heliki area and is bounded by the Selinous River (to the North) and Kerynitis River (to the South), the Heliki's fault (to the West) and the coast line (to the East). Since the paleochannels are expected to develop in a SW-NE direction (parallel to the rivers), a very detailed NW-SE TEM profile (Prof. A) with about 5-50m interval between the measurements, was conducted. Three supplementary sub-parallel profiles were acquired in a SW-NE direction within the flood plain (Profiles B, C and D; Fig. 2), for comparison with the geophysical images.

During the geophysical fieldwork, the team was very careful for the optimum site selection, the installation of the antenna, and other environmental conditions which can produce noisy and bad quality data. The root mean square (rms) error of the final data set was mainly less than 8%. The system was set to transmit current up to 4 Amp with 28 active time gates from 4μs to 512μs and the parameter "stack", which corresponds to the digital stacking of a signal, was set to 5 (each number of this parameter corresponds 13 complete cycles). To define and avoid aliasing effects (high frequency - HF noise from radio sources) the measurements were repeated several times at each sounding location.

Data processing provided the one dimensional (1D) distribution of resistivity with depth. The TEM-RESearcher, a Windows integrated software system, was the tool for data processing of TEM data and inverse problem solution (TEM-RESearcher manual 2007). Raw data were "edited" (e.g. first points were excluded from the curve for further analysis) and "smoothed" before modelling, as the manufacturer suggests (Barsukov et al. 2007). TEM-RES software provides two ways to elaborate a section, transformation and inversion. Since the 1D modelling is inadequate to reconstruct and describe the subsurface, 2D imaging is demanded. TEM-RES software is a great tool for geoelectrical sections construction as well. Thus, the 1D inversion data are received and the user can choose any profile he prefers to illustrate.

4. Results

4.1 Sedimentology

The sedimentary sequence of the deltaic plain deposits of Selinous River mostly consists of fine lithofacies interbedded occasionally with conglomerate facies. According to Koutsios (2009), the stratigraphy and the interpretation of the paleoenvironments, based on the data from the boreholes A1-6 and B1-B10 (fig. 1), is presented in figures 3 and 4. The fine and coarse grained facies identification criteria and interpretation are as follows:

FINE - GRAINED LITHOFACIES

A. Floodplain facies: Constist of silty and clayey sediments, dark yellow or brown in colour, poorly to very poorly sorted and incidentally extremely poorly sorted, with positive to very positive skewness. The CM segments refer to VII, VIII, IX, and III. Massive bedding, horizontal bedding, horizontal lamination, cross-lamination, normal graded bedding, convolute lamination, have been observed. Occasionally present of ostracod fragments and more often gastropod fragments. Thickness of individual beds is of the order of a few millimeters up to a few centimeters or tens of centimeters according to the size of the flood event.

A_1. *Proximal floodplain facies*: Are characterized by the increasing presence of silt in relation to clay and sand fraction.

A_2. *Distal floodplain facies*: Predominance of clay in relation to the silt fraction. The coarser lithology is few up to absent.

$A_{3.}$ *Pond facies*: Pedogenetic characters (5%-15%). Calcite concretions formed around rootlets or caliche nodules.

B. Crevasse splay facies: Consist of gravelly and sandy sediments interbedded with the floodplain deposits. It is characterized by poorly to very poorly sorting and positive to very positive skewness. The CM segments refer to I, II and V fields. Small scale fining- upward sequences are present.

C. Back swamp facies/fresh water swamp facies: Consist of mud and clay sediments, gray or brown in colour, poorly to very poorly sorted with near symmetrical to positive skewness. The

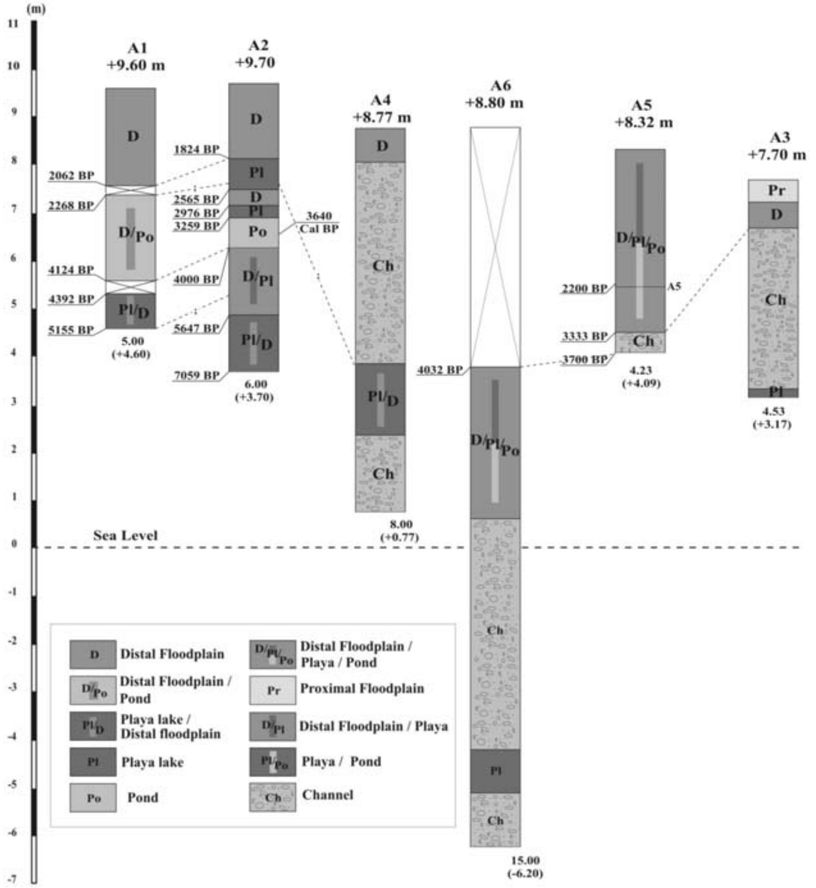

Fig. 3: Vertical profiles of boreholes A1-6, with the interpretation of depositional environments and the age estimation based on radiocarbon data (Koutsios, 2009).

CM segment correspond to VII field. Structures are absent. The sand fraction has a high concentration of plant remains and organic material. There is a significant presence of the fresh water Ostracodes (*Candona*) and gastropods *(Planorbis, Pisidiun, Bithynia, Valvata, Limnea*) and oogonia of the charophytes.

D. Permanent shallow fresh water lake facies: Consist of fine grain size sediments, gray or brown in colour, very poorly sorted with positive to very positive skewness. The CM segment correspond to VIII field. Massive structure or lamination has been observed. The sand fraction has a low concentration of plant remains, as well as calcite concretions and organic material. Significant presence of the fresh water ostracodes (*Candona, Ilyocypris*), gastropods (*Bithynia, Valvata, Limnea*) and oogonia of the charophytes has been observed.

E. Ephemeral fresh water lake facies: Consist of fine-grain sediments, gray, brown or orange in colour, very poorly sorted with positive to very positive skewness. The sand or silt content is often considerably. The CM segment correspond VII, VIII and T. Massive structure or lamination is present. Significant presence of the fresh water ostracodes (*Candona, Ilyocypris*), gastropods (*Planorbis, Bithynia, Valvata, Limnea*) and oogonia of the charophytes have been

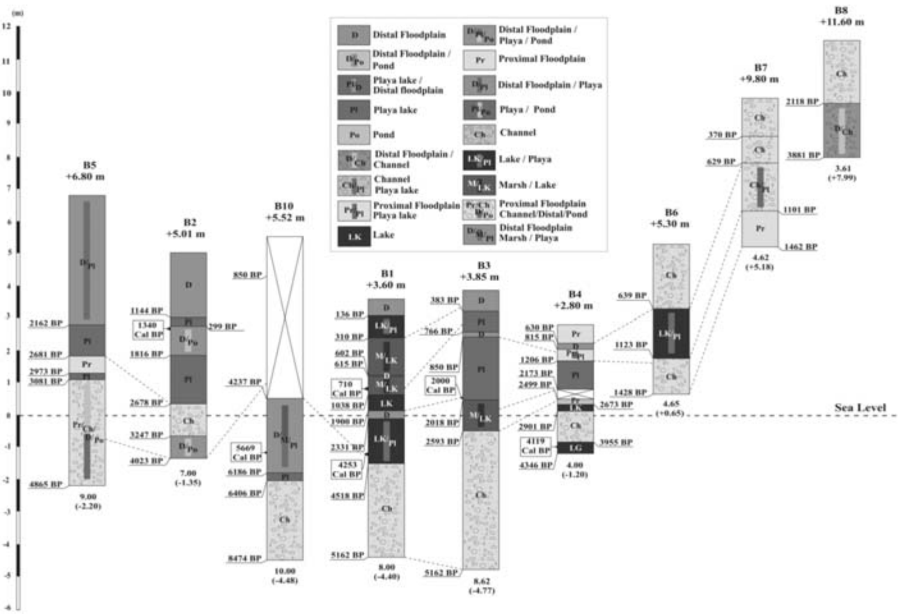

Fig. 4: Vertical profiles of boreholes B1-10, with the interpretation of depositional environments and the age estimation based on radiocarbon data (Koutsios 2009).

observed. Calcite concretions range between 15% and 100%. There is a significant presence of manganese concretions and caliche nodules too.

COARSE - GRAINED LITHOFACIES

The coarse grained facies consists of pale yellow or brownish red pebble conglomerates. It has poorly to very poorly sorting and positive to very positive skewness. The conglomerates are represented by CM segments I, II, IV, and V. The structures generally are absent. Sometimes normal or reverse graded bedding is present. The organic matter and fossils are missing. There is an insignificant presence of reworked fossils.

4.2 Geophysical Data Acquisition – Processing - Modelling

Profile A is 2.695 meters long (Fig. 5) and was taken along the railway (Fig. 2) but in some distance to avoid contamination (noise) of the TEM measurements. The average depth of penetration was around 35 meters. Inside the riverbeds (in Selinous and Kerynitis Rivers) and in order to define the thickness of the sedimentation, 15 sounding using 25x25m loop were collected (maximum depth of about 75 meters). Moreover, in Kerynitis River, a 50x50m sounding was additionally carried out in order to provide clearly the thickness of the sediments (riverbed).

Along the tomographic image of Profile A, several lenses of unsaturated conglomerates (high resistivity areas defined by dotted ellipses) were found. The lenses are surrounded by fine grained clay (high conductivity-blue colours) materials. The average depth of these lenses is about 7-13 meters below the surface and the average width of the lenses is about 20-30 meters. In the areas of the river beds (the Selinous and Kerynitis Rivers), different depositional materials were found, respectively. In Kerynitis riverbed (to the South-East) a normal depositional sequence was defined (the di-

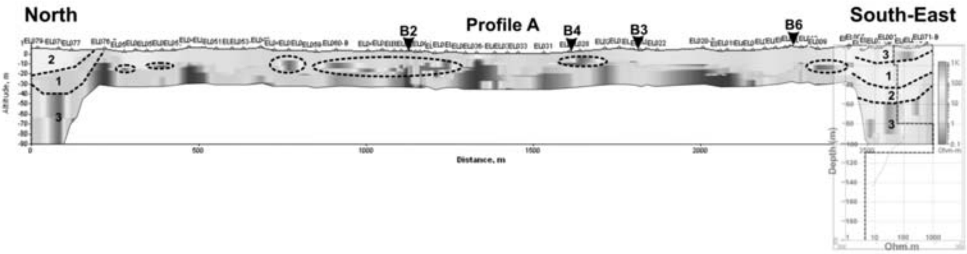

Fig. 5: Two dimensional imaging of the resistivity distribution in depth is given for Profile A. 1,2,3 are different facies of sedimentation (see text for more explanation). B# are boreholes along the profile (see fig. 4) and black dashed ellipses depict the high resistive anomalies correlated with paleochannels.

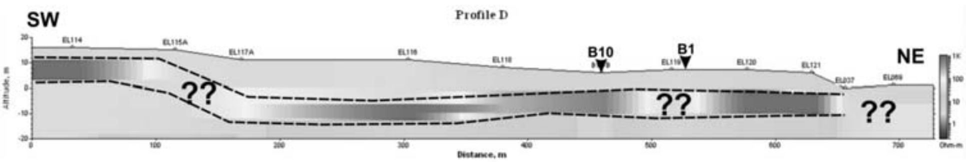

Fig. 6: Two dimensional imaging of the resistivity distribution in depth is given for Profile D (fig. 2). Question marks depict the discontinuities in the defined horizon. B# are the boreholes (figs 3 and 4) along the profiles.

ameter/size of the grains are increased with depth), where conglomerates, sand and gravels (high resistivity-red colours) (facies 3, in Fig. 5) were defined at the bottom of the model and the sedimentation was continued to finer facies (2 and 1 in Fig. 5). As mentioned above, the results of the tomographic image was not very clear and one deep (till the depth of 150 m) sounding was conducted proving that the depth to the bedrock (thickness of the riverbed) is 110 meters (stepwisedashed line). In Selinous riverbed (to the North), similar results were observed concerning the sedimentation but some changes in the deposition of the different lithological facies (2, 1 and 3), was found.

Profile D is 729 m long and is the most representative of the supplementary geophysical measurements which were acquired and as a result it was decided to present it as is shown in Figure 6. It can be assumed that, a paleochannel was defined (based on logs and after pers. com. with some expert geologists in sedimentology) along the collected measurements where the layer is not laterally persistent (question marks in Figure 6). This feature could be explained by changes in direction of the paleochannel. Based on the reconstructed tomographic model, the paleochannel seems to have the same thickness.

5. Discussion and Conclusions

A detailed geo-electromagnetic survey was carried out acquiring almost two hundred soundings in order to reconstruct the 2D subsurface resistivity distribution. This detailed survey in combination with the available sedimentological and paleogeographical data of the area is a useful tool for the determination of the major geomorphological shallow characteristics of the area under investigation. This work shows that a detailed study using a modern geophysical method (TEM-Transient Electromagnetic Method), can provide possible information about the existence and geometry of paleochannels of the flood plain and the paleoenvironment of the area of the ancient Heliki (between Selinous and Kerynitis Rivers).

The lithostratigraphy of the delta plain is extremely heterogeneous as shown by Figures 3 & 4. This happened due to high variable deposition and erosion on a geologically active fan delta plain. Floods and shifting distributaries from the rivers produced a patchwork of fine and coarse deposits over much of the delta plain, until the Selinous and Kerynites Rivers were confined by levees about fifty years ago (Soter & Katsonopoulou, 2005). The resulting lithostratigraphy varies, in the study area, greatly over horizontal scales of only a few meters as found in boreholes test excavations and geophysical research. Soter & Katsonopoulou (2005) have shown the presence of a layer of coarse clastic material sand, gravel, pebbles or cobbles, usually more than a meter thick.

According to Soter & Katsonopoulou (2005) the pebbles are generally angular and in some locations are more rounded. The above authors interpret the angular deposits as a terrestrial flood from the Katourla Fan (Fig 1), while the more rounded material as a marine beach which prograded and ascended with sea level rising. The lowest part of this coarse layer dates from about 7 to 8 kyr BP.

Koutsios (2009) has shown the presence of layer from coarse-grained material proportional to this from Soter & Katsonopoulou (2005). The detail sedimentology research of this material suggests a stream channel environment. The top of the layer has surface elevation about 3 meters and its low surface is approximately 5 meter below the present sea level (Figs. 3 & 4). The upper-most part dates from 2600 to 3000 BP and the lowest part from 8000 to 8500 BP.

From SW to NE, at the beginning of the geophysical profile D up to the first discontinuity is shown the latest part of a channel emerging on to the Katourla fan surface (Fig. 6), while after the first discontinuity, there is another paleochannel at a lower level (Fig. 6). Both paleochannels are similar to the deposits, described by Soter & Katsonopoulou (2005) and revealed by the bore holes B1-B10 from this study.

Profile A depicts the presence of several lenses of conglomerates located 130 m before and about 400m after B2 borehole. Those lenses represent paleochannel cross-sectional areas and the coarse facies of the boreholes B1, B2, B3, B4 and B10. These are below the present sea level and at a depth of 4 to 10 meters.

It is clear that at the both sites between the borehole B3 and of borehole B2 was operated a distributary paleochannel system of Selinous River up to 2600BP. According to Koutsios (2009) there was a stagnant body of water among the distributaries. This paleogeogrphic configuration suggests that the settlement was absent in the Selinous low delta plain because of the flood events and wetland environment. The ancient Helike was probably above the 20m-counter line.

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PETROLOGICAL CHARACTERS OF THE EARLY CRETACEOUS BOEOTHIAN FLYSCH, (CENTRAL GREECE)

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Abstract

This paper is aimed to study the petrographic characters of the Boeothian Flysch, an Early Cretaceous turbidite deposit which marks the boundary between the External/Internal Hellenides in central-southern Greece, in order to define a preliminary palaeogeographic reconstruction of the Pindos segment of the Alpine Tethys.

The Boeothian Flysch is mainly made up by basal conglomerates and arenaceous-pelitic lithofacies, locally interlayered with Calpionellid micrite limestones.

This formation is here supposed to belong to the Early Cretaceous flysch family, which marks the contact between the internal and external areas along all the western and central European Alpine Chains for more than 7,000 km, from the Gibraltar Arc to the Balkans via the Calabria-Peloritani Arc.

Provenance of these flysch is commonly connected to internal areas, mainly made up by Hercynian crystalline basements and, locally, by ophiolitic complexes.

The petrographic data obtained from representative sandstones of the Boeothian Flysch suggest a provenance from internal sources, formed by a Jurassic carbonate platform, metamorphic basements and by ophiolitic complexes, which can be identified with the Pelagonian Terranes (Auct.).

An Early Cretaceous uplift and rejuvenation processes, probably related to the late Cretaceous tectogenesis, widely recorded in almost all the central-western Alpine Tethis, affected these internal domains with consequent production of abundant detrital supply in the innermost sector of the Pindos Ocean, whose external margin was bounded by the Parnassos microcontinent.

Key words*: External Hellenides, Early Cretaceous flysch, sandstone petrography, provenance, palaeogeographic reconstruction.*

1. Indroduction

Early Cretaceous flysch along the Europe Alpine and Betic-Maghrebian Chains; correlations and palaeogeographic significance

The boundary between the internal and external areas in the western and central Europe Alpine

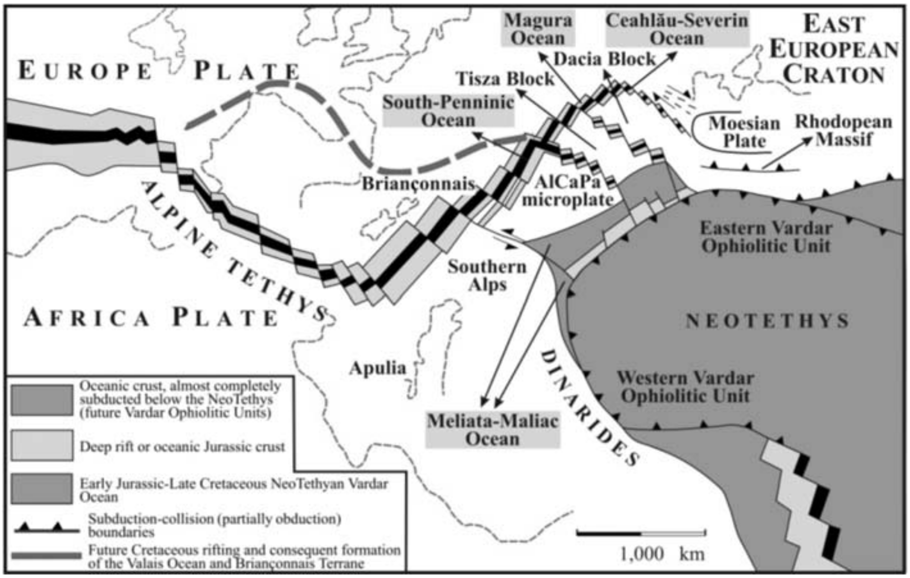

Fig. 1: Large-scale palaeogeographic reconstruction for Late Jurassic (from Puglisi 2009, modified by Channell and Kozur 1997, Csontos and Vörös 2004; Stampfli 2005; Schmid et al. 2008).

Chains is usually marked by the presence of Early Cretaceous flysch.

These crop out for more than 7,000 km from the Gibraltar Arc (Betic-Rifian Chain, Los Nogales and Jebel Tisirène Flysch, in Spain and Morocco, respectively) to the Calabria-Peloritani Arc (Monte Soro Flysch in Sicily), via the Maghrebian Chain (Guerrouch Flysch in Algeria) as far as the Balkans, through Apennines, Alps, Dinarides (Bosnian Flysch), Hellenides (Boeothian Flysch) and Carpathians (Sinaia Flysch).

These turbidite sequences (Late Jurassic-Early Paleocene) were deposited in sedimentary basins connected with the break-up of the Pangaea (Alpine Tethys s. l.), which started an early process of closure, due to their Late Cretaceous-Early Tertiary convergence-related evolution with subduction of oceanic lithosphere and consequent formation of large ophiolitic bodies (Schmid et al. 2004; Schmid et al. 2008 and references therein).

The following two steps summarize the Mesozoic tectonic history of these palaeogeographic elements:

1- rifting with formation of oceanic troughs or large oceans (Alpine Tethys), coupled with the drifting of microcontinents during Middle Triassic to Late Jurassic times,

2- successive convergence of the plates, with subduction of oceanic lithosphere, collision of continents and nappe emplacement. These compressive events reached their highest intensity at Late Jurassic, Early and Mid-Cretaceous (Albian).

Thus, almost all the oceans of the central Alpine Tethys (Ligurian-Piedmont, Vahicum and Valais Oceans and Rhenodanubian Flysch Basin; Fig. 2) as well the easternmost sectors (Magura Basin, Pieniny Klippen Belt, Severin-Ceahlău Ocean and "Nish-Troyan flysch trough" in the Carpathians and Balkans) experienced a middle-late Cretaceous plate tectonic re-organization with consequent strong deformations of the Early Cretaceous flysch (Oszczypko 2006; Săndulescu 1994; Plašienka

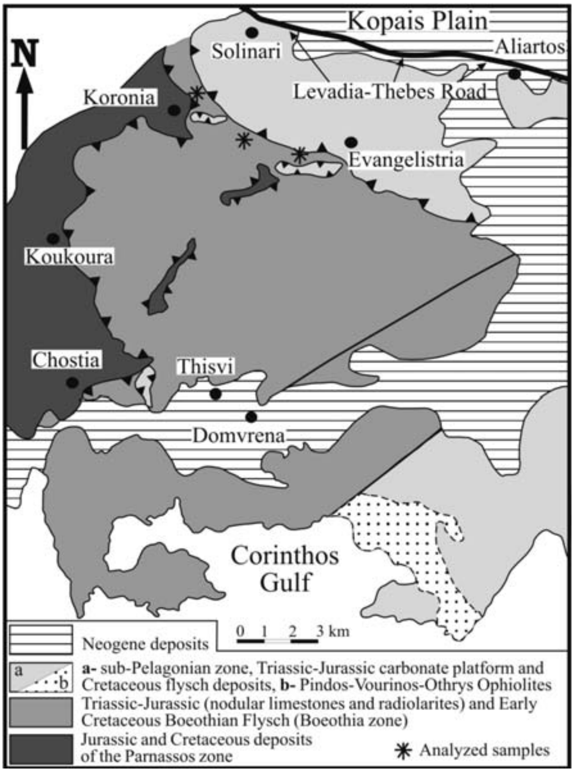

Fig. 2: Geological sketch map of the southern Boeothia (central-southern Greece), where the analyzed samples have been collected.

2003; Zagorchev 2001; Schmid et al. 2008).

Nevertheless, only the Maghrebian Chain seems to have escaped these tectonic events, which have never been recorded or, if recognized, they have often been neglected and/or not sufficiently emphasized (Puglisi 2009).

In particular, the Boeothian Flysch (Clément 1971; Celet et al. 1974; Celet et al. 1976), object of this paper, represents an early Cretaceous flysch of the Hellenides segment of the Alpine Chain probably deposited in the inner sector of the Pindos Ocean, an Early Triassic-to-Eocene basin located between the Apulian microplate and the Pelagonian terranes (Biju-Duval et al. 1977; Channel and Kozur 1997; Van Hinsbergen et al. 2009).

This study, mainly performed by a petrographic approach, is mainly focused on verifying this palaeogeographic scenario and to compare the petrographic features of the Boeothian Flysch with other coeval deposits of different sectors of the central Europe Alpine Chains, in order to emphasize the existence of a same tectonic framework.

2. Geological setting of the Boeothian Flysch

The Boeothian Flysch crops out in the innermost sector of the External Hellenides (southern part of the Boeothia, south of the Kopais plain, Fig. 2) and it represents a thin turbidite sequence (30 to 120

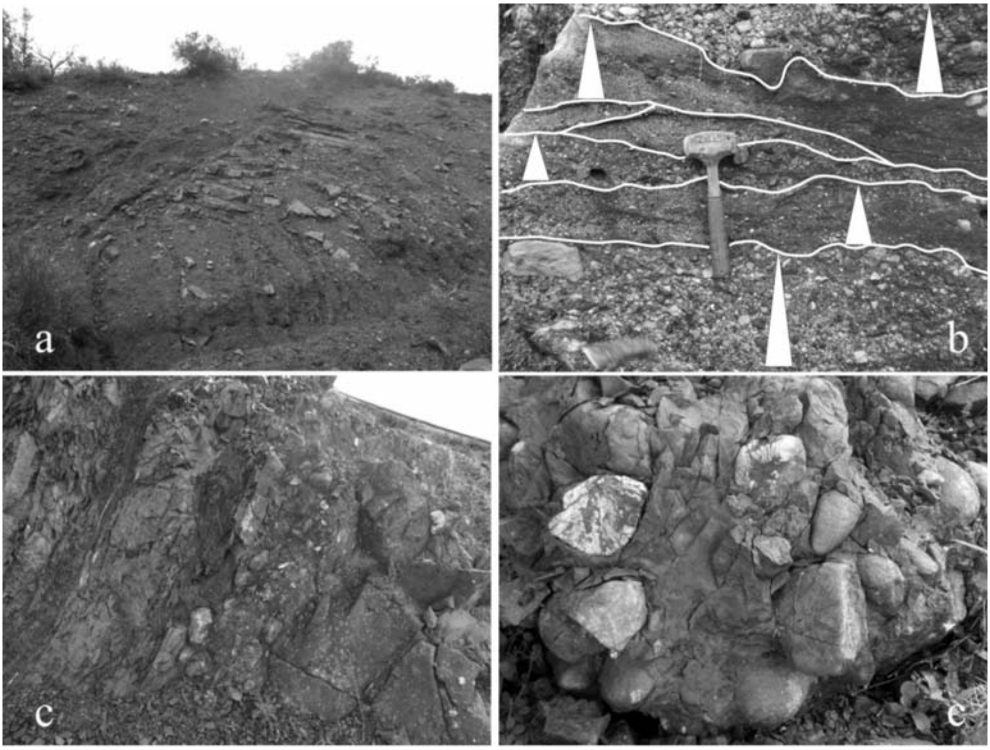

Fig. 3: a) Typical arenaceous-pelitic lithofacies of the Boeothian Flysch with thin- to medium-bedded sandstones and shale interlayers; b) stratified, gravelly graded and amalgamated medium- to coarse-grained turbidites, interlayered with organized clast-supported conglomerates; c) disorganized and clast-supported conglomerate horizons, sporadically with scarce sandy-gravelly matrix, characterizing the base of the Boeothian Flysch; d) disorganized conglomerates with subrounded pebbles and rare boulders, floating into an abundant fine- to medium-grained siliciclastic sandy matrix.

m thick), formed by a rhythmic succession of variegated marls, shales, thin-bedded sandstones (Fig. 3) and marly limestones, with conglomerate horizons in its lower part.

Limestone beds, locally rich in calpionellids, have been aged to Upper Berriasian (Newmann and Zacher 2004, and references therein).

The sedimentary basin of the Boeothian Flysch can tentatively been identified with the innermost sector of the Pindos Ocean, which represented one of the two branches of the central sector of the Neotethys Ocean (Pindos Ocean to the west and Vardar-Axios Ocean to the east; Clift 1992; Degnan and Robertson 1998), separated by the Pelagonian microcontinent.

The Boeothian Flysch represents the first siliciclastic sedimentary input in the Pindos Ocean, occurred during Early Cretaceous times, when westerly directed compressions affected the Pelagonian microcontinent, leading the progressive suturing of the Hellenide orogenetic belt.

This compression firstly emplaced remnants of the Vardar-Axios Ocean (ophiolite obduction) onto the Pelagonian microcontinent during Early Cretaceous times, while the subduction of the Pindos oceanic basement eastwards beneath the Pelagonian microcontinent continued until the

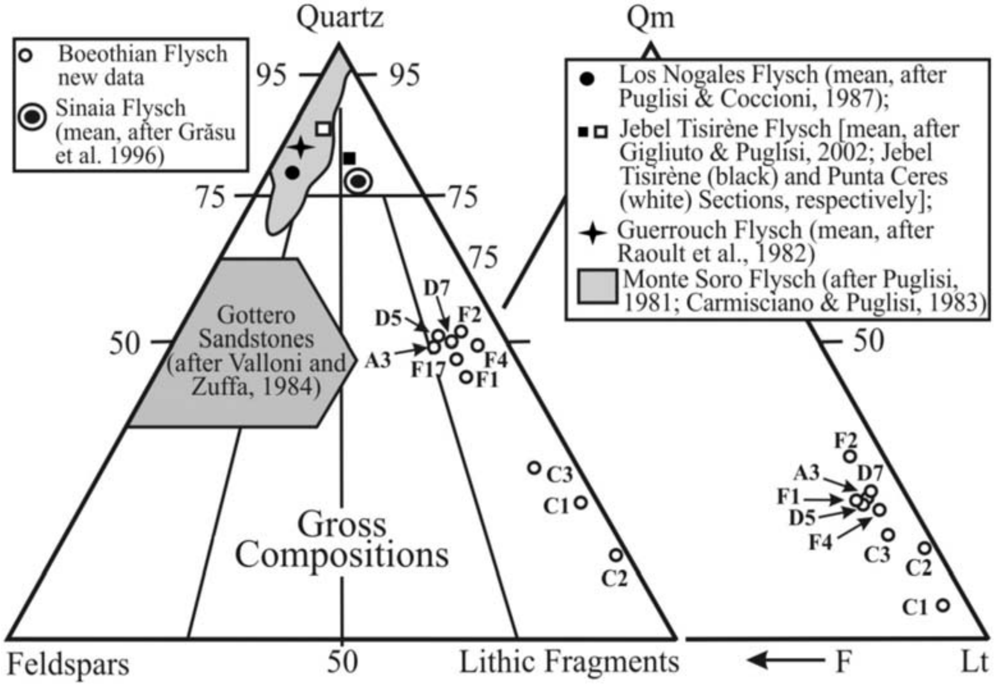

Fig. 4: Triangular plots showing the framework modes of the analyzed terrigenous arenites compared with the mean values of analogous Early Cretaceous flysch sandstones of the Maghrebian Chain (i. e. Los Nogales, Tisirène, Guerrouch and Monte Soro Flysch), northern Apennines (Gottero Sandstones) and eastern Carpathians (Sinaia Flysch). Quartz-Feldspar-Lithic Fragment and Monocrystalline quartz grains-Feldspars-Total lithic fragments diagrams, on left and wright respectively.

end of Cretaceous with accretion of the main volume of Mesozoic-Upper Cretaceous sediments of the Pindos Ocean basin to the western margin of the Pelagonian microcontinent.

Furthermore, the Late Cretaceous sedimentary evolution of the Pindos Ocean is marked by abundant radiolarian and organic-rich facies, followed by a Middle Cenomanian sediment-starved characterized by the presence of black shales, suddenly interrupted by new calcareous and/or siliciclastic turbidite events during Late Cretaceous times (Newmann and Zacher 2004).

3. Petrographic characters of the Boeothian Flysch sandstones

The analyzed Boeothian Flysch sandstones show grain size ranging between -1,5 ϕ and 0 ϕ and they are formed by abundant ophiolitic clasts, sub-angular to sub-rounded quartz grains and by a mainly metamorphic and carbonate lithic fraction.

The lithology of the carbonate rock fragments is much diversified (micritic and peloid limestones, calcarenites and breccia limestones, locally rich in algal and sponge fragments.

The results of the modal analyses, performed by thin section point-counting according to the criteria suggested by Dickinson (1970), Gazzi et al. (1973) and Graham et al. (1976), listed in Table 1, show:

Table 1. Modal point counts of the Boeothian Flysch sandstones.

		A3	C1	C2	C3	D5	D7	F1	F2	F4	F17
Q	**Qm**	118.8	7.4	11.1	10.7	19.4	20.7	17.6	20.6	19.2	17.5
	Qp	21.3	11.6	13.0	12.4	27.5	26.8	20.9	25.3	24.2	22.9
	Ch	2.4	0.6	0.9	1.3	2.1	1.5	1.1	2.2	1.7	1.4
F	**Ps**	5.3	2,5	3.5	4.9	6.3	5.9	5.7	4.3	3.9	5.5
	Ks	-	-	-	-	-	-	0.4	0.7	-	0.9
L	**C**	10.3	40.5	36.3	36.6	17.6	15.0	7.0	8.5	6.4	9.9
	Oph	13.7	15.8	13.8	10.3	5.7	7.2	16.9	14.7	13.7	8.5
	Ls	5.8	3.1	4.3	6.1	3.3	6.9	2.3	1.7	4.3	0.9
	Lm	10.1	11.9	9.6	8.7	10.5	11.3	17.1	12.6	17.4	19.7
	Ms	2.3	-	-	1.7	3.4	1.1	1.2	1.1	1.9	3.5
	Op	2.1	2.4	1.9	2.9	-	-	0.8	1.9	2.5	1.7
	Mt	6.2	4.2	5.6	4.4	4.2	3.6	6.9	4.9	0.9	1.3
	Cm	1.7	-	-	-	-	-	2.1	1.5	3.9	6.3
		100.0	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**
	Q	48.4	21.0	13.4	26.8	53.0	51.4	44.5	53.1	49.7	47.9
	F	6.0	2.7	1.9	5.4	6.8	6.2	6.9	5.5	4.3	7.3
	L	45.6	76.3	84.7	67.8	40.2	42.4	48.6	41.4	46.0	59.4
		100.0	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**
	Qm	21.5	7.9	12.0	11.8	21.0	21.7	19.8	22.7	21.1	20.1
	F	6.0	2.7	1.9	5.4	6.8	6.2	6.9	5.5	4.3	7.3
	Lt	72.5	89.4	86.1	82.8	72.2	72.1	73.3	71.8	74.6	72.6
		100.0	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**
	Lc*+ Ls	40.4	61.4	63.9	69.9	56.3	54.2	23.4	31.3	25.6	27.7
	Lm	25.3	16.6	14.8	13.8	28.3	28.0	38.5	31.7	41.6	50.5
	Oph	34.3	22.0	21.3	16.3	15.4	17.8	38.1	37.0	32.8	21.8
		100.0	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Symbols of the parameters adopted for the modal analysis

Q= Qm + Qp, where: **Q**= total quartzose grains including **Qm**= monocrystalline quartzose grains, **Qp**=polycrystalline quartzose grains and **Ch**= chert;

F= total feldspar grains, nearly exclusively represented by single grains of plagioclase (**Ps**);

L= Lc + Lm + Ls+Oph, where: **L**= unstable fine-grained rock fragments (< 0.06 mm, including: **Ls**= terrigenous sedimentary, **Lc**= carbonate, **Lm**= epimetamorphic lithic fragments), **Oph**= ophiolitic-like clasts;

Lt= L + Qp, where: **Lt**= total lithic fragments (both unstable and quartzose);

Ms= micas and/or chlorites in single grains; **Op**= opaque minerals, **Mt**= siliciclastic matrix; **Cm**= carbonate cement; **Lc***= carbonate rock fragments (also including the chert clasts, **Ch**).

1) abundance of lithic fragments (carbonate and ophiolite-like clasts, and, subordinately, epimetamorphic and plutonic rock fragments), quartz grains and low percentages of feldspars (mainly plagioclase single grains).

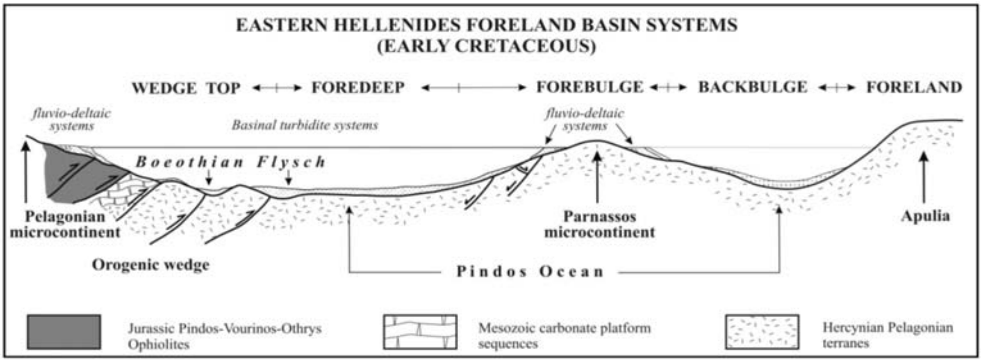

Fig. 5: Early Cretaceous palaeogeography of the Boeothian Flysch basin (i. e. Pindos Ocean) in the context of a foreland basin system showing the uplift processes in the sediment sources (Pelagonian microcontinent), connected with their incipient deformation.

The ophiolitic clasts are usually sub-rounded with a porphyritic-like texture characterized by plagioclase phenocrysts, set in fine-grained groundmass.

Epimetamorphic rock fragments (mainly phillites and metapelites) show very frequent polycrystalline detrital quartz grains with crenulated and sutured crystal-crystal boundaries, whose provenance is connected to low rank metamorphic sources.

Finally, feldspars are very scarce and mainly represented by single grains of plagioclase crystals whose content never exceeds the 7 %; K-feldspar is nearly always absent and its presence is only recorded in traces, within some very rare coarse-grained plutonic-like rock fragment.

In conclusion, the composition of the Boeothian Flysch sandstones can be related to the litharenite clan (*sensu* Folk 1974), well marked by a middle-low textural maturity, due to (i) the sub-angular to sub-rounded shape of the grains, to (ii) a very poor sorting and to (iii) locally abundant siliciclastic matrix. These characters strongly points to very short transports, probably related to a rugged topography, as a consequence of a very unstable tectonic setting, and to a location of the sedimentary basin very near to the source areas.

In Table 2 and Figure 4, the detrital modes of the Boeothian Flysch sandstones are compared to those of Maghrebian Early Cretaceous flysch (Jebel Tisirène, Guerrouch and Monte Soro Flysch), of Late Cretaceous turbidites of northern Apennines (Gottero Sandstones) and of the eastern Carpathians Early Cretaceous Sinaia Flysch.

In particular, the Q-F-L ternary plot clearly displays the different gross compositions between the above-mentioned Early Cretaceous flysch, closely related to different source rocks.

The main difference is the absence of ophiolitic detrital supply in the Early Cretaceous Maghrebian flysch. The Maghrebian Basin, in fact, seems to have been mainly developed on thin continental crust and, locally, it experienced only a partial oceanization, as testified by the occurrence of Middle to Upper Jurassic slices of basic rocks with an E-MORB affinity, scattered in the Rifian Chain (Morocco) and in Sicily (Durand-Delga et al. 2000). Otherwise, the other sectors of the Alpine Tethys reached real oceanic conditions, testified by ophiolitic slices, olistoliths or slide-blocks, included within the Cretaceous sedimentary deposits of the Ligurian-Piedmont Basin (Rampone and Piccardo, 2000).

Table 2. Quartz-Feldspar-Lithic Fragment detrital modes of arenites of Early Cretaceous flysch from Betic-Maghrebian Chain, northern Apennines and eastern Carpathians. **Q, F** and **L**= total Quartz, Feldspar and Lithic Fragment grains. **x** and **σ** = average and standard deviation, **n** = number of analyzed samples (modified after Puglisi 2009).

	Jebel Tisirène Flysch (Rif, Morocco; Gigliuto and Puglisi 2002)						**Los Nogales Flysch (Puglisi & Coccioni 1987)**		**Guerrouch Flysch (Raoult et al. 1982)**		**Monte Soro Flysch Gigliuto and Puglisi 2002)**				**Monte Soro Flysch (Puglisi 1981; Carmisciano and Puglisi 1983)**		**Gottero Sandstones (Valloni and Zuffa 1984)**	**Sinaia Flysch (Grasu et al. 1996)**
	Jebel Tisirène Section				**Punta Ceres Section**		**Betic Coirdillera (Spain)**		**Algeria**		**Sicilian Maghrebian Chain**						**Northern Apennines**	**Eastern Carpathians**
	Calcareous turbidites (n= 5)		**Arenaceous turbidites (n= 7)**		**Arenaceous turbidites (n= 8)**		**Arenaceous turbidites (n= 11)**		**Arenaceous turbidites (n= 16)**		**Calcareous turbidites (n= 50)**		**Arenaceous turbidites (n= 17)**		**Arenaceous turbidites (n= 33)**		**Arenaceous turbidites**	**Arenaceous turbidites**
	x	**σ**	**x**	**σ**	**x**	**σ**	**x**	**σ**	**x**	**σ**	**x**	**σ**	**x**	**σ**	**x**	**σ**	**x**	**x**
Q	17.5	4.95	79.3	6.98	88.1	6.24	78.6	7.23	83.8	13.8	11.7	3.55	85.0	4.23	82.2	5.61	51,0	76.5
F	2,3	1.37	6.2	1.84	9.9	2.69	15.5	5.71	13.1	6.22	0.2	0.27	13.7	3.06	13.8	4.15	39.0	10.5
L	80.3	9.53	14.5	5.13	2.0	1.23	3.9	2.75	3.1	2.31	88.1	7.38	1.3	0.35	4.0	2.12	10.0	14.0
	100.0		100.0		100.0		100.0		100.0		100.0		100.0		100.0		100.0	100.0

Table 3. Semiquantative mineralogical analysis of sandstones from the Boeothian Flysch

Sample	Qtz	Fl	Cc	ill	K	Chl	sm	m/l	Total clays
F1	21	13	25	12	8	3	17	1	40
F2	50	12	7	9	6	2	13	1	30
F3	46	4	10	6	3	4	25	2	34
F4	38	9	23	7	7	6	7	3	30
F5	39	10	21	10	10	4	4	2	30
F6	37	4	22	14	12	4	5	2	37
F7	40	9	9	13	16	3	6	3	42
F8	35	11	10	13	9	6	12	4	44
F9	30	6	6	14	11	5	24	4	58
F10	17	7	27	27	11	5	0	5	50
F11	27	8	16	18	7	6	14	3	49
F12	26	6	18	8	5	10	23	3	50
F13	30	6	14	7	5	14	20	4	50
F14	42	13	15	8	5	4	11	1	29
F15	15	12	15	21	6	10	18	3	59
F16	57	10	3	3	3	4	14	4	30
F17	57	9	6	7	10	6	4	2	29

Explanatory notes: Qtz= quartz, Fl= feldspar and plagioclase, Cc= calcite, Chl= chlorite, K= kaolinite, ill = illite, sm= smectite, m/l= mixed layers.

The gross composition of the Boeothian Flysch sandstones has also been checked by means of semi-quantitative mineral phase analyses obtained with diffractometric methodologies (Table 3)

Mineralogical analysis was carried out by using an X-Ray powder Diffractometer of Siemens D-5005 type, with copper tube and graphite monochromatographer.

The mineralogical phases were determined by using computer and the software of SOCABIM Company (DIFRAC PLUS 2004, EVA ver. 10) and the files of JCPDS, at the laboratories of the University of Athens, Faculty of Geology and Geoenvironment.

Semiquantative analyses were estimated according to Cook et al (1975) proposed method.

Representative samples were analysed for their mineralogical composition in order to determine the variations of clastic, carbonate and clay fractions. All samples belong to the outcrop located along the old National Road, 500 m before the intersection to Evaggelistria village.

The XRD analysis revealed that the mineralogical composition is mostly characterized by quartz, feldspars, calcite and clay minerals (Table 3). The clay minerals are illite, kaolinite, chlorite, smectite, and mixed layers. The quartz and calcite contents seem to be competitive, as expected. The total clay fraction represents both clastic and clays formed by alteration, as a consequence of that, there is no direct relation between total clay amount and quartz. The relative high total clay minerals portion, ranging between 29 % and 59 %, is represented by poorly crystallised minerals, indicative of intense alteration processes of the primary clastic minerals.

4. Conclusive remarks

Detrital modes of the Boeothian Flysch sandstones suggest a provenance from internal domains, which can tentatively be identified with the Hercynian Pelagonian terranes and their Mesozoic carbonate covers and with ophiolitic complexes.

Pelagonian zone, in fact, has recently been interpreted as a Hercynian continental fragment of Gondwanan affinity (Robertson and Mountrakis 2006; Himmerkus et al. 2007), covered by a thick and widespread Mesozoic carbonate platform.

Furthermore, ophiolitic nappes were detached onto this platform as a consequence of the obduction processes occurred in the western margin of the adjacent Vardar Ocean since Late Jurassic (Eohellenic orogenic phase, Auct.).

In particular, the ophiolite-like detritus can be derived from the western side of the Vardar Ocean (i. e. Pindos-Vourinos-Othris Ophiolites; Robertson and Mountrakis 2006) and it can not to be correlated to the so-called Vardar-Axios Ophiolites. These last, in fact, seem to have been tectonically emplaced onto the Pelagonian massif during Cretaceous times (Van Hinsbergen et al. 2009, and references therein), slightly later the deposition of the Early Cretaceous Boeothian Flysch.

Furthermore, contribution from Mesozoic carbonate sources is testified by the abundance of carbonate clasts, whose litology (mainly calcarenites and reefal limestones) suggests a provenance from widespread Jurassic platforms lcated within the Pelagonian Zone.

Finally, low-rank metamorphic detritus (mainly phyllite and quartzite clasts) has always been recognized in the sandstones of the Boeothian Flysch. Provenance of these clasts can be derived from the Hercynian Pelagonian massif, not yet affected by an Alpine metamorphic overprint.

Moreover, we consider that the western part of the Pelagonian microcontinent (i. e. the Boeothian and Parnassos domains), uncovered by ophiolite nappes, formed the foreland basin system (*sensu* DeCelles and Gilles 1996) of the orogeny.

During Early Cretaceous times, in fact, the Boeothian domain corresponded to the foredeep depozone of the foreland basin system, filled by material derived from the erosion of the emerged ophiolites and its Pelagonian basement, whereas the Parnassos domain, west of the Boeothian foredeep, could correspond to the forebulge depozone of the same system, separated from the Apulian continent by a westernmost small oceanic strand of the Pindos Ocean, as a probable backbulge (Fig. 5).

The following westward migration of the orogeny is marked by the Paleogene flysch of the Parnassos area, which started when this zone was transformed into a foredeep depozone.

In conclusion, on the basis of the detrital modes, provenance and tectonic framework of the Boeothian Flysch, we emphasize its belonging to the Early Cretaceous flysch family, cropping out along all the western and central European Alpine Chains, from the Gibraltar Arc to the Balkans.

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AGE DETERMINATION AND PALAEOGEOGRAPHIC RECONSTRUCTION OF DIAPONDIA ISLANDS IN NW GREECE, BASED ON CALCAREOUS NANNOFOSSILS

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Abstract

Diapondia islands - Ereikoussa, Othonoi and Mathraki – extended in the north-western area of Greece, are part of the external Ionian zone of the Hellenides. The exposed sedimentary succession of the three islands consists of up to 74m thick submarine fans, interpreted as inner fan deposits. The determination of the sediment ages is based on the study of calcareous nannofossils, which came from almost 63 samples covering geological cross sections across the coast line of the three islands. The recorded nannofossil associations are assigned to the biozones of Martini's (1971) standard scheme. According to the age determination clastic sedimentation in the studied area started during the Late Oligocene and finished during the Early Miocene time. Moreover, the age determination and in accordance with the previous results, indicate that also the Ionian thrust activity started during Late Oligocene.

Key words: *Diapondia islands, Erikoussa, Othonoi, Mathraki, calcareous nannofossils, turbidites, external Ionian zone, Ionian thrust.*

1. Introduction

The Ionian zone has been studied in detail during the last century and is subdivided by internal thrusting into three sub-basins (internal, middle and external) (Aubouin, 1959; I.G.S.R. & I.F.P, 1966). The studied area (North-western Greece) is a part of the external Ionian zone. Clastic sedimentation in the Ionian zone took place from middle Eocene to late Miocene in a foreland basin, the Pindos foreland (Avramidis et al., 2002; Vakalas et al., 2001) which was subdivided due to internal thrusting and changed to a complex type foreland basin. It belongs to the external Ionian zone and thus to the western part of the Pindos foreland, bounded eastwards by the middle Ionian internal thrust and westwards by the Ionian thrust. The presence of strike-slip faults, with ENE-WSW direction, internal to the foreland basin, influenced the depositional conditions in the studied area. Internal thrust activity together with the sedimentation, has influenced transportation and grain-size distribution, whereas strike-slip faults many times acting as pathways to deliver coarse-grained sediments in more distal parts (Avramidis & Zelilidis, 2002; Vakalas et al., 2001). Many times the continuous uplift due to internal thrusting produced large slumps horizons of the uncondensed sediments, deposited over the uplifted area (Avramidis et al., 2002).

Fig. 1: Map of the studied area, where the major structural elements are presented.

The aim of this work is to determine the depositional age of the submarine fans, accumulated in the studied area. This age is based on the study of calcareous nannofossil content of the sediments. The nannofossil associations from each sample are revealed by paleontological determination of characteristic species. They are interpreted biostratigraphically using Martini's (1971) standard zonal scheme. All palaeontological determination of nannofossils, as well as biostratigraphic interpretation and conclusions are implemented by K. Stoykova.

2. Geological setting

The studied area is a part of the Pindos foreland. It belongs to the external Ionian zone of the Hellenides, and comprises the three Diapondia islands – Othonoi, Mathraki and Erikoussa (NW Greece). To the north it is bounded by the Borsh-Khardhiqit strike slip fault, to the south by the Corfu margin, to the east by the Middle Ionian thrust, and to the west by the Ionian thrust. Therefore the studied area is situated backward of the Ionian thrust and corresponds to a piggy back basin, where sedimentation is continuous (Fig. 1).

The sedimentation in this basin (Fig. 2) is characterized by fine-grained sediments with channelized sandstone intercalations. These deposits are interpreted as inner fan deposits (Makrodimitras and Zelilidis, 2009) accumulated in the external Pindos foreland, resulted from the segmentation of the Pindos foreland basin due to internal thrusting during Oligocene, which migrated in a westward direction (Underhill 1985; 1989, Clews 1989, Alexander et al. 1990, Avramidis 1999).

According to Makrodimitras and Zelilidis (2009) the sedimentation of submarine fans was continuous in the studied part of the foreland basin, before the Ionian thrust activity. Due to the Ionian thrust activity the western part of the area was uplifted and the deformation of turbiditic sequence was started. Especially, in Mathraki Island the whole sedimentary sequence has strongly deformed, whereas in Erikousa Island two slump horizons were produced, the lower one up to 5m thick and 70m long, and the upper one, up to 10m thick and more than 100m long. Both slump horizons show an eastward thinning trend, and consist of thick sandstone clasts. In Mathraki Island the strongly deformed sedimentary sequence is in contact with Triassic evaporates, which came up due to Ionian thrust activity, whereas in Othoni Island Mesozoic limestones outcropped.

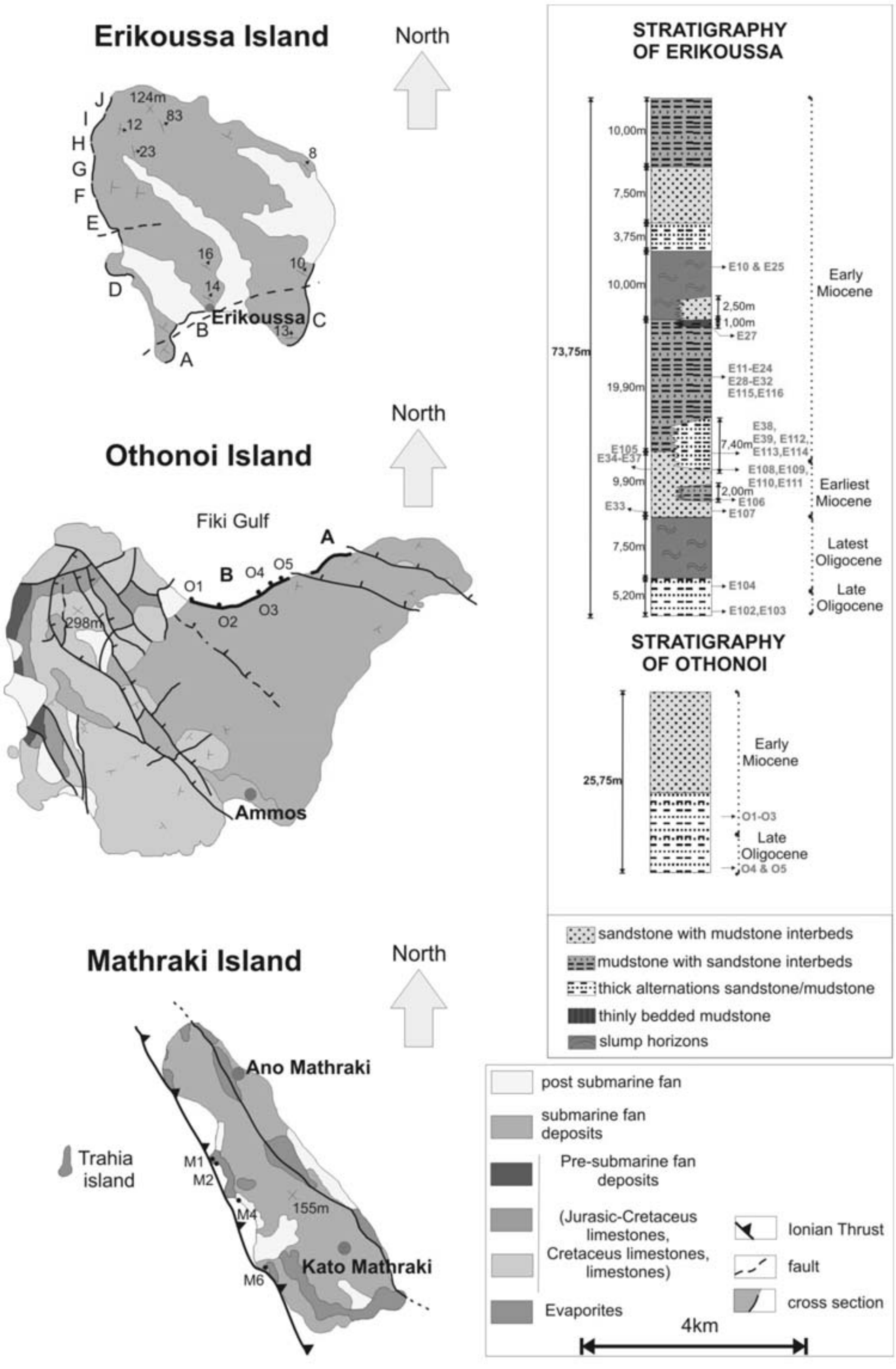
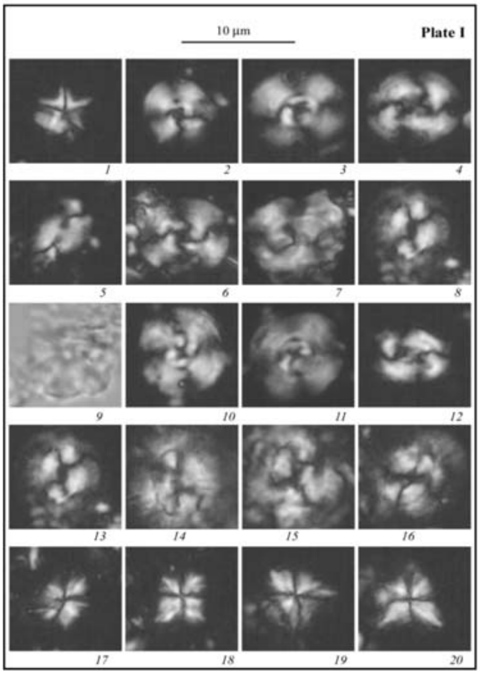
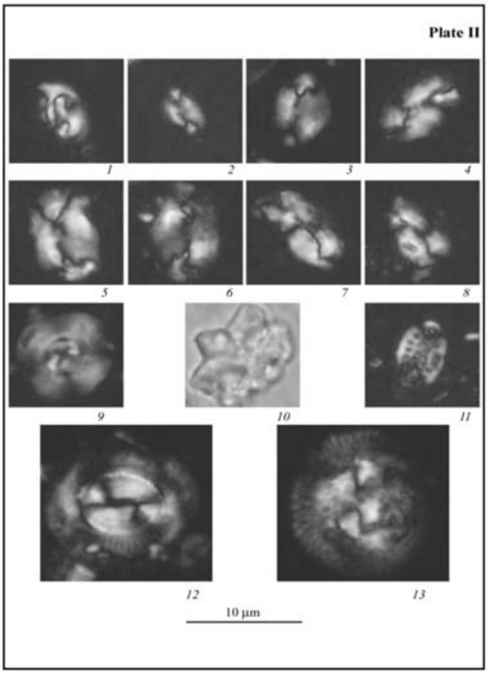


Fig. 2: Geological maps of Erikoussa, Othonoi and Mathraki Islands.





Plates I &II: nannofossil species from Othonoi Island

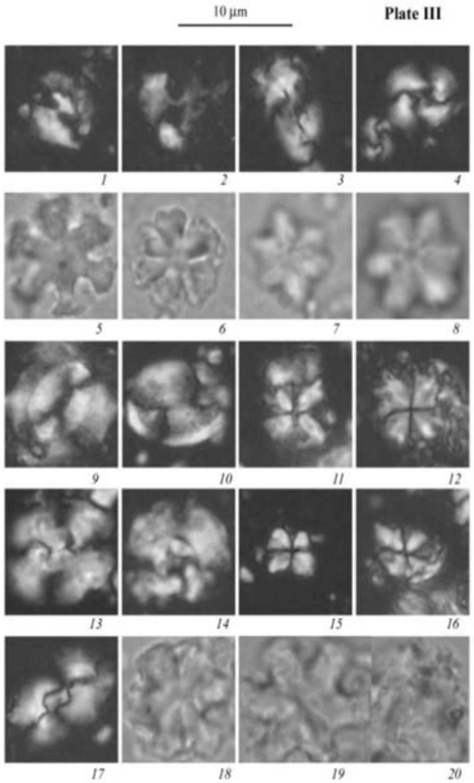
Plate I: 1. *Micrantholithus* sp. indet., sample O5, c.p. 2-3. *Cyclicargolithus floridanus* 2 - sample O5, c.p. 3 - sample O3, c.p. 4. *Reticulofenestra retiformis*, sample O5, c.p. 5. *Helicosphaera* sp. aff. *obliqua*, sample O5, c.p. 6. *Cyclicargolithus floridanus*, sample O4, c.p. 7. *Dictyococcites bisectus*, sample O4, c.p. 8. *Coccolithus pelagicus*, sample O4, c.p. 9. *Discoaster adamanteus*, sample O4, t.l. 10-11. *Cyclicargolithus abisectus*, 10 – sample O4, 11 – sample 106, c.p. 12. *Reticulofenestra retiformis*, sample O2, c.p. 13. *Coccolithus pelagicus*, sample O4, c.p. 14-16. *Coccolithus eopelagicus*, sample O4, c.p. 17-18. *Sphenolithus disbelemnos*, sample O3; 17- c.p with angle 45°; 18 - c.p with angle 90°. 19-20. *Sphenolithus conicus*, sample 106, 19 - c.p. with angle 45°; 20 - c.p with angle 90° (Abbreviations: c.p. = cross-polarised light; t.l. = transmitted light.

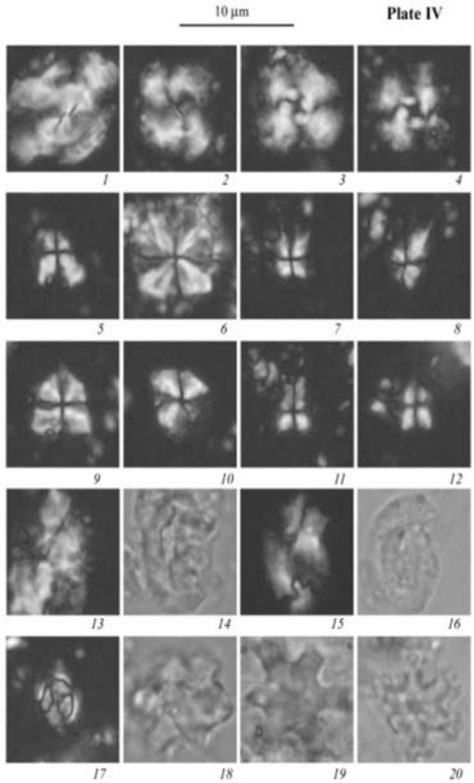
Plate II: 1. *Helicosphaera* sp. aff. *elongata*, sample O3, c.p. 2. *Helicosphaera scissura*, sample O3, c. p. 3-4. *Helicosphaera compacta*, sample O3, c.p. 5-6. *Helicosphaera perch-nielseniae*, sample O3, c.p.7-8. *Helicosphaera elongata*, sample O2, c.p. 9. *Cyclicargolithus abisectus*, sample O3, c.p. 10. *Discoaster adamanteus*, sample O4, t.l. 11. *Pontosphaera multipora*, sample O3, c.p. 13-14. *Coccolithus miopelagicus* sample O3, c.p.

Paleocurrent analysis shows both N-S and an E-W trend, indicating the Ionian thrust activity influence on depositional conditions.

3. Methodology

The determination of the sediment ages is based on the study of calcareous nannofossils, originating from 63 samples, distributed across the geological sections along the coastline of the three islands. All samples were processed and smear-slides were prepared using Canada Balsam as a fixative. Each slide was observed under cross-polarized and normal light using a Zeiss Axioskop 40 Pol microscope at 1250x magnification.





Plates III & IV: nannofossil species from Erikoussa Island

Plate III: 1-2. *Helicosphaera mediterranea*, sample E1, outcrop A, c.p. 3. *Helicosphaera kamptneri*, sample E1, outcrop A, c.p. 4. *Reticulofenestra retiformis + Dictyococcites*, sample E1, outcrop A, c.p. 5. *Discoaster deflandrei*, sample E1, outcrop A, t.l. 6. *Discoaster* cf. *calculosus*, sample E1, outcrop A, t.l. 7-8. *Discoaster adamanteus*, 7 – sample E2, 8 – samle 3, t.l. 9. *Coccolithus eopelagicus*, outcrop A, c.p. 10. *Pontosphaera multipora*, sample E1, outcrop A, c.p. 11-12. *Sphenolithus moriformis*, sample E4, outcrop A, c.p. 13. *Dictyococcites bisectus*, sample E2, reworked species in Lower Miocene, c.p. 14. *Cyclicargolithus abisectus*, sample E1, outcrop A, c.p. 15-16. *Sphenolithus conicus*, 15 – sample E2, 16 – sample E4, outcrop A, c.p. 17. *Helicosphaera euphratis*, sample E7, outcrop A, c.p. 18-20. *Discoaster calculosus*, 18- sample E4, 19, 20 – sample E3, outcrop A, t.l.

Plate IV (outcrop C, Fig. 2): 1-2. *Dictyococcites bisectus*, sample E103, outcrop C, c.p. 3-4. *Cyclicargolithus abisectus*, sample E103, outcrop C, c.p. 5. *Sphenolithus* aff. *calyculus* sample E105, outcrop C, c.p. 6. *Sphenolithus moriformis*, sample E106, outcrop C, c.p. 7-8. *Sphenolithus dissimilis*, sample E106, outcrop C, c.p., 8- angle 45°. 9-10. *Sphenolithus conicus*, sample E106, E107, outcrop C, c.p. 11. *Sphenolithus calyculus*, sample E107, outcrop C, c.p. 12. *Sphenolithus disbelemnos*, sample E113, outcrop C, c.p. 13-14. *Helicosphaera kamptneri*, sample E106, c.p. and t.l. 15-16. *Helicosphaera carteri*, sample E113, outcrop C, c.p. and t.l. 17. *Clausicoccus fenestratus*, sample E108, outcrop C, c.p. 18. *Discoaster adamanteus*, sample E106, outcrop C, t.l. 19. *Discoaster* cf. *drugii*, sample E109, outcrop C, t.l. 20. *Discoaster* aff. *deflandrei*, sample E113*, outcrop C, t.l.

Biostratigraphic interpretations are based on the first and last occurrence of stratigraphically important nannofossil taxa. In order to achieve accurate age, standard biozonation of Martini (1971) is employed.

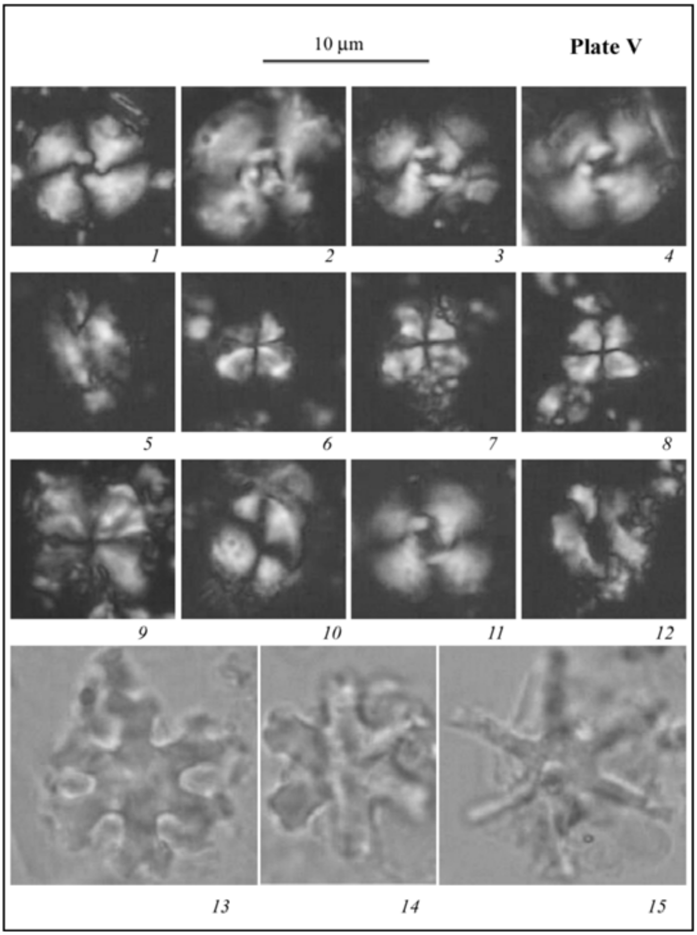


Plate V: nannofossil species from Erikoussa island

Plate V (Outcrop C, Fig. 2): 1-2. *Cyclicargolithus floridanus/ abisectus*, sample E107, outcrop C, c.p. 3-4. *Cyclicargolithus abisectus*, sample E108, outcrop C, c.p. 5. *Helicosphaera kamptneri*, sample E109, outcrop C, c.p. 6-8. *Sphenolithus heteromorphus*, sample E110, outcrop C, c.p. 9. *Sphenolithus moriformis*, sample E111, outcrop C, c.p. 10. *Coccolithus pelagicus*, sample E116, outcrop C, c.p. 11. *Cyclicargolithus floridanus/ abisectus*, sample E113, outcrop C, c.p. 12. *Helicosphaera ampliaperta*, sample E116, outcrop C, c.p. 13. *Discoaster deflandrei*, sample E109, outcrop C, t.l. 14. *Discoaster musicus*, sample E109, outcrop C, t.l. 15. *Discoaster petaliformis*, sample E113, outcrop C, t.l.

4. Results

4.1 Erikoussa stratigraphy

In Erikoussa 41 samples have been studied in order to form the island stratigraphy. These samples have been chosen according to their position in the stratigraphic column to cover the entire succession. The results of the biostratigraphical analysis are shown in the table 1, whereas the selected samples and studied sections are shown in table 2.

Table 1. Erikoussa samples age determination.

Sample	Age (NP and NN zones of Martini, 1971)	Nannofossil species in the association in situ
E11-E24, E28-32, E116	Early Miocene, NN1-NN4	*Cyclicargolithus abisectus, Cy. floridanus, Sphenolithus moriformis, S. compactus, S. conicus, Bicolumnus ovatus, Coccolithus pelagicus, C. miopelagicus, Helicosphaera granulata, H. kamptneri, Discoaster sp, Discoaster deflandrei, D. druggi, D. calculosus, Sphenolithus dissimilis, Reticulofenestra daviesi, Pontosphaera multipora, S. calyculus, Pyrocyclus orangensis, Discoaster adamanteus, Helicosphaera intermedia, Reticulofenestra minuta, small-sized Reticulofenestra, Helicosphaera californiana, Braarudosphaera bigelowii, Micrantholithus spp, Helicosphaera paleocarteri, Sphenolithus disbelemnos (NN2-3), Sphenolithus belemnos, Coccolithus eopelagicus, Sphenolithus heteromorphus, H. elongata, H. carteri, H. Carteri hyalina, H. euphratis, H. ampliaperta, Calcidiscus leptoporus.*
E102-E104	Late Oligocene to Earliest Miocene, NP24-NN1	*Coccolithus pelagicus, C. eopelagicus, Cyclicargolithus floridanus, Cy. abisectus, Sphenolithus moriformis, Dictyococcites bisectus, D. scrippsae, Helicosphaera compacta, H. intermedia, H. euphratis, Pontosphaera multipora, Reticulofenestra retiformis, Helicosphaera kamptneri, Discoaster deflandrei, Discoaster cf. calculosus, Transversopontis sp. indet.*
E106	Early Miocene, NN1	*Discoaster adamanteus, D. deflandrei, Cyclicargolithus abisectus, Sphenolithus moriformis, S. calyculus, S. conicus, S. pacificus, S. dissimilis, Dictyococcites bisectus, Reticulofenestra retiformis, Coccolithus pelagicus, Helicosphaera kamptneri, Pontosphaera multipora.*
E33-37, E105, E107	Latest Oligocene to Early Miocene, NP25 to NN3	*Coccolithus pelagicus, C. miopelagicus, Cyclicargolithus abisectus, Cy. floridanus, Helicosphaera compacta, H. euphratis, Sphenolithus compactus, S. moriformis, S. conicus, S. calyculus, Pontosphaera multipora, Discoaster calculosus, Dictyococcites bisectus, D. scrippsae, C. eopelagicus, R. daviesi,Pyrocyclus orangensis,Helicosphaera kamptneri, Reticulofenestra minuta, small-sized Reticulofenestra, S. compactus, Discoaster druggii, Helicosphaera paleocarteri.*
E38, E39, E108-E114	Early Miocene, NN1-NN3	*Sphenolithus disbelemnos, S. dissimilis, S. moriformis, S. conicus, S. compactus, Cyclicargolithus abisectus, Cy. floridanus, Helicosphaera kamptneri, H. intermedia, Discoaster deflandrei, Coccolithus pelagicus,Coccolithus miopelagicus, Reticulofenestra minuta, Pyrocyclus orangensis,H. euphratis,Clausicoccus fenestratus, Pontosphaera multipora, C. eopelagicus, Pontosphaera multipora, Discoaster deflandrei, small-sized Reticulofenestra, Dictyococcites scrippsae, D. calculosus, Discoaster druggii.*
E115, E30-E32	Early Miocene, NN1-NN5	*Small-sized Reticulofenestra, Sphenolithus disbelemnos, Coccolithus pelagicus, Cyclicargolithus abisectus, Cy. floridanus, Helicosphaera kamptneri, H. carteri hyalina, Reticulofenestra minuta, Discoaster adamanteus, Coccolithus miopelagicus, C. eopelagicus, R. daviesi, S. dissimilis, Discoaster deflandrei, Calcidiscus leptoporus, Pontosphaera multipora.*
E27	Early Miocene, NN3	*Sphenolithus belemnos, S. conicus, S. moriformis, S. compactus, Cyclicargolithus abisectus, Calcidiscus leptoporus, Coccolithus pelagicus, Helicosphaera intermedia, H. euphratis, Discoaster calculosus, D. deflandrei, Reticulofenestra daviesi, C. eopelagicus, C. miopelagicus.*
E25, E10	Early Miocene, NN1-NN2	*Discoaster calculosus, D. deflandrei, Sphenolithus moriformis, S. dissimilis, S. compactus, Coccolithus pelagicus, C. miopelagicus, Cy. floridanus, Cy. abisectus, Helicosphaera kamptneri, H. euphratis, Reticulofenestra minuta, Dictyococcites scrippsae.*

Table 2. Erikoussa outcrops and samples.

Erikoussa outcrops	Samples
C	102,103,104,105,107,108,109,110,111,113,114,115
D	10,11,12,13,14,15,16,17,18,19,20,21,22,23,24
E	25,27
F	30,31,32
G/H/I/J	33,34,35,36,37,38,37

4.2 Othonoi stratigraphy

In Othonoi outcrop B, 4 samples have been studied. The sample O1 is from the contact of submarine fan deposits with the Pre-submarine fan deposits to the west (Cretaceous limestones). The results of the analysis are shown in the table 3:

Table 3. Othonoi outcrop B age determination.

Sample	Age (NP and NN zones of Martini, 1971)	Nannofossil species in the association *in situ*	Depositional environment/ reworking/ remarks
O1	Early Miocene, NN2-3	*Discoaster druggii, D. calculosus, D. deflandrei, Cyclicargolithus floridanus, Cy. Abisectus, Sphenolithus dissimilis, S. moriformis, Coccolithus pelagicus, C. miopelagicus*.	Reworking of Upper Cretaceous, Paleocene and Oligocene species.
O2	Early Miocene, NN1-3	Coccolithus pelagicus, C. eopelagicus, Cyclicargolithus floridanus, Cy. *abisectus, Dictyococcites scrippsae, Helicosphaera elongata, H. perch-nielseniae, H. scissura, Sphenolithus moriformis, Discoaster adamanteus*.	Rich and diverse nannofloral association, no reworking.
O3	Early Miocene, NN1-2	*Sphenolithus conicus, S. disbelemnos, Sphenolithus moriformis, Coccolithus pelagicus, Cyclicargolithus floridanus, Cy. abisectus, Helicosphaera compacta, H. scissura, H. sp. aff. elongata, H. perch-nielseniae, Dictyococcites scrippsae, Discoaster deflandrei, Pontosphaera multipora, Reticulofenestra retiformis*.	Recovery of the abundant and diverse nannofloral association, with very good to excellent preservation. It is indicative of favourable conditions for blooming of the nannoflora.
O4	Latest Oligocene to Early Miocene, NP25-NN1	*Coccolithus pelagicus, C. eopelagicus, Cyclicargolithus floridanus, Cy. abisectus, Dictyococcites scrippsae, D. bisectus, Sphenolithus moriformis, Discoaster adamanteus*.	Impoverishment of the association – poor preservation with signs of overgrowth and recrystalization.
O5	Latest Oligocene to Early Miocene, NP25-NN1	*Coccolithus pelagicus, C. eopelagicus, Cyclicargolithus floridanus, Cy. abisectus, Dictyococcites scrippsae, Reticulofenestra retiformis, R. Hillae, Sphenolithus moriformis, Helicosphaera intermedia, Helicosphaera sp. aff. obliqua, Discoaster adamanteus, D. cf. calculosus, D. deflandrei, Micrantholithus sp. indet*.	Rich and diverse nannofloral association, no reworking.

4.3 Mathraki results

In Mathraki the thrust activity has destroyed every old turbiditic sequences. Nevertheless, we choose 3 samples from the west coastline destroyed sequences, and one sample (M1) from the contact of submarine fan deposits with the thrust. The results of the analysis are shown in the table 4:

Table 4. Mathraki samples age determination.

Sample	Age (NP and NN zones of Martini, 1971)	Nannofossil species in the association *in situ*	Depositional environment/ reworking/ remarks
M1	Late Miocene, NN8-9	*Discoaster exilis, D. bollii, D. deflandrei, D. druggii, D. cf. kugleri, Calcidiscus macintyrei, Calcidiscus tropicus, Coccolithus pelagicus, Cyclicargolithus floridanus, Cy. abisectus, Pontosphaera spp., Dictyococcites scrippsae, Sphenolithus moriformis, Helicosphaera kamptneri.*	Rich and diverse nannofloral association, Minor reworking: D. bisectus (Oligocene), Uniplanarius gothicus (Upper Cretaceous).
M2	Latest Oligocene to Early Miocene, NP25-NN1	*Coccolithus pelagicus, Cyclicargolithus floridanus, Cy. abisectus, Dictyococcites scrippsae, Sphenolithus moriformis, Discoaster deflandrei.*	Impoverishment of the association – poor preservation. Large amount of Si-skeletons of microplankton: a lot of spicules of Si-sponges, diatoms, radiolarians are observed.
M4	Early Miocene, NN1-2	*Discoaster calculosus, D. deflandrei, Sphenolithus compactus, Sphenolithus moriformis, Coccolithus pelagicus, Coccolithus miopelagicus, Cyclicargolithus floridanus, Cy. abisectus, Helicosphaera kamptneri, H. intermedia, H. euphratis, Dictyococcites scrippsae, Pontosphaera multipora, Reticulofenestra retiformis.*	Diverse nannofloral association; again abundant Si- skeletons of microplankton observed.
M6	Early Miocene, NN1-2	*Helicosphaera kamptneri, Coccolithus pelagicus, C. miopelagicus, Discoaster calculosus, D. deflandrei, Cyclicargolithus floridanus, Cy. abisectus, Braarudosphaera bigelowii, Pontosphaera multipora, Sphenolithus moriformis, S. compactus.*	Abundant Si- skeletons of microplankton.

5. Conclusions

Considering the age determination results of the studied sections we can conclude that:

1. The sedimentation in the studied area occurred during the Late Oligocene to Early Miocene time.
2. The age of the sediments in studied area (external part of Pindos foreland), is younger than the

other parts situated eastwards, either in the middle or in the internal parts of the Pindos foreland, showing the internal thrusting activity influence on the depositional conditions.

3. The presence of slump horizons in Erikoussa island (Late Oligocene-Early Miocene) and the highly deformed deposits in Mathraki island, overthrusting Triassic evaporites, indicate that Ionian thrust activity started at the end of Oligocene and caused deformation and slumping of the turbiditic sequences.

4. Taking into account that Ionian thrust activity in Zakynthos Island took place during early Pliocene, the different time activities of the different parts of the Ionian thrust could be indicated. These parts are bounded by strike-slip faults and the oldest activity is manifested northwards whereas the younger is shifted southwards.

5. The studied area, with the three islands, changed from a foreland basin that formed in response to the middle Ionian thrust activity, to a piggy back basin, as it is situated on the hangingwall of the active Ionian thrust, after Late Miocene, and when tectonic activity migrated westwards. This piggy-back basin remains unchanged in now days, whereas the new foreland basin, the Ionian foreland, is situated in the footwall of the Ionian thrust.

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QUARTZ MEGACRYSTS IN GREECE: MINERALOGY AND ENVIRONMENT OF FORMATION

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Abstract

Quartz megacrysts in Greece are systematically sampled, described and classified with respect to their morphology, solid inclusion mineralogy, and geological conditions of formation. Quartz deposition took place due to reduction in silica solubility in the hydrothermal fluids in favourable geological environments such as: alpine-type fissures close to major detachment faults, skarns and quartz veins crosscutting and generally related to granitoids and, finally, epithermally altered volcanic rocks of Tertiary age. The varieties of coloured crystals (amethyst, smoky quartz, morion, green quartz, rock crystal), the twinning of the crystals, the mineralogy of solid phases included in quartz (rutile, chlorite, sericite, feldspars) as well as the types and forms of the crystals (Tessin habit, Muzo habit, faden quartz, sceptre, window quartz, interrupted crystals, double-terminated crystals, phantom quartz, gwindel quartz, etc.) give important information on the growth mechanisms and the physico-chemical conditions during quartz formation. The quartz crystals found in several localities are gemmy and their potential for use as gemstones should be evaluated.

Key words: *quartz, megacrysts, habits, solid inclusions, gemstones.*

1. Introduction

Quartz is formed in several geological environments and it is considered as one of the most common minerals in nature. The different conditions, namely the pressure and temperature that characterise each environment, determine which type of SiO_2 mineral will be formed in every case. Moreover, the type and often the habit of the crystals, the accessory minerals, as well as the solid inclusions they contain provide useful information regarding the environment of formation (Rykart, 1995; Dibble, 2002). This paper will focus on quartz crystals formed in three different geological environments: the alpine-type fissures encountered in metamorphic rocks, environments related to granitoids of Tertiary age and volcanic-hosted epithermal environments.

The first group contains quartz crystals which are formed in greenschist phase metamorphic conditions. During the ascend of metamorphic rocks to the surface extensive fissures are formed in shear zones and several minerals, including quartz, are deposited due to the decrease in pressure and temperature. These fissures are usually elongated or sigmoidal, they develop perpendicular to the schistosity of the rock and crosscut the major structural elements of the Alpine compressive deformation.

The second group includes quartz crystals encountered in miarolithic cavities or quartz veins developed in granitoids and pegmatites of Tertiary age. It also contains quartz crystals found at contact metamorphic zones, where skarns are formed. In this case quartz is a typical mineral of the retrograde stage.

The third group contains quartz crystals found in veins in volcanic rocks of Tertiary age, mainly lavas of intermediate or acidic composition as well as pyroclastic rocks. In this case the deposition of quartz is related to the development of hydrothermal and geothermal systems during the last stages of Tertiary volcanism.

2. Geological setting

The Hellenides constitute part of the Alpine-Himalayan orogen and formed when Apulia collided with Europe in Late Cretaceous to Tertiary. The Hellenides are subdivided in several units: the Rhodope Massif, the Servo-Macedonian Massif, the Vardar Zone, the Pelagonian Zone and the Attico-Cycladic Massif (Internal Hellenides) and the External Hellenides built up by Mesozoic and Cenozoic rocks (Dürr et al., 1978; Jacobshagen, 1986). New data suggest that the Hellenides can be considered an accretionary orogen, where a late Precambrian to late Jurassic evolution was marked by the opening and closure of ocean basins and continental crust formation in the accompanying subduction zones (Himmerkus et al., 2006; Reischmann & Kostopoulos, 2007). A Permo-Carboniferous igneous event (known from the Pelagonian Zone, the Rhodope Massif and the Attico-Cycladic Zone) documents an active continental margin evolution in the Precambrian-Silurian basement of the Hellenides. After the closure of the Vardar Ocean, shortening and syn-orogenic exhumation of HP-LT rocks occurred during the late Cretaceous-Eocene, before an acceleration of slab retreat changed the subduction regime and caused the collapse of the Hellenic mountain belt and the thinning of the Aegean Sea from the middle Eocene/late Oligocene to the present (Jolivet et al., 2004). During this post-orogenic episode large-scale detachments formed, which exhumed metamorphic core complexes in a back-arc setting (Cyclades and Rhodope). Tertiary magmatism in the Aegean region occurred mostly in a post-collisional setting behind the active Hellenic subduction zone. The Cenozoic magmatic activity, considered to be associated with the Cretaceous to Miocene Alpine-Balkan-Carpathian-Dinaride orogen, resulted from underthrusting of the African plate beneath the Eurasian plate (Pe-Piper & Piper, 2002). This magmatic event took place after the closure of the last remnants of the Tethys Ocean (Pindos, Vardar-Izmir-Ankara and Intra-Pontide branches) and the collision of the continental blocks of Apulia, Pelagonia and Rhodope with continental Europe. The Pliocene to recent volcanic rocks in the active Aegean volcanic arc seem to have formed as a consequence of active subduction beneath the Hellenic trench.

3. Analytical methods

Twenty-four thin and polished thin sections of quartz crystals with solid inclusions were studied with an optical microscope and a JEOL JSM 5600 scanning electron microscope equipped with back-scattered imaging capabilities, at the Department of Mineralogy and Petrology, University of Athens, Greece. Analytical methods also included X-powder diffraction measurements obtained using a SIEMENS type D-500 diffractometer with Cu tube and Co filter at the Department of Mineralogy and Petrology, University of Athens, Greece.

4. Geological environments of formation

4.1 Alpine-type fissures

In the northern part of Greece alpine-type fissures are encountered in various metamorphic rocks that belong to the Rhodope-Servomacedonian massif (Papanikolaou & Panagopoulos, 1981; Mposkos

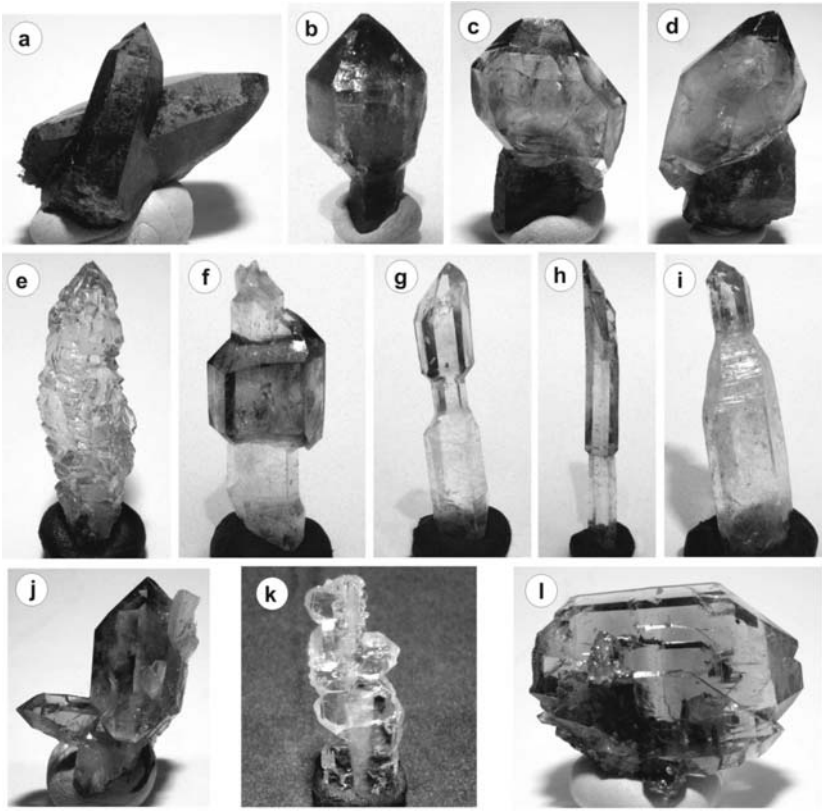

Fig. 1: Quartz crystals from alpine-type fissures (dimensions refer to photo width). (a) Tessin smoky quartz crystals, Dasoto (8cm); (b-d) Amethyst prismatic sceptres on smoky quartz, Dasoto (4cm); (e) Colourless eroded Tessin quartz crystal, Thassos (4cm); (f, g) Triple prismatic quartz sceptres, Thassos (4cm); (h) Prismatic smoky quartz sceptre on prismatic colourless quartz, Thassos (4cm); (i) Prismatic smoky quartz inverse sceptre on prismatic transitional colourless quartz, Thassos (3cm); (j) Smoky quartz, Krieza-Koskina (5cm); (k) Faden colourless quartz, Karystos (3cm); (l) Gwindel smoky quartz, Stamata (5cm).

& Krohe, 2001). Quartz crystals have been found in three sites, near the village of Dasoto in Drama, on the island of Thassos and in Sithonia on the Chalkidiki peninsula. In Dasoto quartz is found in veins in Paleozoic orthogneisses. In these veins the crystals are deposited on a massive milky to black quartz matrix. Morion, smoky or colourless quartz crystals often develop the Tessin habit, whereas normal or inverse sceptres with prismatic amethyst on top are also found (Voudouris et al., 2004a; Melfos, 2005) (Fig. 1a-d). Amethyst in these sceptres can sometimes develop window structures. On Thassos Island quartz crystals are deposited in fissures within metapegmatites, orthogneisses, paragneisses, amphibolites and marbles (Wawrzenitz & Krohe, 1998). The most impressive forms of quartz crystals in this area are the triple sceptres encountered in parageneisses (Voudouris, 2005) (Fig. 1f-i). The base of the sceptres consists of Tessin crystals, often with eroded faces (Fig. 1e), while the first generation is colourless prismatic quartz. The second sceptre is window smoky quartz with Dauphiné habit and the third generation is represented by colourless crystals. Colourless prismatic quartz crystals which form inverse sceptres are also found in the area as well as single Tessin smoky or colourless crystals. Quartz in amphibolites usually forms colourless or amethyst Tessin single crystals. In Sithonia dark smoky quartz crystals with Tessin habit accompanied by feldspar are found in sigmoidal fissures that have been developed in the granite and the pegmatites of the area.

In the Attico-Cycladic massif quartz can be encountered in many areas (Voudouris et al., 2004a; Tsolakos et al., 2008). The Krieza-Koskina area in Evia (central Greece) consists of schists, marbles, amphibolites and orthogeneisses (Katzir et al., 2000; Shaked et al., 2000). Quartz crystals have been formed in quartz veins which usually fill sigmoidal fissures or in seggregations that consist of quartz and feldspar. A wide variety of crystal forms can be found in the area: typical prismatic crystals, gwindel crystals, quartz crystals with chlorite phantoms, faden quartz and flattened crystal forms. The crystals are transparent and can be colourless or smoky (Fig. 1j). In Karystos (southern Evia) prismatic quartz crystals and colourless faden forms (Fig. 1k) are encountered in orthogneisses and amphibolites. In Attica (central Greece) quartz crystals are found in three areas, namely Stamata, Marathonas and Mt. Penteli. All three areas consist of orthogneisses and marbles (Lozios, 1993) which are crosscut by quartz veins that fill alpine-type fissures. The Stamata area is characterised by the same mineralogy and crystal habits (Fig. 1l) that have already been described in Krieza-Koskina. In Marathonas and the mountain of Penteli the fissures are filled with parallel quartz veins in which prismatic quartz crystals as big as 50cm have been found. Window structures are often developed on the faces of some colourless prismatic crystals, while cathedral quartz forms, crystals with chlorite phantoms and dark smoky quartz crystals are also present in the area. However, the most typical crystals encountered are the normal and inverse sceptres that consist of rock crystal, smoky quartz or amethyst. On Seriphos Island milky Tessin quartz crystals were deposited in extensional sigmoidal fissures developed in the Seriphos leucogranite (Iglseder et al., 2009). On the island of Ios colourless and smoky (close to morion) prismatic quartz crystals have been deposited in quartz veins in orthogneisses (Henjes-Kunst & Kreuzer, 1982), where smoky quartz sceptres are also found. Sericite often develops phantoms in quartz crystals, while chlorite can form solid inclusions in smoky quartz.

4.2 Environments related to Tertiary granitoids

In the Rhodope massif quartz crystals are found in many areas, namely Vrontou, Kimmeria, Maronia, the island of Samothraki, and Stratoni on the Chalkidiki peninsula. In Vrontou quartz crystals have been deposited in multiple quartz veins that crosscut the andraditic skarn developed at the contact zone between the Vrontou plutonite and the marbles of the area. Quartz crystals with chlorite phantoms and Dauphiné habit are present. In Kimmeria quartz crystals are found in the Xanthi granodiorite, as well as in the skarn that is formed at the contact zone between the plutonite and the metamorphic rocks of the area (gneisses, amphibolites and marbles) (Liati, 1986). In quartz veins that crosscut the plutonite colourless and milky Tessin quartz crystals can be found (Fig. 2a). At the contact zone quartz crystals are deposited in the exoskarn and their formation is related to the development of quartz veins in the andraditic and wollastonitic skarns of the area. The typical prismatic forms can be found in these sites as well as peculiar needle-like crystals with Dauphiné habits (Fig. 2c). The most impressive form of quartz crystals in Kimmeria is the typical flattened Japan-law twins that are found together with the previously mentioned needle-like Dauphiné crystals (Fig. 2b) (Voudouris & Katerinopoulos, 2004). In Maronia quartz is encountered in the granitoids of the area (granite and porphyritic microgranite) (Melfos et al., 2002). In the microgranite colourless Tessin crystals are developed in milky quartz veins that crosscut the granitoid. In the granite transitional Tessin to prismatic milky to light brown quartz crystals are deposited in miarolithic cavities. On the island of Samothraki milky prismatic and Tessin quartz crystals are found in veins that crosscut the granite of Samothraki. On the Chalkidiki peninsula quartz is encountered near the village of Stra-

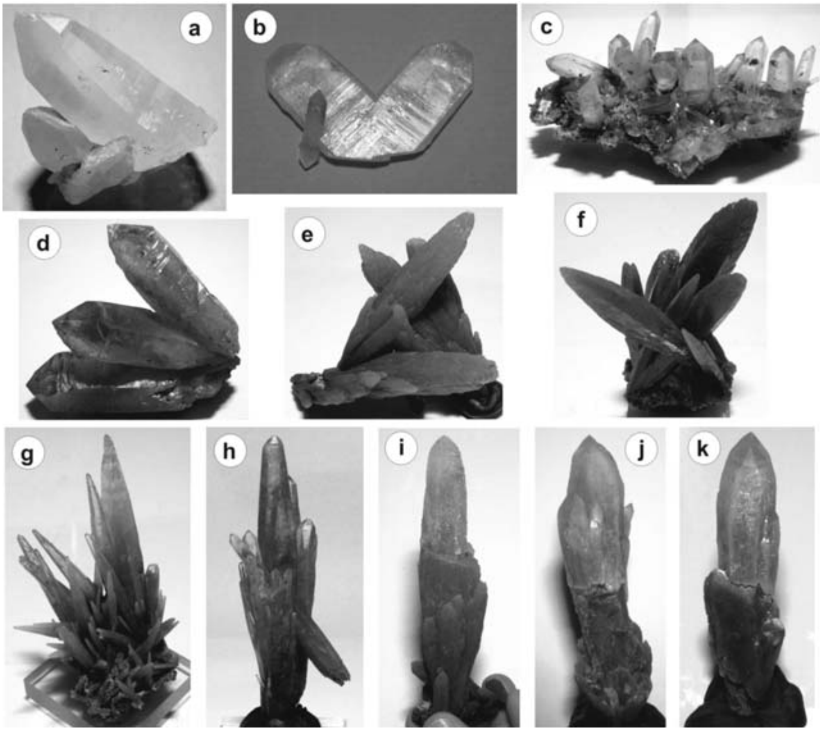

Fig. 2: Quartz crystals from environments related to Tertiary granitoids (dimensions refer to photo width). (a) Tessin colourless quartz, Kimmeria (6cm); (b) Japan-law twin quartz crystals, Kimmeria (5cm); (c) Prismatic and Dauphiné quartz crystals, Kimmeria, (7cm); (d) Prismatic and Dauphiné smoky quartz crystals, Lavrio (10cm); (e, f) Spindle-like green quartz crystals, Seriphos (10cm and 12cm respectively); (g, h) Amethyst-green quartz crystals, Seriphos (7cm and 5cm respectively); (i-k) Normal and inverse amethyst sceptres on green quartz, Seriphos (6cm).

toni. In the carbonate-replacement Pb-Zn-Au deposit of Stratoni gneisses and marbles are crosscut by quartz veins that include typical prismatic quartz crystals, colourless or milky transitional crystals and rarely sceptres (up to 60cm).

In the Attico-Cycladic massif quartz is found in three areas, namely Lavrio (Attica) and on the islands of Tinos and Seriphos. In the carbonate-replacement deposit of Lavrio quartz forms milky and more rarely brown prismatic crystals (Fig. 2d), crystals with rocket habit or trigonal and bundle forms, whereas in some cases large quartz crystals (up to 20cm) are often surrounded by multiple smaller ones (Voudouris et al., 2004b). On Tinos Island prismatic and Tessin smoky quartz crystals have been deposited, together with spessartine and orthoclase, in miarolithic cavities in the Tertiary leucogranite of the area (Mastrakas, 2006). On Seriphos Island quartz crystals were formed in geodes developed in quartz veins that crosscut the granatitic and hedenbergitic skarn at the contact zone of the granodiorite and the gneisses (Salemink, 1980). The form of the crystals is prismatic with a trigonal top and the colour is usually milky or green (actinolite inclusions), whereas amethyst sometimes constitutes the base of inverse sceptres with colourless tops. Locally the hedenbergite is crosscut by veins of green quartz where the famous Seriphos spindle-like quartz crystals are deposited (Gauthier & Albandakis, 1991) (Fig. 2e, f). The crystals are usually green quartz or amethyst or a combination of the two (Fig. 2g, h). Their form might also change from a typical spindle-like base to a hexagonal amethyst top. Prismatic green quartz crystals are also found as well as rocket forms with amethyst in the base and green quartz on top. The sceptres found in the area are normal or inverse with green quartz in the base and an often trigonal amethyst top (Fig. 2i-k). An unusual type of crystals encountered in the area is the interrupted green or amethyst quartz crystals which are formed when flattened calcite crystals are deposited together with quartz in successive layers (Voudouris et al., 2007).

4.3 Volcanic-hosted epithermal environments

In northern Greece quartz crystals are found in many sites that represent epithermally altered volcanic environments, namely Kornofolia, Sapes and Kirki (Melfos 2005). In Kornofolia hydrothermal fluids have deposited short hexagonal prismatic amethyst crystals, colourless quartz crystals and chalcedony in veins in the Tertiary dacitic lavas of the area. In Sapes quartz and chalcedony were deposited in veins developed in pyroclastic rocks and andesitic/dacitic lavas. Colourless quartz sceptres with trigonal tops and window structures on the faces are found, while hexagonal prismatic amethyst crystals are rare. The latter are usually developed on a smoky quartz base. In Kirki chalcedony veins crosscut the submarine dacitic lavas of the area. In cavities in the central part of the veins short amethyst and colourless quartz crystals are formed.

In the northern Aegean island of Lesvos the Miocene lavas (Pe-Piper & Piper, 2002) are crosscut by veins where prismatic amethyst crystals and sceptres are encountered (Voudouris & Katerinopoulos, 2004) (Fig. a-d). Window structures are observed on the faces of the sceptres, the top part of which has developed Muzo and Cipo habits. Large colourless crystals with Muzo habit have also been found in the area. In another site pink quartz forms stalagmitic structures which are covered with small pink quartz crystals (Fig. 3e).

In the Attico-Cycladic massif the island of Milos represents a volcanic-hosted epithermal environment where rhyodacitic lavas and pyroclastic materials of Plio-Pleistocene age are crosscut by chalcedony and amethyst veins. In these veins short prismatic amethyst and colourless quartz crystals have been deposited (Alfieris, 2006).

5. Solid inclusions in quartz

A significant number of minerals are encountered as solid inclusions in quartz crystals. Their presence is often directly related to the colour of the crystals and provides valuable information regarding the physico-chemical conditions that characterised the geological environment where quartz crystals were formed.

Actinolite is encountered in alpine fissures (Fig. 4a, b) and skarns as needle-like green crystals that form solid inclusions in quartz. Its presence in the skarn of Seriphos is particularly significant, since it gives quartz (prase) the characteristic green colour.

Calcite is found together with quartz in environments related to Tertiary granitoids (Seriphos skarn), where it is responsible for the development of interrupted quartz crystals. However, its presence is more usually associated with volcanic environments where tabular calcite crystals accompany chalcedony, quartz and amethyst in geodes.

Chlorite is encountered in numerous areas in all three types of geological environments mentioned in the previous section. Chlorite is particularly common in alpine-type fissures where it forms solid

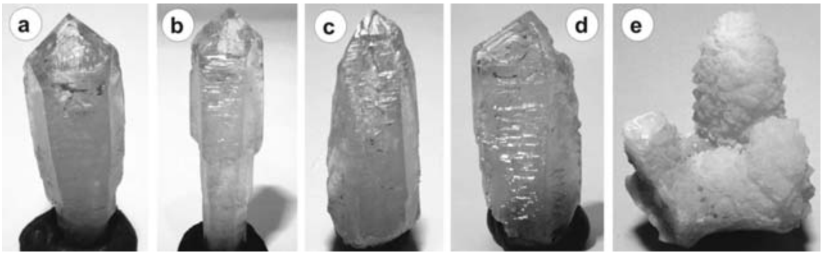

Fig. 3: Quartz crystals from volcanic-hosted epithermal environments (dimensions refer to photo width). (a, b) Trigonal amethyst sceptres that develop window structures, Lesvos (3cm and 4cm respectively); (c) Amethyst with Muzo habit and window structures, Lesvos (4cm); (d) Trigonal amethyst with window structures, Lesvos (4cm); (e) Stalagmitic pink quartz, Lesvos (6cm).

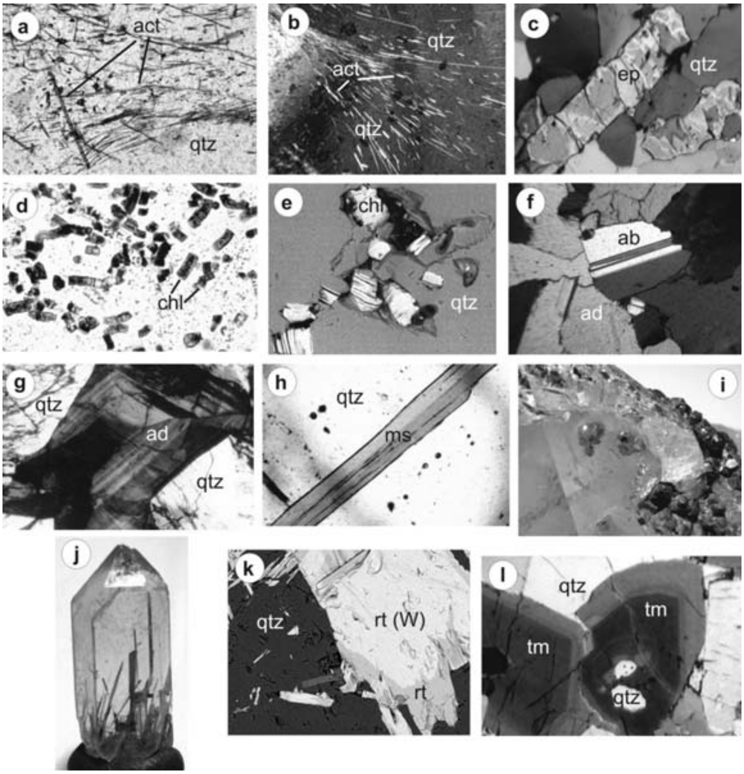

Fig. 4: Solid inclusions in quartz (dimensions refer to photo width). (a, b) Polarising microscope images (//nicols and +nicols respectively) of needle-like actinolite (act) in quartz (qtz), Karystos (0.12mm and 1mm respectively); (c) Polarising microscope image (+nicols) of Mn-rich epidote (ep) together with quartz (qtz), Thassos (0.6mm); (d) Polarising microscope image (//nicols) of chlorite (chl) in quartz, Krieza-Koskina (0.12mm); (e) SEM image of chlorite (chl) in quartz (qtz), Krieza-Koskina (0.35mm); (f) Polarising microscope image (+nicols) of albite (ab) and adularia (ad), Krieza-Koskina (1mm); (g) Polarising microscope image (+nicols) of zoned adularia (ad) together with amethyst (qtz), Sappes (1mm); (h) Polarising microscope image (+nicols) of muscovite (ms) in smoky quartz (qtz), Thassos (0.6mm). i) Pyrite in quartz, Crete (3cm); (j) Red rutile crystals in quartz, Krieza-Koskina (3cm); (k) SEM image of rutile (rt) with a W-rich core (rt (W)) in quartz (qtz), Penteli (0.3mm); (l) Polarising microscope image (//nicols) of zoned tourmaline (tm) together with quartz (qtz), Thassos, (0.6mm).

inclusions in quartz crystals (Fig. 4d, e) and is often responsible for the green colour of quartz as well as the development of phantom quartz crystals. Idiomorphic pseudo-hexagonal chlorite crystals have been found on Thassos where they accompany rutile and quartz in fissures. In the skarn of Vrontou chlorite forms phantoms in quartz, whereas in Kimmeria it covers the faces of the crystals. In volcanic-hosted epithermal environments chlorite usually forms microscopic inclusions in quartz crystals. Representative microprobe analyses of studied chlorites are included in Table 1. All chlorites are classified as Fe-clinochlores. Based on the geothermometer of Cathelineau (1988) the formation temperatures of the studied chlorites vary from 228° to 310 °C (Table 1).

Epidote is found together with quartz in all three types of environments mentioned above. Dark pink Mn-rich epidote accompanies and is included in milky and smoky quartz crystals found in alpine-type fissures on Thassos (Fig. 4c). In other areas where alpine-type fissures occur epidote forms

Table 1. Representative microprobe analyses of chlorite

Wt. %	1	2	3	4	5	6	7	8	9	10
SiO_2	27.85	27.37	28.40	28.43	30.87	30.39	31.50	29.31	28.92	29.12
Al_2O_3	19.21	18.21	19.47	19.91	17.51	18.43	19.65	18.36	19.81	19.61
TiO_2	bd	bd	bd	bd	0.11	bd	bd	bd	0.03	bd
FeO	23.94	25.32	23.78	18.34	22.20	19.84	19.81	14.23	15.03	14.59
MnO	0.31	0.37	0.38	0.38	0.68	0.42	0.39	0.65	0.84	0.74
MgO	17.12	17.05	18.16	21.47	17.75	16.99	17.83	23.37	22.90	23.55
CaO	bd	bd	0.05	bd	0.34	0.37	0.45	0.06	0.10	0.07
Na_2O	0.31	0.46	0.46	0.11	0.70	0.66	0.65	0.08	0.02	0.03
K_2O	bd	0.03	0.02	bd	0.09	0.15	0.19	0.03	0.01	0.01
Total	88.74	88.82	90.72	88.64	90.81	88.14	90.52	86.09	87.66	87.72
Cations on the basis of 28 (O)										
Si	5.752	5.701	5.714	5.693	6.160	6.195	6.195	5.929	5.769	5.786
Al	4.670	4.480	4.620	4.699	4.130	4.445	4.550	4.377	4.657	4.593
Ti	-	-	-	-	0.000	-	-	-	0.000	-
Fe	4.136	4.416	4.009	3.071	3.710	3.395	3.255	2.407	2.506	2.425
Mn	0.050	0.063	0.063	0.064	0.105	0.070	0.070	0.111	0.141	0.125
Mg	5.269	5.294	5.447	6.409	5.285	5.180	5.215	7.047	6.808	6.974
Ca	-	-	0.012	-	0.070	0.070	0.105	0.014	0.021	0.015
Na	0.127	0.190	0.178	0.043	0.280	0.245	0.245	0.000	0.000	0.000
K	-	0.012	0.000	-	0.035	0.035	0.035	0.000	0.000	0.000
T °C Cathelineau (1988)	300.0	308.1	306.1	310.0	234.3	227.9	227.9	271.5	297.2	294.5

1-3: Krieza-Koskina (Evia), 4: Ios, 5-7: Lesvos, 8-10: Sapes (Rhodope) needle-like green crystals in colourless prismatic quartz. In environments associated with granitoids dark green epidote crystals are encountered as inclusions in quartz. On Lesvos Island epidote accompanies amethyst in the lavas.

Feldspars are found as accessory minerals and solid inclusions in quartz crystals in all three types of geological environments that were mentioned in the previous section. In the alpine-type fissures of Evia adularia forms pseudo-rhombohedral milky or green crystals, whereas albite develops idiomorphic colourless crystals that form Manebach and albite-law twins (Fig. 4f). Milky adularia crystals that often form Manebach twins are also found on the island of Thassos. In Maronia orthoclase forms milky crystals, whereas in Samothraki pink orthoclase crystals up to 5cm are found. Milky adularia crystals up to 2cm are encountered in the skarns of Vrontou and Kimmeria. The presence of feldspars is particularly significant in the amethyst veins of Sapes where zoned adularia crystals form solid inclusions and also accompany quartz (Fig. 4g).

Fluorite accompanies quartz in the carbonate-replacement deposits of Lavrio and amethyst in the veins that crosscut the lavas in Lesvos.

Garnet forms small orange crystals (spessartine) that accompany quartz in the alpine-type fissures of Thassos. However, their presence is more important in environments related to Tertiary granitoids, especially in skarns. On Tinos Island spessartine accompanies quartz in miarolithic cavities in the leucogranite of the area, whereas on Seriphos Island andradite is found together with quartz in geodes in the granatitic and hedenbergitic skarn.

Hematite is encountered together with quartz in alpine-type fissures where it develops aggregations of hexagonal tabular black crystals that resemble the form of a rose or, more often, small tabular crystals as inclusions in quartz. Tabular hematite crystals are also found in environments related to Tetriary granitoids.

Muscovite and sericite are quite common as solid inclusions in quartz crystals. In alpine-type fissures on Thassos muscovite forms idiomorphic pseudo-hexagonal crystals that accompany rock crystal and smoky quartz (Fig. 4h). On Ios muscovite creates phantoms in quartz crystals, whereas in Penteli it forms thin tabular crystals in quartz. In environments related to granitoids muscovite is also common as an inclusion in quartz in many areas. Regarding the volcanic environments the most interesting site is Sappes where muscovite forms small inclusions in amethyst crystals.

Rutile is encountered as an inclusion in quartz crystals in many areas where alpine-type fissures have been developed. In Penteli needle-like dark brown to black rutile crystals are found as inclusions in quartz (Fig. 4k), while prismatic tetragonal rutile crystals accompany quartz in fissures in the same area. In Dasoto, Krieza-Koskina (Fig. 4j) and Thassos rutile accompanies quartz and forms needle-like crystals with golden, reddish and dark red colour respectively. In Karystos rutile forms misroscopic inclusions in quartz together with albite and zircon. Rutile was also found in Kimmeria in microscopic inclusions together with muscovite and monazite in the quartz veins that crosscut the granodiorite. Table 2 contains representative microprobe analyses of rutile from Penteli, Karystos and Kimmeria. The rutiles from Penteli and Kimmeria display chemical zoning, where the cores are enriched in WO_3 (up to 4.84 wt. % and 3.11 wt. % respectively), and the rims are WO_3-free (<0.65 wt. % in Penteli and <0.24 wt. % in Kimmeria) (Fig. 4k). Nb_2O_5 (up to 3.41 wt. % in Pendeli rutiles) and SnO_2 (up to 0.5 wt. % in Kimmeria) were also detected (Table 2).

Various sulphide minerals are found as accessory minerals and solid inclusions in quartz in all three types of geological environments. In alpine-type fissures pyrite can form quite large crystals in colourless quartz (Fig. 4i). The presence of sulphide minerals is more important in environments related to

Tertiary granitoids where galena, pyrite, sphalerite, bismuthinite and molybdainite are found as solid inclusions in quartz or as accessory minerals. Regarding the volcanic environments, sulphide minerals are only found in the area of Kirki where pyrite accompanies quartz in chalcedony veins.

Tourmaline is encountered together with quartz, hematite and chlorite in the alpine-type fissures of Thassos Island where it forms needle-like black crystals (Fig. 4l).

Wollastonite is found in environments associated with granitoids where it accompanies quartz crystals (Maronia) or forms the base of the veins where the Japan-law twin quartz crystals were deposited (Kimmeria).

Table 2. Representative microprobe analyses of rutile.

Wt. %	1	2	3	4	5	6	7	8	9
SiO_2	bd	0.30	0.05	0.14	0.77	0.17	0.32	0.29	0.05
Al_2O_3	0.07	0.05	0.03	0.05	0.12	0.17	0.03	0.10	bd
TiO_2	91.66	96.93	99.25	88.02	97.53	95.06	98.72	95.41	95.60
Fe_2O_3	3.09	1.03	0.63	3.52	0.40	1.84	0.67	1.64	1.19
MnO	bd	bd	0.11	bd	0.19	bd	bd	bd	bd
MgO	bd	bd	bd	bd	0.13	bd	bd	bd	bd
CaO	bd	bd	bd	bd	0.87	bd	bd	bd	bd
Na_2O	bd	bd	bd	bd	0.05	bd	bd	bd	bd
Cr_2O_3	0.02	0.08	0.04	0.03	bd	0.31	0.11	bd	0.47
Nb_2O5	0.85	0.27	0.21	3.41	bd	bd	bd	bd	bd
SnO_2	bd	0.24	bd	bd	bd	0.11	0.48	0.14	bd
WO_3	4.81	0.65	0.47	4.84	bd	3.11	0.24	2.56	3.00
Total	100.50	99.55	100.79	100.01	100.06	100.77	100.57	100.14	100.31
Cations on the basis of 2 (O)									
Si	-	0.004	0.001	0.002	0.010	0.002	0.004	0.004	0.001
Al	0.001	0.001	0.000	0.001	0.002	0.003	0.000	0.001	-
Ti	0.956	0.970	0.994	0.928	0.977	0.961	0.987	0.965	0.958
Fe	0.032	0.010	0.006	0.037	0.005	0.019	0.006	0.016	0.011
Mn	-	-	0.001	-	0.002	-	-	-	-
Mg	-	-	-	-	0.002	-	-	-	-
Ca	-	-	-	-	0.013	-	-	-	-
Na	-	-	-	-	0.001	-	-	-	-
Cr	0.000	0.001	0.000	0.000	-	0.003	0.002	-	0.005
Nb	0.005	0.002	0.001	0.022	-	-	-	-	-
Sn	-	0.001	-	-	-	0.001	0.002	0.001	-
W	0.017	0.002	0.002	0.018	-	0.011	0.001	0.009	0.010

1-4: Penteli (Attica), 5: Karystos (Evia), 6-9: Kimmeria (Xanthi).

6. Conclusions

Quartz is encountered in many areas in Greece where it develops a variety of habits and forms. The colour of quartz as well as the minerals that form solid inclusions in the crystals and the accessory minerals that accompany quartz are determined by the lithology of the parent rocks. Therefore, the type of crystal that is formed in each site reflects the conditions that prevail in the environment where quartz is formed. In this paper three main geological environments of formation have been distinguished, namely the alpine-type fissures, the environments related to Tertiary granitoids and the volcanic-hosted epithermal environments. Some quartz crystals found in various areas are of gem quality and their potential for use as gemstones should be evaluated. Such is the case of the amethyst in Dasoto, the colourless quartz crystals from Thassos Island, the smoky quartz from Krieza-Koskina, the quartz crystals with needle-like rutile solid inclusions in the area of Penteli, the green quartz and amethyst crystals from Seriphos Island and the amethyst in Kornofolia, Sapes, Lesvos and Milos. Moreover, numerous sites contain rare quartz crystals which should be preserved in mineralogical geotopes. Such is the case of Dasoto, Thassos, Evia, the area of Penteli, Kimmeria, Maronia, Samothraki Island, Lavrio, Seriphos Island, Kornofolia, Sapes, and the islands of Lesvos and Milos. Lastly, other sites can serve an educational purpose since they clearly reflect the results of geological activity in the area, like the different generations of sceptres that are found on Thassos, which represent the different stages in the emergence of the Rhodope massif, the skarns in Kimmeria and Seriphos and the epithermal environments of Sapes, Lesvos and Milos. These sites should also be preserved since they represent parts of the geological heritage of Greece.

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THE AURIFEROUS SUBMARINE FANS SANDSTONES OF THE IONIAN ZONE (EPIRUS, GREECE)

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Abstract

During recent decades many studies have be done on the rocks that developed in the area of Western Greece and especially in Epirus, known in geoscientific literature as Ionian Zone of External Hellenides. These rocks have undergone geological research (basic geological mapping, research for hydrocarbons, metals and inert materials) and exploitation (inert materials). Recently, within the sedimentary succession of the Ionian zone submarine fans, in the region of Peta–Kompoti, in the prefecture of Arta, have been identified positions where sedimentary gold is present. Recently, positions where sedimentary gold is present, within the sedimentary rocks of the submarine fans, in the region of Peta–Kompoti, prefecture of Arta, have been identified. For the continuation and the practical application of these positive results, it was necessary to obtain a documented reference of geological parameters. After a series of new sampling and detailed analysis of the samples, this work presents the detected gold concentrations, illustrates the limits of grouping areas of interest as well as delineating and illustrating palaeogeographic factors that have contributed to the creation of gold-bearing formations. The highest gold concentration found was in the Ta Bouma sequence. The observation of constant indications of high gold values above background that suddenly increase in certain places up to 260 ppb, leads to the conclusion that in the broader area and within locations with equivalent formations procedure, there could be gold pockets of exploitable concentrations.

Key words: *gold exploration, gold concentration, gold-bearing formations, flysch, Ionianzone, Epirus, Western Greece.*

1. Introduction

Different hydrocarbon zones are distributed over wide areas on both margins of the Adriatic and Ionian Seas. Major episodes, of paleogeographically widespread source-bed deposition, occurred in the Mesozoic and Cenozoic. Cenozoic rocks, of fine marly to coarse terrigenous source, accumulated preferentially in foreland basins, e.g. the Ionian Zone (External Hellenides). This basin is suitable for hydrocarbon exploration (Zelilidis et al., 2003). The exploration, which began 50 years ago, has brought to light an abundance of information on the structure and palaeogeographic evolution of the basin. Furthermore, a considerable amount of stratigraphic data has been accreted, which constitutes the basis for the evaluation of the palaeoenvironmental setting, the depositional evolution of the basin (I.G.S.R./I.F.P., 1966), and creation of geological maps of western Greece 1:50000 by the Institute of

Geology and Mineral Exploration (IGME).

However, none of the investigations conducted so far has provided long-term data on the existence of mineralization in the wider region. Recently, there have been identified positions, within the sedimentary rocks of the submarine fans in the region of Peta–Kompoti, prefecture of Arta, where sedimentary gold is present. In these rocks gold occurs as free metal in granules of 5-1000 microns in size (Pantelaki, 2001; Stamboliadis et al., 2002; Stamboliadis et al., 2003).

For the continuation and the practical application of these positive results, it was necessary to obtain a documented reference of geological parameters. These would indicate the places, entrenched with gold concentrations above background values, in the thick and spread sequence of submarine fans. Based on a series of new sampling and analysis of the samples, this work presents the detected gold concentrations and illustrates the palaeogeographic factors that have contributed to the creation of gold-bearing formations.

2. Geological setting

The geological area under investigation belongs to the Ionian zone of Western Greece. After the accumulation of predominantly calcareous sediments and during the Mesozoic and the Paleocene-Eocene, the uplift and the subsequent erosion of the cordillera, situated east of the Ionian Zone, caused clastic deposition in the active Pindos Foreland Basin, associated with Mesohellenic and Neohellenic tectonic cycles (Fleury, 1980; Jacobshagen, 1986). The proximal clastics of the internal areas are thicker and coarser than the distal ones of the middle or even external parts. Accordingly, submarine fans sedimentation, mainly clays and sandstones with conglomeratic beds, started earlier in the east than in the west (Bizon, 1967), and earlier in the north than in the south (Avramidis et al., 2002). The western border of the Ionian trough is the slope of the Apulian Platform, known as the Pre-Apulian Zone, and was not covered by submarine fan deposits. The carbonatic-pelitic sedimentation on this platform continued up to the Upper Miocene (I.G.S.R./I.F.P., 1966; BP, 1971). According to Richter (1974, 1976) the internal, middle and external parts of the Ionian Basin are separated by intrabasinal highs. This arrangement of the sea-floor was the main factor that controlled the flow direction and the extension of the clastic terrigenous turbidity currents (Avramidis & Zelilidis, 2001; Avramidis et al., 2002).

This long year's research work has created many views on the distribution of submarine fan deposits in the three sub-basins, as well on the lithostratigraphic nomenclature reflected in the geological maps of Western Greece. According to palaeocurrent direction and sedimentlogical data, the sediments of the basin originate mainly from the east. The two-stage rotation, suffered by the broader Helladic area, has played an important role in the evolution of the basin; according to palaeomagnetic data (see Avramidis, 1999).

Apart from the classical theories, related to the spatial correlation of lithostratigraphic units of the submarine fans, recent theories have appeared. These theories extended not only in the age correlation of submarine fans, (Leigh, 1991; Bellas et al., 1995; Bellas, 1997), but also in the distribution of the different facies (Avramidis, 1999; Vakalas, 2003) and in the direct relationship between locations of origin and evolution of palaeocurrents. All the above allows the interpretation of a genetic model of the overall sequence of the Pindos foreland submarine fan deposits.

3. Experimental Procedures

Cyanidation is the usual method for the recovery of finely disseminated and liberated metallic gold. According to the procedure used the ore sample is crushed and ground to liberate gold. One kg of the ground sample is mixed with 3 lt of water in a glass bottle. The following reagents are also added in the pulp: 7,5 gr $Ca(OH)_2$ for the adjustment of pH in the desirable level, (pH 11), 4,5 gr NaCN, that corresponds to concentration 1500 ppm NaCN in the leaching solution or 4,5 kg NaCN per ton of ore and 50 gr active carbon (+ 1.7 mm), for the adsorption of the dissolved gold. The bottle is rolled for 48 hours. At the end of the reaction period the pulp is screened at 1.00 mm, to remove the active carbon. The loaded active carbon and the remaining barren ore are fire assayed for gold. According to this method a certain quantity of the sample to be assayed, 30g from mineral samples and 1g from active carbon samples, are mixed with the appropriate quantities of Na_2CO_3, PbO, $CaCO_3$, SiO_2, $Na_2O.2B_2O_3.10H_2O$ etc. and fired at about 950 ^oC to obtain a lead button that is separated from the slag after cooling. The lead button undergoes cupellation at 1050 ^oC in order to obtain the gold nugget that also contains any silver (Ag) present in the ore. The nugget is consequently dissolved in aqua regia and assayed for gold by atomic absorption spectrometry. In any cyanidation test the gold content of the feed is the sum of the gold quantity distributed in the active carbon and the non dissolved quantity in the residue. Obviously the gold absorbed by the active carbon is the recoverable gold, the non-recoverable gold exists either finely disseminated, non liberated metallic gold, which can be recovered by further grinding, or is in the form of refractory gold, in the lattice of sulphide minerals mainly pyrite and arsenopyrite, that can be recovered only after destruction of the host minerals.

4. Sampling and Results

Three sampling sets were conducted in the major area of the Arta prefecture, where all the lithostratigraphic units of the Internal Ionian Zone submarine fans exist, as indicated in the geological map of Peta, scale 1:50000. In this map the submarine fan sequence developed above the Palaeogene limestone of the Ionian Zone and consists of the Peta sandstones, the Araxthos marls, the Anemorachi sandstones, and finally the formation of Distrato. In this area the above sequence has a thickness more than four kilometers forming a large synclinal structure. The first sampling set in the area was based on the above initial geological data and eighteen (18) random samples were collected. Only six (6) of the above samples indicated the existence of gold and are presented in Table 1. The rest of the samples had zero gold concentrations.

The above eighteen samples were collected along a natural section in the area of Kompoti (Arta prefecture). Three different sub-environments were identified in this section, presented in Figure 1, and from the bottom to the top they are: a) the outer fan sub-environment b) the inner fan sub-environment and c) a ponted basin sub-environment. Thickness of inner fan deposits is from 150 to 900 m. The appearance of sandstones of facies C2.1, that are characterized by an upwards decrease of their thickness

Table 1. General description of the first six positive samples.

Sample Number	Location	Recoverable Au (ppb)
A1	Turn after Kompoti, lower center of the lence type bank	263
A2	Turn after Kompoti, upper center of the lence type bank	194
A3	Turn after Kompoti, middle center of the lence type bank.	4,0
A4	West side	9,0
A5	Center	49,0
A6	Upper	4,0

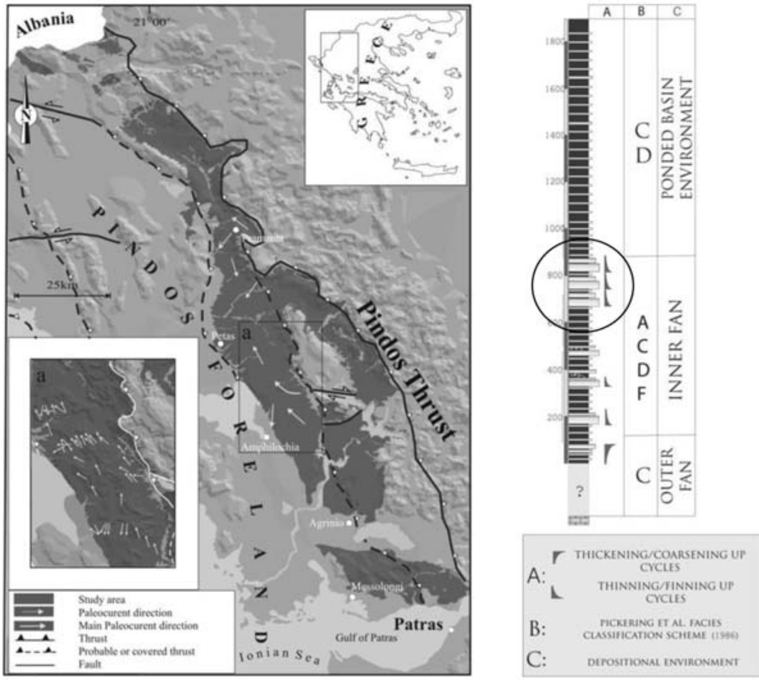

Fig. 1: Palaeocurrent directions in the investigated area. On the right side appears the stratigraphic column of Kompoti section (Vakalas, 2003) and the position of the positive samples 1-6 (cycle).

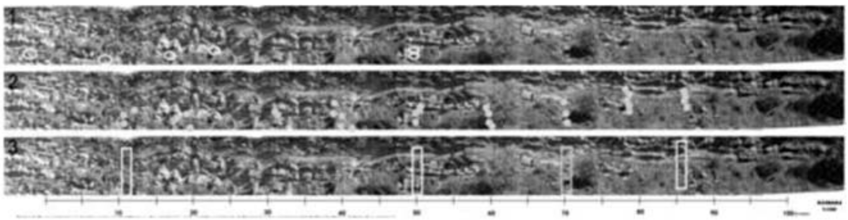

Fig. 2: Panoramic view, showing part of the Kompoti section, with three set sampling area. From top to bottom: first set with 18 samples, second set with 36 samples and third set with 4 samples. The position of the section is shown in Fig. 1. Detail of the profile Kompoti by Vakalas (2003).

and grain size, classifies this facies to a channel environment of the inner fan (Vakalas, 2003).

After investigation of the palaeocurrent directions in the broader area, a differentiation can be detected, in relation to the major palaeocurrent direction. Although the directions further north are towards south-southwest, in the studied Kompoti area the directions not only changed towards north-northwest but they show also characteristics of this turn, see Figure 1.

After the evaluation of the first sampling set results, it was important to have a second more detailed sampling set in the area, which not only provides the most comprehensive geological information but also focused on the higher gold values in the first random sampling. In the following systematic sampling, 36 samples of about 2 kg each were collected from successive positions of the section as seeing in Figure 2.

Table 2. General description of the second campaign samples.

Sample Number	Sample location	Recoverable Au (ppb)
B1	Position 92 m. Base of bank 3. Third bank on the east side 75 cm thick	19
B2	Position 92 m. Top of bank 3.	19
B3	Position 92 m. Upper 30 cm of the clastic sequence.	15
B4	Position 92 m. Base of bank 4, bank thickness 47 cm with intensive evidence of bioturbation and many plant residues.	14
B5	Position 80 m. Upper part of the middle clastic sequence between banks 2 and 3.	16
B6	Position 80 m. Base of bank 3.	16
B7	Position 80 m. Top of bank 3.	14
B8	Position 80 m. Middle of clastic zone between banks 3 και 4.	14
B9	Position 80 m. Base of bank 4, above the clastic sequence that is reduced to the west (bank 4 contains many plant residues.)	20
B10	Position 70 m. Top of bank 1. Only its roof appears at this point.	21
B11	Position 70 m. Bank 2, about 80 cm thick at this point.	18
B12	Position 70 m. Base of bank 3, about 85 cm thick at this point.	17
B13	Position 60 m. siltstone below the base of bank 1. the visible thickness below bank 1 is 90 cm	19
B14	Position 60 m. Base of bank 1. Thickness at this point 1 m.	11
B15	Position 60 m. roof of bank 1.	17
B16	Position 60 m. Base of bank 2, thickness of bank 2 at this point 50 cm.	17
B17	Position 50 m. Base of bank 1. thickness of bank 1 at this point 115 cm.	19
B18	Position 50 m. top of bank 1.	38
B19	Position 50 m. siltstone between banks 1 and 2, the thickness of siltstone between banks 2 and 3 is 85 cm.	6
B20	Position 50 m. Base of bank 2.	18
B21	Position 40 m. siltstone below bank 1.	9
B22	Position 40 m. base of bank 1.	13
B23	Position 40 m. top of bank 1.	16
B24	--	-
B25	Position 40 m. siltstone between banks 1 and 2.	18
B26	Position 40 m. Base of bank 2.	17
B27	Position 30 m. siltstone below bank 1.	18
B28	Position 30 m. Base of bank 1.	18
B29	Position 30 m. Top of bank 1.	17
B30	Position 30 m. siltstone between banks 1 and 2.	16
B31	Position 20 m. Base of bank 0.	18
B32	Position 20 m. Intermediate fine banks.	15
B33	Position 20 m. Base of bank 1.	14
B34	Position 10 m. siltstone below bank 0.	14
B35	Position 10 m. Bank 0.	13
B36	Position 10 m. siltstone between banks 0 and 1.	17

The results of the second sampling set are presented in Table 2, while the recoverable gold is presented in Tables 2 and 3.

After the evaluation of the above samples a third sampling set was also conducted in the same area. A total of four larger samples were collected, varying from 12 to 28 kg each, in a vertical cut of the natural section as showing in Figure 2 as well. The results are presented in Table 3.

Table 3. Recoverable gold of the third sampling set.

Sample number	Recoverable Au (ppb)
C1	4.71
C2	0.00
C3	0.20
C4	0.00

Following the evaluation of all samples, eight of them, from the 36 ones of the second set, were ground further finer than 90 μm. The finely ground samples were treated by cyanidation in order to study the effect of size in the liberation of gold and its recovery. The results of Table 4 show a considerable increase in gold recovery after grinding that indicates a very fine dissemination of gold in the rock environment (Batsalas, 2006).

Table 4. Comparison of recoverable gold between coarse and fine grinding.

A/A	Coarse sample -500 μm Recoverable Au (ppb)	Fine sample -90 μm Recoverable Au (ppb)
B2	19	26
B9	20	20
B10	21	22
B11	18	26
B13	19	21
B17	19	22
B27	18	23
B28	18	21
Average	19.0	22.6

5. Discussion and Results

The classical methodology followed for gold search is based on the statistical processing of a large number of data (Keppie et al., 1986; Nekrasov, 1996). As is appears from the presentation of the obtained data, although the gold values show a non uniform distribution (nugget effect) however, both in the first random sampling set, as well as in the next geologically controlled ones, gold values are well above the expected background. The average gold values vary in the different types of rocks. Clay sediments of deep sea have an average gold content of 3.0 ppb (Crocket, 1993). Carbonaceous sediments have the lowest gold content than any other sedimentary type of rock. It is reminded that most of the gold in all the word has been recovered from sedimentary rocks. As a whole the conglomerates, the sandstones and the siltstones give an average gold content of 8.1 ppb (Crocket, 1993).

Generally, there are a large number of geological models explaining gold depositions. Some research workers accept that the generation of gold depositions is related to large masses of rocks through reactions between fluids and existing rocks deep in the earth crust, while others give emphasis to the importance of relatively limited rock generating groups of rocks that make the so called "mother rocks" that accumulated gold above the ordinary values. It is therefore important to know the average content of gold in different types of rocks and at the same time the gold content that suggests a probable ore generation. Areas, with a gold content about 10000 times greater than the back ground, can be characterized as gold ores. Nevertheless, gold concentrations of some tens ppb may indicate procedures of formation of a gold deposition (Crocket, 1993).

The mass flows are very common in mountainous as well as in sea environments. The mechanics of mass flow on the earth surface and below sea level differ in many aspects and it is important to notice that probability of conservation of the depositions formed by mass flows under the sea is much higher than the one of terrestrial environments. However, under sea formations are difficult to be studied and they have rarely been observed on their genesis. May be this is the reason why there is such a debate in literature concerning these procedures. Very often, the depositions of undersea mass flows have larger dimensions than on the earth surface and can fill with sediments a great part of sea basins. Even more, the lake and sea gravitational flows of sediments are very often developed into turbidity currents that create such structures called "turbidites".

Since many gravitational flows of sediments change from uniform into fully turbulent systems, a precise correspondence of the natural flows to ideal ones is usually very difficult. It is only in depositions of gravitational flows that have been conserved where their internal structure and sedimentary structures may register the manner of the final deposition but they cannot fully reveal the probably variable character of the flow during its transportation from an inclined to the basin of deposition, (Middleton & Hampton, 1976; Middleton, 1993; Einsele, 1996; 2000).

In accordance to the complicated and over-discussed procedures of gold accumulation in sedimentary deposits, in the case of turbidic currents, which create an environment of dispersion and classification at the same time, one could extrapolate the general rules of heavy minerals enrichment in aqueous currents. Both in aqueous turbidic currents, turbulence are the main mechanism that moves the sediments.

A coarse grain of quartz has the same settling velocity as a smaller grain of a heavier mineral. These two grains although they are different in size they are hydraulically equivalent. I the case of a narrow pass where the velocity is high there is no deposition of material. When the pass is broadening the velocity of the water or turbidic current slows down and the hydraulically heavier minerals start to settle while the lighter ones move further apart. Generally, the high density of gold allows its deposition under complicated natural processes in all sedimentary environments. In all cases it is the gravity, the type of liquid as well as the type of flow that determine the dynamic of the probable accumulations (Eyles, 1995).

The specific area of sampling, confirmed only on inner fan deposits (the lower stratigraphic unit of the studied section) are sediments accumulated by turbidic currents. In a wide flow environment, no other flow type is capable to result in a concentration of gold, because of the great difference in the density of gold. The highest gold concentration found was in the Ta Bouma sequence (Bouma 1962).

The observation of constant indications of high gold values above background that suddenly increase in certain places up to 260 ppb, leads to the conclusion that in the broader area and within locations with equivalent formations procedure, there could be gold pockets of exploitable concentrations. Accordingly the area that has been specified with the above criteria can be enlarged to a wider border. Gold exists as free metal and is not in the lattice of another mineral (refractory gold) but is very finely disseminated. This is better supported from the fact that finer grinding of the samples has resulted in better liberation and hence a better recovery of the precious metal.

A series of paper (Leigh & Hartley 1992, Faupl et al. 1996, Faupl et al. 1998, Avramidis & Zelilidis, 2001) provides evidence for the origin of the material that fueled the turbidity currents. Apart from the erosion material of rocks of the Pindos nappe, also materials derived from erosion of internal zones nappes, transported over the Pindos nappe, were involved. Although they may be several assumptions, for the moment there is no evidence to indicate the provenance of gold bearing materials.

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THE FLUVIAL ACTION OF THE KARLA BASIN STREAMS IN A NATURAL AND MAN – MADE ENVIRONMENT

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Abstract

This study investigates the fluvial action of streams draining the Lake Karla basin, located in the plain of Thessaly, in Central Greece. Until a few decades ago, a large part of this area had been occupied by a lake. In order to find out the relation between the channel bed morphology and the oscillations of the local base level due to variations in water level and human intervention in the lake, the following streams were investigated: the flumes of Mpegiatiko, Bagiorema, Bathurema, Xerias and Maurorema. The width and the length of all channels were measured with a laser range finder while the incision and the erosive events were recorded by GPS with sub-meter accuracy. Furthermore, an integrated GIS analysis was undertaken in order to illustrate the changes in the water level of Lake Karla coupled with historical data and data from previous studies. It will be shown that there were two main evolutionary stages which controlled the local base level changes of the studied area. The first one is connected to the continuous changes in the lake's water level and its reduction from 64m to 45m a.s.l. This resulted in the incision of the channels and the creation of characteristic knick points upstream. The second stage is associated with the draining of Lake Karla in 1962. This intervention mostly altered the streams that developed into fine-grained material channel beds.

Key words: *drained lake, Karla, Thessaly, plain, lake-level changes*

1. Introduction

The aim of this paper is to study the natural fluvial processes in terms of the channel bed morphology developing in the hydrological basin of what once was Lake Karla and how they have been affected by human intervention in the lake. In order to be able to study the natural processes in the channels, it was necessary to explore and represent the changes that occurred on the water's surface and the volume of Lake Karla prior to its drainage, which determine the local base level of the basin.

The studied area is located in the Thessalian Plain, Central Greece (Fig.1). Lake Karla was drained in 1962, after a massive draining program for agricultural development which was also effected in other parts of Greece (e.g. Lake Kopaida). The area of the hydrological basin of the former Lake Karla is 1,121 km^2 and covered the largest part of the Thessalian Plain. The basin is surrounded by Mt. Maurovouni and Mt. Kissavos to the East, by Mt. Pilio and Mt. Megavounio to the SE and south respectively and by low mountains and hills to the West.

From a geomorphological point of view, the Karla basin can be considered semi polje due to the pres-

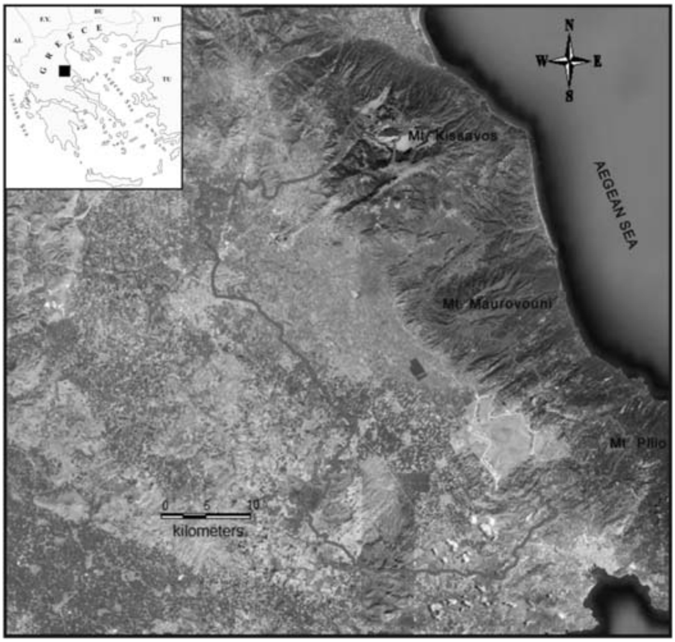

Fig. 1: Regional setting of the study area.

ence of karstified rocks and sinkholes which contributed to the underground draining of the former lake. Also, typical is the bedrock appearance at places inside the basin (hums). (Palikaridou, 1998).

2. Materials and Methods

A geomorphological analysis of the hydrological basin of the former Lake Karla was done through the use of the geological and topographic maps of the area. The HMGS and IGME map sheets of Agia, Farsala, Larissa, Volos, Velestino, and Platykampos at a scale of 1:50,000 were used.

A terrain analysis through the use of a digital elevation model (DEM) was performed in order to study the morphology of the lower part of the basin and to depict the impact of the local base level changes on the erosive upstream processes in the drainage network of the lake's hydrological basin. Furthermore, historical data and data from previous studies were used to determine the water level variations of the drained Lake Karla.

Finally, detailed field work was done to study the morphological changes in network channels. Concerning the morphological characteristics of the channels, the width and depth of each were measured with a laser range finder. In addition, the incision and the erosive events were recorded. For that purpose, a GPS with sub-meter accuracy was used to survey the position of all cross sections.

3. Results

3.1 Historical data revealing the water level variations of the drained lake Karla

Due to the relatively small depth of the Karla basin, the lake never exceeded 5m in depth although the water surface increased significantly with a rise in water discharge.

Table 1. Summary table of the most important bibliographical data on the water level variations of Lake Karla.

TIME PERIOD	WATER LEVEL	WATER SUFACE
Neolithic Age	>50m	
Mycenaean Age	64m	
1921	50.10m	
1945		78.35km^2
1953	45.85m	

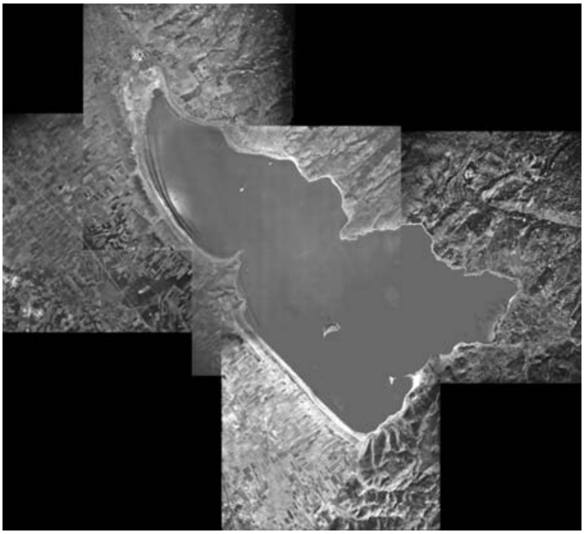

Fig. 2: Aerial photos of the year 1945, illustrating former Lake Karla (Moumou, 2007).

In this study, archaeological data, studies from other researchers, historical maps and aerial photos before the lake's drainage were collected in order to reveal the water level variations of the former lake.

During the Middle Neolithic age, the level of the lake was over 50m (Apostolopoulou – Kakavogianni, 1979), reaching a maximum water level of 64m a.s.l. during the Mycenaean Age (Grundmann, 1937; Gallis, 1989; Palikaridou, 1998). Also, it is known that the water levels in 1921 and 1953 reached 50.10m and 45.85m, respectively (Ananiadis 1956; Palikaridou, 1998). Finally, through the use of aerial photos taken in 1945 the water surface of the former Lake Karla was calculated at 78.35 km^2 (Fig. 2).

A summary table (Table.1) lists levels and surface area obtained from the historical data.

3.2 Terrain analysis

A terrain analysis was performed in order to study the morphology of the lower part of the basin. The vertical accuracy of the HMGS topographic maps was not suitable for the study of these low relief areas. Thus, a DEM derived from the SRTM data (Shuttle Radar Topography Mission) was used. (Fig. 3)

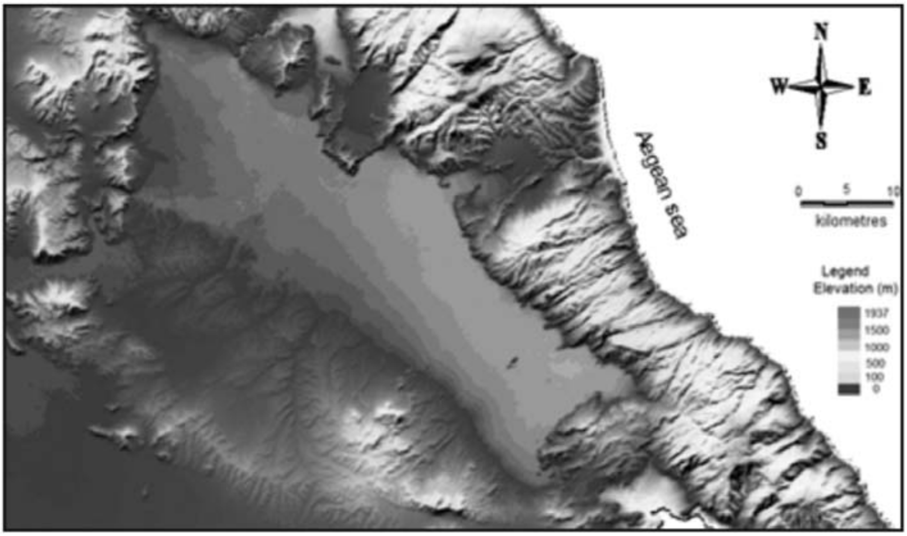

Fig. 3: Digital elevation model (DEM) of the studied area.

Based on the fact that there are no areas with distinct morphological features of deltaic deposits and alluvial fans at the lower part of the wider area including the hydrological basin of the drained lake, it was assumed that there were uniform and relatively low sedimentation rates. Thus, for the shoreline representation derived from the terrain analysis of DEM data, for the last 3000 years, the thickness of that recent layer was not extracted.

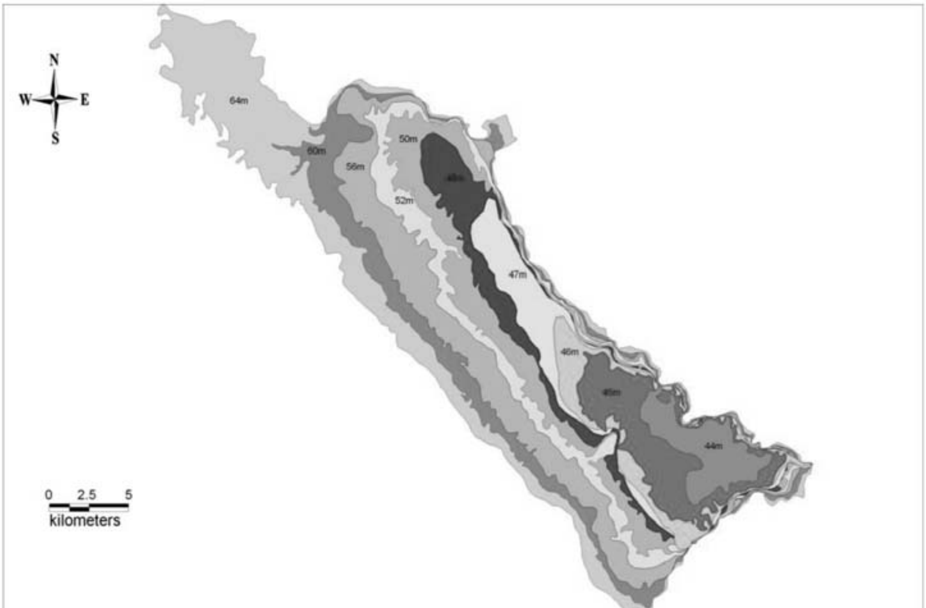

Fig. 4: Stages of shoreline migration derived from the terrain analysis of DEM data.

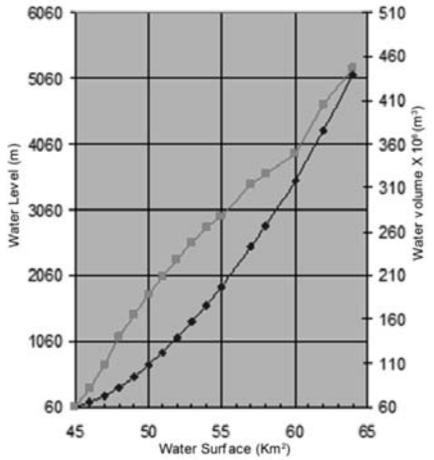

Fig. 5: Plot diagram of water level - water surface and water volume – water surface.

Table 2. Water Volume and Water Surface obtained through the use of DEM.

Water Level (m)	Water Volume x10^6 m^3	Water Surface km^2
45	61	60.67
46	132	81.39
47	231	108.3
48	359	140.8
49	515	164.5
50	694	188.6
51	895	209.2
52	1115	228.3
53	1355	248.1
54	1613	264.5
55	1889	278.5
57	2490	313.9
58	2813	326.3
60	3496	348.1
62	4269	405.7
64	5125	446.6

In order to correlate the upstream erosion rates and the channel's morphological changes with the lowered base level of the drained lake, it was necessary to know the location of the lake's shorelines and their fluctuations. Therefore, with the use of the elevation model for the absolute elevations of 44m, 45m, 46m, 47m, 48m, 50m, 52m, 56m, 60m, and 64m, a restoration of the water surface and the water volume of Lake Karla was attempted (Fig. 4, 5, Table 2).

The study of the shoreline's location obtained from the elevation model showed a large migration to the basin's center due to the constant drop in the lake's water level. On the western side of the basin, with regard to the total lowering of the lake's water level, a displacement of 4.5km was estimated. On the opposite side of the basin (SE) the displacement was estimated at 1.6km, while in the eastern part the average displacement was only 500m. These displacements have greatly affected the fluvial – erosional action of streams located in that area.

3.3 Channel morphological analysis

Detailed field work was done to study the morphological changes in the drainage network channels. The selection of the channels was based on specific criteria. In particular:

- The channels reaching directly the 45m shoreline of the drained Lake Karla were selected, since they were directly affected by the changes in the local base level.
- The channels with no human interference in their channel bottom morphology and their discharge were opted for.
- Channels were excluded due to their small development and, consequently, their small hydrological basin; thus, any changes that occurred were not measurable.

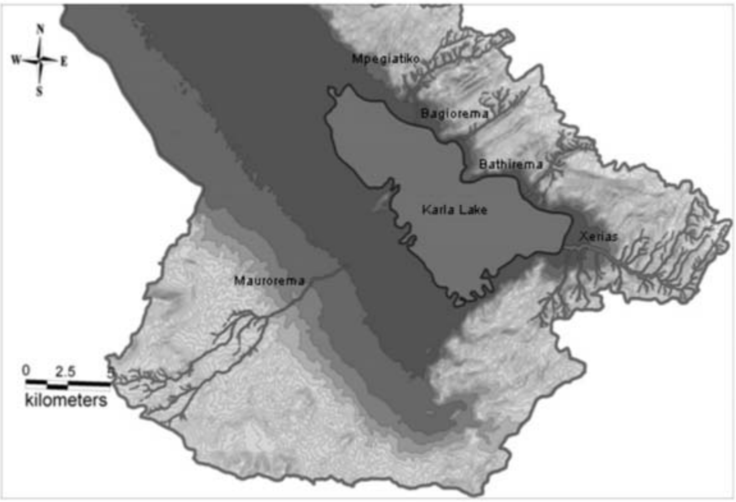

Fig. 6: Regional setting of the five main channels that were selected for the field study.

Following the aforementioned criteria, the study focused on five main channels of the following flumes: Mpegiatiko, Bagiorema, Bathirema, Xerias and Maurorema (Fig. 6)

The field survey focused on the channel sections situated on their alluvial fan deposits. The rates of upstream erosion were very low due to the last man-made change in the lake's water level (2m). The only segments with high erodibility and distinctive morphological changes due to upstream erosion were those between the lake shoreline and the alluvial fan apex.

A significant factor in the final formation of the channel graded profiles was the flood event of 9th October 2006. On that day, the estimated rainfall for the hydrological basin of the studied area was 230 mm (precipitation rate). These extreme discharge values triggered the erosive upstream processes and created new graded profiles.

Fig. 7: Photo of Mpegiatiko stream showing the dense vegetation inside the channel bed.

Fig. 8: Bed river of Bagiorema stream with the prevailing coarse-grained materials.

• Mpegiatiko Creek

The field study performed on the stream of Mpegiatiko showed that it is a seasonal flow stream, whose interior presents a wide channel bed with dense vegetation. No erosion was measured in the channel, apart from some incidents in the past. (Fig. 7) As the results from the morphological profile of the studied channel segment showed, the average slope is 2.8%.

• Bagiorema Creek

The field study for this stream showed that it is a seasonal flow stream, presenting a small hydrological basin. The coarse-grained materials of the river bed have been a restraining factor in the erosive processes (Fig. 8). The morphological profile showed that the average slope of the Bagiorema studied channel segment amounts to 6.6%.

• Bathirema Creek

The field study for the stream of Bathirema showed that it is a seasonal flow stream. The various incidents of erosion measured are older stream terraces unrelated to the recent changes in the area after the drainage of the lake. A restraining factor in the erosive processes, despite the large slope of the streambed, has been the coarse grain size of the alluvial deposits on the channel bed, and the short period of time that has elapsed since the base level change (Fig. 9). The morphological profile

Fig. 9: Photo of Bathurema stream showing the coarse grain size of the alluvial deposits.

Fig. 10: Photo of Xerias stream. No erosion has been observed.

showed that the average slope of Bathirema's studied channel segment corresponds to 6.06%.

• Xerias Creek

The field study undertaken for the stream Xerias showed that it is a stream with a large hydrological basin and high peaks in flow discharges. The stream flow in combination with the gentle channel slopes allowed a shortage of the streambed's alluvial sediments (coarse-grained materials close to the apex and sandy sediments further downstream). The final change of the base level after the drainage of the lake shifted the coarse bedload further downwards (Fig. 10). Finally, the processing of the morphological profile gave us an average slope channel segment of 1.8%for Xerias.

• Maurorema Creek

In the field study of the stream of Maurorema the characteristic V-type erosion was measured inside the channel, which is recent and related to the drained Lake Karla (Fig. 11). The last flood event in combination with the gentle slope of the channel segment and the fine-grained bottom are responsible for the upstream erosion and the formation of a new graded channel profile. The average slope of the studied channel segment is 1.15%.

Fig. 11: Photo of Maurorema stream showing the V - type erosion inside the channel.

4. Conclusions

For each different lake level, the water volume and the surface of the lake were calculated. According to the historical and archaeological data of the Neolithic period, Lake Karla had the largest surface, delimited by a present-day contour of 64m. Since then, the former lake began to shrink, its water level reaching the absolute elevation of 45.85m by 1962, when it was eventually drained.

Probing into the coastlines of the former Lake Karla at each water level, a great shoreline displacement was observed, mainly in the western part of the basin due to the morphology of the lake's basin relief. The measured displacement reaches a maximum of 4.5 km and is connected to the gentle slopes prevailing in this part of the basin. In contrast, in the eastern part, lake level changes did not cause vast shoreline displacements (displacement of up to 500m) due to the steep slopes of the relief.

From the morphological analysis of the stream channels flowing into the former lake, it is clear that those that developed in the eastern part of the basin did not present erosive incidents connected to the lake's drainage. The observed terraces are connected to the fluctuations of the local base level due to water level changes of the lake. Additionally, the formation of alluvial fans consisting of coarse-grained material is the main feature of the streams (Mpegiatiko, Bagiorema, Bathyrema) developed in this part of the basin and are related to the small shoreline displacement of the former Lake Karla. Contrary to this, the drainage of the lake had an impact on the morphological profile of the streams that developed in the western part of the basin, where the bedrock is easily eroded and the relief is characterized by gentle slopes. V-type erosion inside the channels (Maurorema stream) is connected to the drainage of the former lake. Also, the latter's major shoreline displacements in this part of the basin washed over the deposited materials, resulting in the absence of alluvial fans.

In conclusion, there are two main stages for the local base level variations of Lake Karla's hydrological basin:

- The first one is associated with the continuous variations of the lake's water level, and its reduction from 64m to 45m a.s.l. The upstream channel erosion is continuous and the channels did not achieve equilibrium until our days. The incised channels of the torrents in their own alluvial fan deposits and the knick point migration further upstream support this theory.
- The second one is associated with the hydraulic works after 1962 and the man-made drainage of the lake. The change in the water level is about 2m corresponding to the depth of the water in that final stage. The upstream erosion started only on fined-grained material channel beds (Maurorema) and not those that were developed on coarse-grained channel beds (Mpegiatiko, Bagiorema, Bathyrema).

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TECTONOSEDIMENTARY SIGNIFICANCE OF THE MESSINIA CONGLOMERATES (SW PELOPONNESE, GREECE)

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Abstract

The marine fill of the Gavrovo-Tripolis foreland basin in the Messinia area (SW Peloponnese), includes facies and facies associations, deposited by sediment gravity flows in slope and inner fan settings. The above-mentioned gravity-driven sedimentary processes, resulted in the formation of thinning-upward sequences and fining fan facies associations, composed of impressive sheet-conglomerates at the base (Agia Mavra, Agia Varvara and Mali units), presenting mainly normal internal structure, while clay and sand-clay members predominate at the top. These conglomerates advocate a significant sediment supply and extended accommodation space, during periods of dramatic tectonic uplift, associated with the westward propagation of Pindos thrust front. In the prograding fan system, dominate paleo-currents with main flow direction to southwest. The finer fan facies associations show rapid lateral variations, both in lithology and thickness, indicating rapid changes in the inner, incised, part of the foredeep. Nannofossil analyses suggest that the sedimentation took place during Oligocene (NP22 to NP24 biozones). Three NNW-SSE trending thrust fault zones bound the above-mentioned units and they caused an important structural thickening of the fan facies associations. Biostratigraphic analyses date the end of the thrust activity in Gavrovo-Tripolis zone in Late Oligocene (biozone NP24).

Key words: *submarine-fan facies associations, conglomerate, thrust faults, Oligocene, Gavrovo-Tripolis foreland basin, External Hellenides.*

1. Introduction

Research on the origin and evolution of foreland basins has made strong advances, principally due to developments in understanding the mechanics of sedimentary basin formation. Geodynamic models proposed by Beaumont (1981), Stockmal et al. (1986) and others show the relations between the foreland subsidence and the resulting thickness of the foreland basin flysch-type clastic fill. There is a close relation between the nature, geometry and internal organization of clastic sediments and the evolution of the associated orogen. Furthermore, the eustatic movements play an important role, since they influence the accommodation space of the clastic sediments. In Mutti et al. (2003) there is an up today synthetic approach of the turbidites and the turbidity currents while Mutti et al. (2009) deal with the control of the fluvial regime on the turbidite sedimentation in deeper waters. Among the dif-

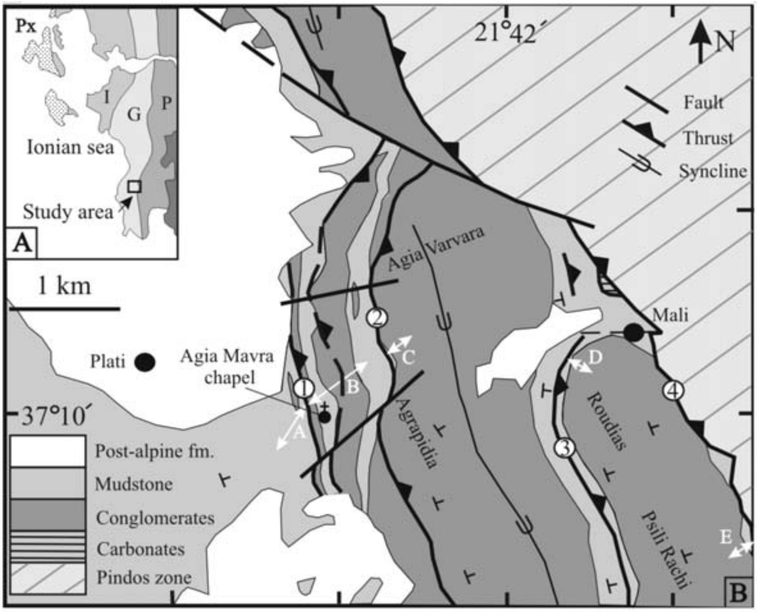

Fig. 1: A) Location map (Px: Pre-Apulian zone, I: Ionian zone, G: Gavrovo-Tripolis zone, P: Pindos zone). B) Geological map of the area studied, showing the location of stratigraphic cross-sections (A: Plati section, B: Agia Mavra section, C: Agia Varvara section, D: Mali west section, E: Mali east section), 1: Agia Mavra thrust fault (AMF), 2: Agia Varvara thrust fault (AVF), 3: Mali thrust fault (MF), 4: Pindos thrust fault (PT).

ferent kinds of the clastic sediments, the conglomerates are less abundant than other deep-water facies, but make up an important part of the deep-sea sedimentary record (Walker & James, 1992).

The Messinia region (SW Peloponnese, Greece) represents a very good study example, since thick conglomerate associations outcrop in the Gavrovo-Tripolis foreland basin near Pindos thrust (PT).

In this paper, we examine the ancient submarine fan-facies associations and the depositional systems that dominate this part of the Gavrovo-Tripolis foreland basin. Moreover, new structural and micropaleontological data are also presented towards a better understanding of the Gavrovo-Tripolis foreland basin evolution during Oligocene.

2. Geological setting

The fold-thrust belt of External Hellenides is the result of the collision between the Apulian plate (Adria Plate) and the Eurasian continent, which initiated in Late Cretaceous - Early Eocene times and continued during Tertiary (Dewey et al., 1973; Mountrakis, 1986; Doutsos et al., 1993; Karakitsios, 1995).

The pre-orogenic sequence of this fold-thrust belt consists, from east to west, of Mesozoic carbonates of Pindos, Gavrovo-Tripolis, Ionian and Paxos (Pre-Apulian) zones (Aubouin, 1959; Fleury, 1980; Karakitsios, 1995). In Late Eocene, the underlying Pindos zone detached from its basement and moved westwards along the Pindos thrust (Jacobshagen et al. 1978).

The tectonic load of the orogenic belt and the subsequent flexural subsidence have as result the formation of a foreland basin developed on the Ionian and Gavrovo-Tripolis zones. During the syn-orogenic period, thick turbidite sequences were deposited in the foreland basin, which progressively was involved during the orogenic process (Fleury, 1980).

In SW Peloponnesos, the foreland basin overlies Palaeocene to Eocene carbonates of Gavrovo-Tripolis zone (Fleury, 1980; Thiebault, 1982). According to these authors, the onset of the flysch sedimentation took place on the earliest Oligocene, whereas Fytrolakis (1971) considers that it took place in Late Eocene.

Based on our field observations, four flysch units have been distinguished in the study area, imprinting the conditions of the foreland basin fill during Oligocene. Plati, Agia Mavra, Agia Varvara and Mali unit are described in stratigraphic cross-sections A, B, C and D/E respectively based on the type and geometry of the sediments, and the internal structure of the beds (Fig. 1 & Fig. 2).

3. Structural data

The studied area is located west of the Pindos thrust (PT) which is trending NNW-SSE in this part of the fold-thrust belt. It is a mountainous area, that consists of two elongate ridges (Agia Varvara and Roudias), trending generally parallel to PT (Fig. 1B). The western flanks of these ridges are characterised by steep relief, while the eastern ones present a smoother relief. Conglomerates occupy the uppermost part of the ridges, while clay successions outcrop at the low relief areas. Fieldwork reveals new data concerning the structural deformation of flysch sediments.

The thrust fault activity controls the structural configuration of the foreland basin, imprinted in a series of ridges. In particular, three thrust faults zones, striking NNW-SSE and dipping to the east, have been recognized on clay successions, identifying three tectonosedimentary units, namely Agia Mavra, Agia Varvara and Mali.

The Agia Mavra's thrust fault zone (AMF), located on the lower part of the western flank of Agia Varvara ridge, influences both the upper part of Agia Mavra's clays and the lower part of Agia Mavra's conglomerates (Fig. 1B). On the footwall of AMF, the age of the uppermost members of Plati clays, based on nannofossil analyses, dated of late Oligocene (biozone NP24; cooccurrence of *Sphenolithus distentus* and *S. ciperoensis*) while the Agia Mavra's clays, above the AMF, dated of early Oligocene age (biozone NP23; detected by the cooccurrence of the nannofossil species *S. distentus* and *S. predistentus, Retculofenestra bisecta, Helicosphaera compacta*).

Further eastwards, Agia Varvara thrust fault (AVF) defines the tectonic contact between Agia Varvara and Agia Mavra units (Fig.1B). The base of Agia Varvara unit dated from early Oligocene age (NP 23), while the uppermost part which is situated on the footwall of AVF, dated from late Oligocene age (nannofossil biozone NP24).

The Mali thrust (MF), located in the lower part of Roudias ridge, is in line with the crest of this ridge (Fig. 1B). The low angle thrust fault plane dips to the east and strikes almost parallel to the mudstone stratification. Samples taken from mudstone indicates late Oligocene age (nannofossil biozone NP24) for the youngest sediments of the footwall and earliest Oligocene age (biozone NP22; detected by the co-occurrence of the species *Sphenolithus predistentus, Reticulofenestra umbilica* and *R. hillae* combined with the absence of *Sphenolithus distentus* and *S. ciperoensis*) for the hanging wall lowermost sediments. Furthermore, samples from the footwall of the Pindos thrust dates from late Oligocene age (nannofossil biozone NP24).

The frequent occurrence of nannofossil markers of biozone NP24 on the footwall of the above-mentioned thrust faults, as well as the Pindos thrust, suggests that the Pindos thrust emplacement and the main thrust activity in Gavrovo-Tripolis foreland basin, took place during the late Oligocene (nannofossil biozone NP24). These evidences are in accordance with other studies (Fleury, 1980; Sotiropoulos et al., 2003).

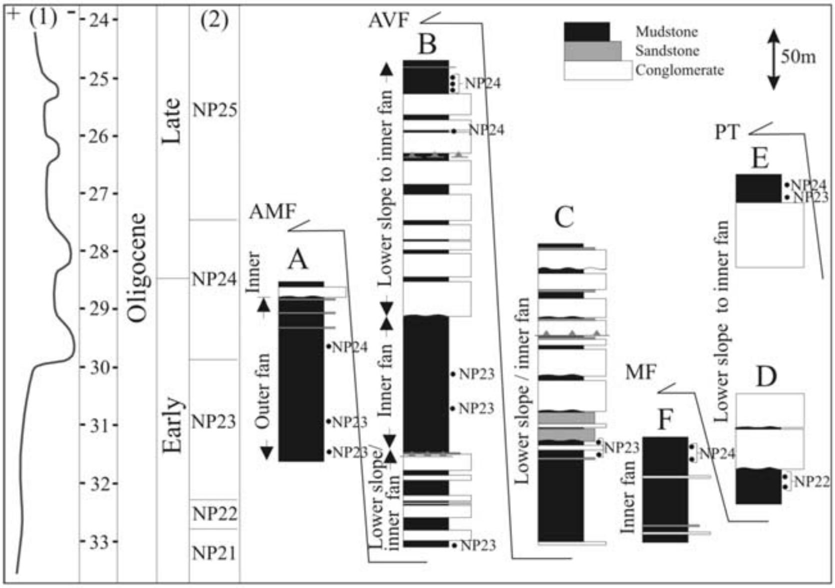

Fig. 2: Correlation of stratigraphic cross-sections during Oligocene (1): Eustatic short term curves, (Haq et al., 1987), (2): Biozones of calcareous nannoplankton (Martini, 1971), A: Plati section, B: Agia Mavra section, C: Agia Varvara section, D: Mali west section, E: Mali east section, F: Stavros section (out of the studied area). The location of all sections is presented in figure 1B.

Oblique normal faults are also recognized in the studied area. A representative case is the NE-SW trending oblique normal fault cutting across the AMF and AVF near the Agia Mavra chapel (Fig. 1B). Moreover, several ENE-WSW and ESE- WNW trending normal faults, affect the flysch deposits associated with the latest extensional stress field.

4. Sedimentary facies and depositional environments

4.1 Plati unit

It outcrops in the neighbourhood of Plati village (Fig. 1B) and it consists of silty mudstone / fine-grained sandstone alternations, presenting marked lateral continuity of at least 20 kilometres. They are characterised by sand /mud thickness ratios<1, more frequently with base-missing and / or rarely complete Bouma type-sequences (facies MS, Ghibaudo, 1992). The mudstones present laminated, parallel bedding, while the sandstones are thin-bedded and 'plane-stratified' (facies D, Mutti & Ricci Lucchi, 1972, D2, Mutti & Ricci Lucchi, 1975, facies MS of Ghibaudo, 1992). The depositional mechanisms are associated with low-density currents producing typical turbidites (outer fan associations).

The upper members of Plati unit outcrop west of Agia Mavra chapel (Fig.1 and Fig. 2, section A). They consist of fine-grained depositional intervals expose indistinct or poorly defined parallel bedding (subfacies TM / MT Ghibaudo, 1992). They present lateral variations in lithology (muddy or gravely sandstones) and include dispersed pebbles and gravels, locally concentrated in lenticular gravel or sand bodies (facies G, Mutti & Ricci Lucchi, 1972). Medium to fine-grained massive sandstones, up to 1 m. thick, are rarely enclosed in the silty mudstone which passes upwards to siltstone. These sandstone beds are bound by even, parallel, surfaces having rather good lateral continuity and are inferred to be equivalent to facies C (Mutti & Ricci Lucchi, 1972). The above-mentioned depositional system of facies is interpreted as indicative of an inner fan association.

At the top of Plati unit, 1.5 - 3 m thick, coarse-grained, poorly sorted disorganised conglomerate (facies A, Mutti & Ricci Lucchi, 1972, mG Ghibaudo, 1992, A_{1-1} Pickering et al., 1986a, 1989) overlie the mudstones with a sharp contact. Conglomerates are irregular shaped, commonly amalgamated and characterised by an undulating, low-relief erosional lower surface and planar or slightly irregular upper one. They are clast-supported massive beds with limestone cobbles and boulders of Pindos zone origin, dispersed mainly at their basal part (facies A1, Mutti & Ricci Lucchi, 1978, subfacies, m Ghibaudo, 1992). Moreover, thin, sandy matrix-supported gravel depositional intervals are observed in the uppermost conglomerate beds, presenting ill-defined normal gradation (facies A, Mutti & Ricci Lucchi, 1972, subfacies GyS/ gGyS Ghibaudo, 1992). These facies type/group is related to highly erosive - debris flow - mechanisms and eventually rapid sedimentation in the lower slope to inner part of the submarine fan.

The presence of *Sphenolithus distentus, S. predistentus* and *Cyclicargolithus abisectus*, at the lower part of section A, suggests early Oligocene age (nannofossil biozone NP23), while the cooccurrence of *Sphenolithus predistentus* and *S. ciperoensis*, at the upper part, indicates late Oligocene age (nannofossil biozone NP24).

4.2 Agia Mavra unit

This unit consists of distinct depositional intervals made up of conglomerate and thin sandstone, at the base and siltstone/ silty mudstone couplets at the top (Fig. 2, section B). Sandstone beds are either absent or represent thin (up to 5 cm), very coarse-grained, parallel plane-laminated, depositional intervals. The finest constituents are upward increasing in thickness (2 m). This type of bed intervals is common between the lower members of Agia Mavra unit. The base of the gravel-bed intervals is characterized by a sharp contact generally expressed by a broadly undulating erosion surface and rarely by a sharp flat, while the upper boundary is almost planar and rarely undulated. The transition to the overlying sand-beds is either abrupt or gradual with an intermediate clast or sand-supported interval (subfacies gGS, Ghibaudo, 1992).

Considering the type of bed interval, the gravel part is coarse-grained, poorly to moderately well sorted, either well cemented with calcite, characterised by poorly defined normal grading, or loose, usually structureless (subfacies gGS and mG, Ghibaudo, 1992). Normal to inverse graded gravel beds are not very common. Amalgamated gravel beds are locally observed, presenting an irregular geometry due to either erosion or uneven depositional relief The dominating pebble size is 8 cm, ca. Some sand clasts were also observed at the lower part of the conglomerates. Conglomerate populations are dominated by light grey-coloured limestone, cherts and radiolarite from the Pindos zone, well to very well rounded pebbles and cobbles. These deposits suggest long-distance transport and rapid deposition by turbidity currents or debris flows (facies A1, Walker & Mutti, 1973, A1-1, Pickering, 1986, 1989, facies A1, Mutti & Ricci Lucchi, 1978, facies G/GS Ghibaudo, 1992).

The siltstone - mudstone depositional division is normally overlying the sand or the gravel bed intervals and it presents indistinct or poorly developed plane-parallel bedding. It includes dispersed gravels mainly in the muddy divisions. Thin lenticular bodies of sand and conglomerate are also enclosed in these intervals suggesting facies G/D (Mutti & Ricci Lucchi, 1972), probably subfacies ITM Ghibaudo, 1992). Lateral variations in thickness and local "discordant" contact with the underlying irregular shaped gravel-sand units are related to submarine erosion and channel fill geometry. The above-mentioned coarse and fine-grained intervals generally compose positive sedimentary sequences (Mutti & Ricci Lucchi 1974), deposited by debris flow and more dilute currents, respectively. They are interpreted as a slope – inner fan association.

A marly mudstone sequence, composed of laminated silt-mud depositional intervals with indistinct or poorly developed parallel bedding, predominate upwards, in the surrounding area of Agia Mavra chapel. This bed type comprises a silty lower division and a muddy upper one (facies lTM/IMT, Ghibaudo, 1992) and it is usually characterised by silt /mud thickness ratio<1. Very thin (few cm thick), discontinuous bedded sand layers, lenticular sand bodies and conglomerates are also rarely enclosed in this interval. At the base of this mudstone sequence, a conglomerate-sandstone facies association occurs, about 2 m thick suggesting facies S (Ghibaudo, 1992), C (Mutti & Ricci Lucchi, 1972). This sedimentary sequence, considered in a more extent sedimentary context, presents a channel-shaped irregular geometry, with significant lateral thickness changes. The individual bed intervals represent thinning-upward positive sequences (Mutti & Ricci Lucchi, 1974). The transport-depositional mechanism is inferred to be controlled mainly by dilute currents (inner fan association).

A thick conglomerate sequence, ca 190 m, overlies the above-mentioned marly mudstone sequence and it creates successive morphological steps as well as an impressive steep relief (Fig. 2, section B). A characteristic bed occurs at the base of this conglomerate-sequence, including white coloured, angular, medium to fine-grained, moderately sorted, pelagic limestone, silex and lydite gravels of Pindos origin. It is a coarse sand matrix-supported bed interval, (subfacies gG, Ghibaudo, 1992) with coarser-grained basal part, cemented with calcite. This sedimentary episode is related with a change in nature of the source rock in the feeding area.

The overlying conglomerates are either poorly to moderately sorted, medium-grained (8-10 cm) massive (facies mG, Ghibaudo, 1992), amalgamated, or graded occasionally with coarse-grained its basal part (facies gsG). Clast or sand supported beds are also recognised. The above types of bed intervals are associated with thin sand - muddy silt depositional divisions (<1 m locally up to 3 m). They consist of commonly thinning and fining-upward sequences (Walker & Mutti, 1973), including beds with parallel, almost even bounding surfaces (facies A2, Mutti & Ricci Lucchi, 1972). The entire sequence of conglomerate beds presents significant lateral thickness variation due to their channel geometry. The deposition took place in a lower slope to inner fan environment. The transport-depositional mechanism is mostly high-density turbulent "granular flow" or sandy "debris flow" when the sandy matrix content is high (Shanmugam, 2000; Mohrig and Marr, 2003).

Based on heavy mineral associations of the siliciclastic deposits of western Messinia, Faupl et al. (2002), state that the occurrence of coarse material in the structurally upper sequences of the Gavrovo-Tripolis flysch, witnesses a substantial erosion especially of the stratigraphic lower successions of Pindos flysch deposits.

The general feeding direction, based on imbricate structures, is from northeast to southwest. Some rare indications of flow direction towards WNW and N were also measured. The latter suggests flow parallel to the axis of the foreland basin. Kamperis et al. (2005) also report similar flow directions for the sedimentary flysch successions attributed to early Oligocene in the Gavrovo-Tripolis foreland basin, in the area of NW Peloponnese.

At the top of Agia Mavra unit, a mudstone-siltstone sequence overlies the above- mentioned conglomerate beds and it is characterised by significant thickness variations. It consists of couplets of parallel laminated silty division and muddy upper division (lTM facies, Ghibaudo, 1992). The sequence becomes coarser-upward, enclosing thin sandstone and conglomerate lenticular bodies. The depositional intervals are typical thin-bedded turbidites (facies D, Mutti & Ricci Lucchi, 1972), including also dispersed gravels. They are interpreted to be the product of dilute currents that acted in the inner part of the submarine fan.

The lower part of section B is inferred to be of early Oligocene age (NP23 nannofossil biozone) due to the presence of *S. distentus*, *S. predistentus* and *C. abisectus*, while the upper one is of late Oligocene age (NP24 nannofossil biozone) due to the cooccurrence of *S. ciperoensis*, and *S. predistentus* (Fig. 2).

4.3 Agia Varvara unit

This unit consists of two sequences, a thick upper one, made up of conglomerate and a lower one composed of silty mud-sand depositional intervals (Fig. 2, section C). The lower sequence consists of various combinations of mud-silt and mud-sand depositional intervals (facies MT to MS, Ghibaudo, 1992). Thicker muddy divisions are observed in the lower members (facies G, Mutti & Ricci Lucchi, 1972). The uppermost members also include fine-grained, plane-stratified, sand dominated (facies SM, Ghibaudo, 1992) depositional intervals (< 1 m thick). Individual sand beds are discontinuous, with wedging, commonly in sharp contact with the overlying siltstones and mudstones. Bed thickness ranges between 3 and 15 cm (facies E, Mutti & Ricci Lucchi, 1972, Walker, 1978). This type of bed interval is related to interchannel / overbank deposition and local grain flow processes. Thick channel fill deposits (40 m), are enclosed in the uppermost members. They consist of sandstones associated with thin siltstone and mudstone beds, characterised by almost planar, even and parallel bounding surfaces (facies C, Mutti & Ricci Lucchi, 1972). They are classified in thinning and fining-upward sequences. The bed intervals could include complete Ta-e Bouma sequences. The lower sequence facies association indicates deposition by dilute suspensions, including turbidity currents and grain flows in the lower slope to inner part of the submarine fan.

An uneven depositional relief separates the lower sequence and the overlying conglomerates (Fig. 2, upper part of section C). These conglomerates outcrop at Agia Varvara and Agrapidia ridges, creating an impressive steep relief which is the most prominent feature in the studied area (Fig. 1B). The individual beds of conglomerates are grey-coloured, poorly to moderately sorted, with the clast size ranging between 18 cm (lower beds) and 5 cm (upper beds). The clastic elements consist of platy to sub-spherical cobbles of grey sparitic limestones, lydites and rarely of dispersed sandstone clasts, classified in fining - upwards depositional intervals. This type of bed interval is well cemented with calcite and the grading is mainly normal and rarely inverse. They also present clast-supported or coarse-grained sand divisions in their upper part (subfacies gG, Ghibaudo, 1992). Some gravel beds consist of more depositional divisions, where their lower part is characterised by coarser-grained portion (subfacies gsG). Moreover, gravel beds with fining-upward depositional divisions occur, where sand predominates in the upper parts, locally associated with thin discontinuous beds of siltstone.

The Agia Varvara conglomerates commonly represent amalgamated beds, up to 8 m. thick, having an irregular geometry, due to channelling. The transport-depositional mechanism is mostly high-density turbulent “granular flow” or sandy “debris flow”. The deposition of these gravity flow beds took place in the lower slope to inner fan environment. These conglomerates correspond to facies A (Mutti & Ricci Lucchi, 1972), A2 (Walker & Mutti, 1973), A2-3 (Pickering et al. 1986).

Pebble imbrications are also observed indicating flow directions from SSW to NNE, almost parallel to the basin axis. At Foinikounda area, further south of the studied area, Konstantopoulos et al. (2007) and Konstantopoulos (2009) measured the same paleo-flow directions.

The uppermost members of conglomerate sequence outcrop on the eastern flank of Agrapidia ridge.

These conglomerates are loose, poorly sorted, characterised by angular coarse elements, (cobbles and boulders), mainly clast supported. They consist of thick, often amalgamated gravel beds with chaotic internal structure suggesting facies A1-1 (Pickering et al. 1986), formed at the lower slope.

Fine-grained sediments, which consists of thin-bedded silt-mud depositional intervals (facies TM and MT, Ghibaudo, 1992), outcrop eastwards, in the valley at the foot of Roudias and Psili Rachi ridges, referring probably to the uppermost members of Agia Varvara unit (Fig. 1B). This succession becomes thicker further to southeast, near Stavros village, including rare intercalations of thin conglomerate as well as thin, sand bed intervals (Fig. 2, section F), representing inner fan facies G (Mutti & Ricci Lucchi, 1972).

The base of Agia Varvara conglomerates (Fig. 2, section C), dated as early Oligocene age (NP23 biozone), while the uppermost members of this unit dated as late Oligocene age (NP24 biozone) due to occurrence of *S. predistentus* and *S. ciperoensis* (Fig. 2, section F).

4.4 Mali unit

The easternmost Mali unit outcrops on Roudias and Psili Rachi ridges, located on the hanging-wall of Mali thrust fault (Fig. 1B). The lowermost members of this unit consist of blue to grey-coloured, marly mudstones normally underlying a thick sheet-conglomerate that extends for many kilometres (Fig. 1B, Fig. 2, section D). These deposits consist of various ratios of mud/silt - sand depositional intervals (facies MT to MS, Ghibaudo, 1992) with the thicker muddy divisions observed at the base (facies G, Mutti & Ricci Lucchi, 1972). Rare thin conglomerate-lenses are also noticed in this sedimentary succession.

The overlying conglomerates are disorganized, thick-bedded and often amalgamated (Fig. 2, sections D and E). They are also loose, poorly sorted, characterised by angular coarse elements, pebble-cobbles and boulders, usually clast matrix-supported. The bedding surfaces are generally slightly undulate and sharp. The type of bed interval is mainly of A1-1 facies (Pickering et al. 1986). Rare depositional intervals made up of sandstone, less than 1m thick, are locally intercalated in the uppermost conglomerates of Mali unit. These sand bed intervals are discontinuous, characterised by wedging, indicating channel fill deposition (facies C, Mutti & Ricci Lucchi, 1972). Moreover, laminated, marly, silty mud-sand depositional divisions with few conglomerate-lenses (facies MT to MS, Ghibaudo, 1992) are developed on the top of Mali unit, underlying the Pindos thrust (Fig. 2, section E). They show common characters of the classic turbidites (facies D Mutti & Ricci Lucchi, 1972, Walker, 1978).

The Mali unit represents a submarine fan formed in the close proximity of the Pindos thrust by strong paleo-currents. The above-mentioned group of facies is inferred to be lower slope to inner fan association. The macroscopic sedimentary characters indicate that Mali unit represents the most proximal facies association of Gavrovo-Tripolis foreland basin in the studied area.

The nannofossil assemblage, contained in the lower members of Mali unit of the hanging wall of Mali thrust fault, suggests earliest Oligocene age (NP22 biozone) due to the occurrence of *Reticulofenestra umbilica, R. hillae, S. predistentus* and the absence of *S. distentus* and *S. ciperoensis* (Fig. 2, section D). The uppermost members of unit, located at the footwall of the Pindos thrust dated late Oligocene age (NP24 biozone) due to the occurrence of *S. ciperoensis*, *C. abisectus* and the absence of *S. predistentus* and S. distentus. The underlying mudstone beds are inferred to be of early Oligocene age (NP23 biozone) due to the occurrence of *S. predistentus, S. distentus, C. abisectus, R. bisecta, C. floridanus* and *H. recta* (Fig. 2, section E).

5. Foreland evolution

Previous studies suggest that the flysch sedimentation was widespread in the tectonically driven foreland basin, in front of Pindos thrust, during early Oligocene indicating significant subsidence rates in this interval (Fleury, 1980, Clews, 1989, Gonzales-Bonorino, 1996).

The limited presence of samples corresponding to NP21-NP22 biozones (base of Early Oligocene) in the study area indicates restricted flysch sedimentation during this period. The occurrence of the above samples close to the Pindos thrust (Fig. 2, section D) is related to the intensive thrust fault activity and was also recognized in similar parts of the same foreland basin northwards, east of Skolis mountain (Kamperis et al. 2005) and in Aetoloakarnania area (Sotiropoulos et al., 2003). Early Oligocene (NP23) is generally characterized by high eustatic sea levels (Haq et al., 1987; Fig. 2). Submarine fans formed in the foreland basin, which became wider and deeper (Avramidis et al, 2002, Sotiropoulos et al., 2003, Kamberis et al., 2005). A typical example of this interval in the area studied is Plati fan facies associations; deposited in the more distal parts of the basin, particularly in outer fan (Fig. 2, section A).

The onset of late Oligocene (the base of NP24 biozone) is marked by a dramatic sea level fall (Fig. 2). Coarse sediments were accumulated in foreland basin. This significant sea level change is generally portrayed in stratigraphic cross-sections, where conglomerate-successions overlie fine-grained sediments (Fig. 2). However, several parts of stratigraphic cross-sections are not related with the eustatic sea level changes. In particular, the uppermost mudstones of Plati unit deposited in outer fan during NP24 biozone (Fig. 2, section A), the lowermost conglomerates of Agia Mavra unit, deposited in NP23 biozone (Fig. 2, section B), the base of Agia Varvara conglomerates accumulated in NP23 biozone (Fig. 2, section C), as well as the base of Mali conglomerates were probably deposited during NP22-NP23 biozones (Fig. 2, section D).

Therefore, the thrust fault activity should be the primary factor that controls the depositional environment conditions, while the eustatic sea level changes play a secondary role. In addition, it is noteworthy, that the onset of the coarser-grained sediments accumulation took place progressively in the foreland basin, earlier in the more proximal part (during NP22 biozone in section D), later in section C (during NP23 biozone) and eventually during the NP24 biozone on the more distal section A (Fig. 2). This procedure seems to be less dependent of the sea level fluctuations and advocates to the significance of the thrust fault activity. The end of the flysch sedimentation in the Gavrovo-Tripolis foreland basin took place in late Oligocene (NP24 biozone), as the age of younger sediments on the thrust footwalls witnesses (Fig. 2). The same age has been determined northwards, in south Aitoloakarnania (Sotiropoulos et al., 2003, Sotiropoulos et al., 2008).

6. Conclusions

- Thrust faults activity influences the flysch sediments extensively, during Oligocene, resulting in the significant structural thickening of flysch.
- Conglomerate-successions were deposited by debris flows, acting in incised restricted continental slope, while the more fine-grained sequences deposited by limited muddy floods and turbidity currents in the inner channelized fan, near the feeder channel. The sedimentary facies of the conglomerate-successions suggest that the more eastward Mali unit deposited in the close proximity of Pindos thrust, whereas the western ones (Agia Varvara and Agia Mavra units) in a relatively more distal depositional environment.
- The onset of the conglomerate deposition took place progressively in the foreland basin, earlier, at the more proximal part (during NP22 biozone) and later, at the more distal part (during NP24 bio-

zone).

- The depositional conditions are mainly controlled by the thrust fault activity and less by the eustatic sea level fluctuations.

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CORELLATION OF LATE TRIASSIC AND EARLY JURASSIC LOFER-TYPE CARBONATES FROM THE PELOPONNESUS PENINSULA, GREECE

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Abstract

Correlation of the Late Triassic carbonate successions, formed at the passive Pelagonian margin (SE of Dhidymi Mt.) with the Early-Middle Liassic successions of the Gavrovo-Tripolitza zone (SE of Leonidion), in eastern and central Peloponnesus respectively, is attempted. Detailed microfacies analysis revealed that the studied carbonate formations were deposited in analogous restricted inner-platform environments (lagoon-peritidal domain) and are composed of meter-scale, shallowing-upward, mostly incomplete peritidal cycles. The top of the supratidal and/ or shallow subtidal deposits are often affected by meteoric diagenesis tracing sea-level lowering and periodic emersions episodes. The well-developed pedogenic features observed in the Early Jurassic platform carbonates indicate long-lasting subaerial exposure intervals and semi-arid to arid climate. Instead, the Late Triassic strata preserve vadose diagenetic indices which point to shorter exposure events, weaker meteoric alteration and slightly wetter climatic conditions. The detected sedimentological features suggest the occurrence of wide lagoonal-peritidal depositional systems during Late Triassic and Early Jurassic, eastern and western of the Pindos basin, respectively. The basic facies pattern and the meter-scale cyclicity show many analogies with the Lofer cycles of the Alpine Triassic, supporting that in the Hellenides the Dachstein-type platform systems evolved till Early-Middle Liassic (Gavrovo-Tripolitza zone).

Key words: *peritidal facies, Lofer cycles, subaerial exposure, Peloponnessus, Greece.*

1. Introduction

Lofer cyclothems—i.e., distinct meter-sized lagoonal-peritidal cycles, were first recognized and described in the Norian-Rhaetian Dachstein Limestone (Austria) by Sander (1936). According to Fischer (1964) the typical Lofer cyclothems is a deepening-up, asymmetric sequence and each cycle is composed of : (i) a disconformity at the base (d); (ii) a basal argillaceous member/ "palaeosol" (member A); (iii) an intertidal laminated carbonate member (member B: loferites); and (iv) a subtidal massive fossiliferous carbonate member (member C). Subsequent studies modified as symmetric the ideal basic stacking pattern of Lofer cyclothems (Haas, 1982, 1991) or reinterpreted them as regressive, shallowing-upward cycles (e.g. Goldhammer et al., 1990). Dachstein-type platform carbonates have been also recognized in different areas along the Late Triassic Tethys (e.g. Eastern Alps, Southern Alps, Dinarides, Hellenides) and they are well-studied by several authors (e.g. Fis-

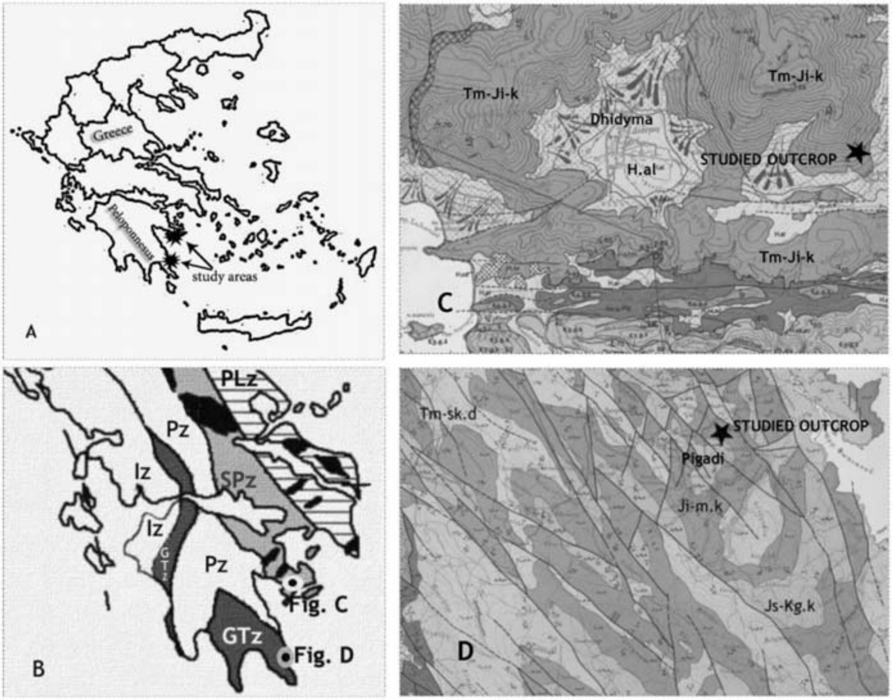

Fig. 1: (A) Geographical location of the studied areas (✷). (B) Map of the central-southern Greece showing the studied areas (⊙) and their setting within the geotectonic zone framework of the Hellenides. (C) Dhidymi section; geological map showing the study area and its location (★). "Spetses-Spetsopoula Sheet" 1:50.000 (Gaitanakis et al., 2007). (D) Fokianos section; geological map showing the study area and its location (★). "Leonidion Sheet" 1:50.000 (Dimadis et al., 1978). Key: GTz=Gavrovo-Tripolitza zone; PLz=Pelagonian zone; SPz=Subpelagonian zone; Pz=Pindos zone; Iz=Ionian zone; Tm-Ji-k=M. Triassic-Lias; H.al=Alluvial deposits; Tm.sk.d=M.-U. Triassic; Ji-m.k=E.-M. Jurassic; Js-Kg.k=Upper Jurassic-L. Cretaceous.

cher, 1964; Haas, 1994, 2004; Haas and Balog, 1995; Enos and Samankassou, 1998; Pomoni-Papaioannou et al., 1986, Pomoni-Papaioannou, 2008). However, Lofer cycles have been observed in platform strata of different age from that of the Dachstein Limestone (Dozet, 1993). Autocyclic (e.g. Satterley, 1996), tectonic (e.g. Satterley, 1996; Bosence et al., 2009) or allocyclic (e.g. Fischer, 1964; Haas, 2004) mechanisms have been proposed to explain the formation of the Lofer cycles.

This paper aims to report the sedimentological and diagenetical features of the analyzed Late Triassic (Dhidymi succession, "Pantokrator facies"-Pelagonian carbonate platform, Argolis peninsula) and Early Jurassic (Pigadi-Fokianos succession, Gavrovo-Tripolitza zone, SE of Leonidion) shallow-water platform carbonates and to compare the loferitic facies detected.

2. Geological setting

The Pantokrator facies-Pelagonian carbonate platform: The investigated Late Triassic shallow-water carbonate sediments (Fig. 1, 2) cropping out in the area of Argolis peninsula are part of the Late Triassic–Early Jurassic extensive and thick neritic carbonate series ("Pantokrator facies") that formed at the passive Pelagonian continental margin.

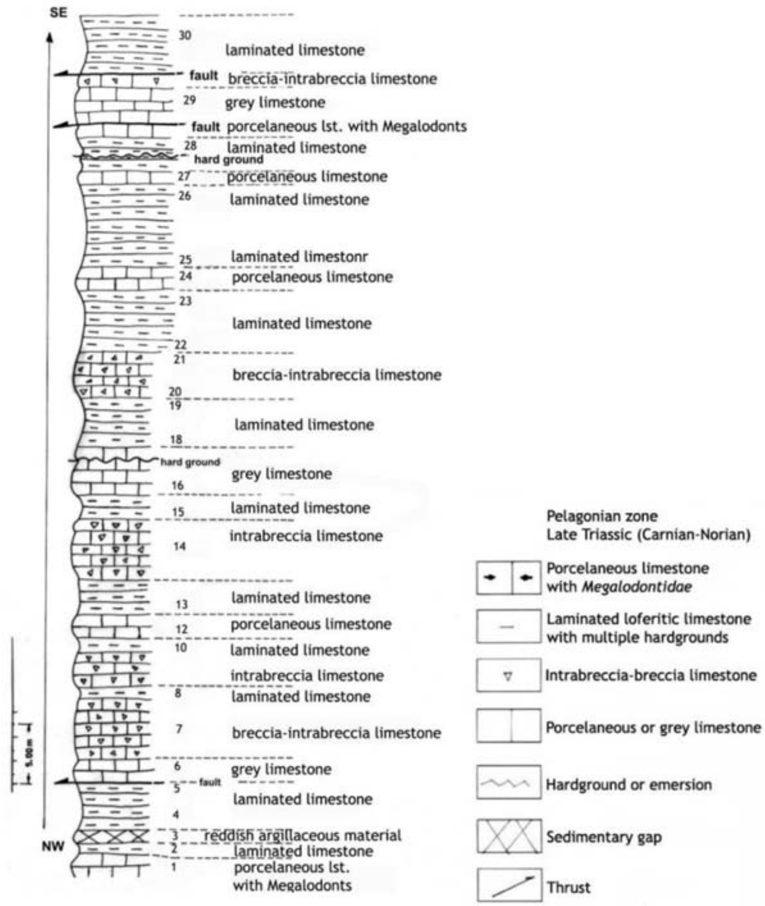

Fig. 2: Dhidymi section.

The Argolis peninsula belongs to the Pelagonian-Subpelagonian domain of the Hellenide nappe and its geological structure have been studied in detail by several authors (e.g. Bachmann and Risch, 1979; Vrielynck, 1981-1982; Baumgartner, 1985; Photiades, 1986; Gaitanakis and Photiades, 1991, 1993; Photiades and Skourtsis-Coroneou, 1994; Bortolotti et al., 2003; Gaitanakis et al., 2007). The Pantokrator carbonate formation covers a great part of the Argolis Peninsula. The Dhidymi Mt. is also built up of these facies (Gaitanakis et al., 2007). The Late Triassic to Liassic shallow-water facies are dominant in the Iria area and in the Dhidymi Mt. region of SW Argolis (Schäfer and Senowbari-Daryan, 1982; Vartis-Matarangas and Matarangas, 1991). In the Dhidymi area, Late Triassic Lofer cycles have been studied by Pomoni-Papaioannou and Photiades (2007) and Pomoni-Papaioannou (2008).

The Gavrovo-Tripolitza zone (GTz): The studied stratigraphic section (Fig. 1, 3) of Early Jurassic age is exposed SE of Leonidion town. It forms part of the thick neritic Triassic-Jurassic carbonate platform succession that appear along the eastern coasts of Peloponnesus and geologically are included in the GTz of the Hellenide nappe. The Gavrovo-Tripolitza platform developed early — in the Late Triassic-Liassic and persisted throughout the rest of the Mesozoic — within the passive continental margin of the Southern Tethys. The GTz consists of thick neritic carbonate successions

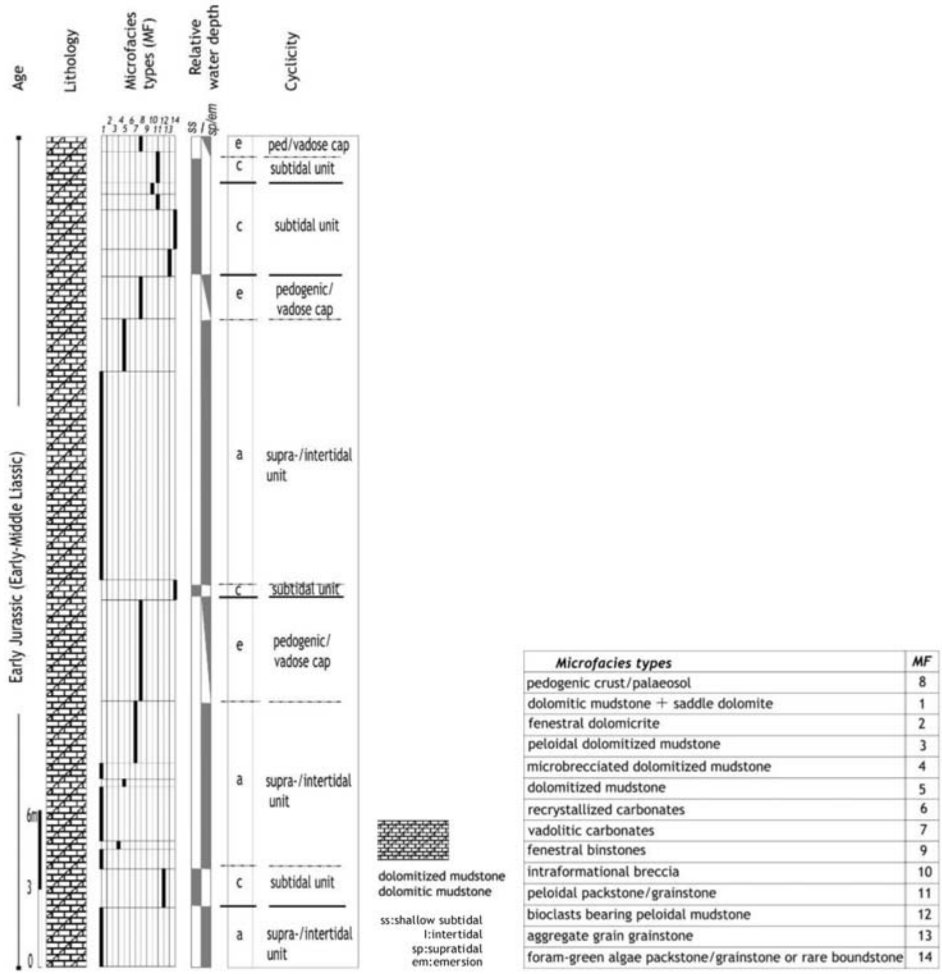

Fig. 3: Fokianos section.

ranging in age from Late Triassic to Late Eocene (Thiebault 1973; Fleury 1980; Zambetakis-Lekkas and Alexopoulos 2007). The Late Palaeozoic-Triassic volcano-sedimentary sequence of "Tyros Beds" (Ktenas, 1924) underlain the GTz in Peloponnesus and considered to be its original basement (Thiebault, 1982). Shallow-water facies of cyclic pattern are observed in the Late Triassic and Liassic deposits of GTz (Kalpakis and Lekkas, 1982; Pomoni-Papaioannou et al., 2005; Kati et al., 2007; Pomoni-Papaioannou and Kostopoulou, 2008).

3. Results of sedimentological analysis

3.1 Carbonate microfacies and depositional environments

Dhidymi section — The investigated Dhidymi section (5.5 Km E of Dhidyma) is approximately 70m in thickness and shows a succession of Late Triassic neritic carbonates that are part of the thick Late Triassic–Early Jurassic "Pantokrator carbonate facies" formed at the passive Pelagonian con-

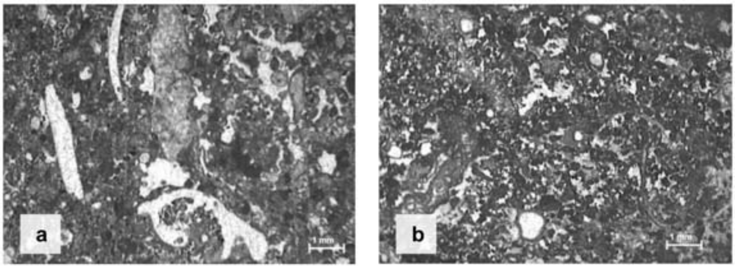

Fig. 4: Shallow subtidal/lagoonal environment - a. Packstone with fragments of megalodonts, benthic forams and calcareous algae (Dhidymi). b. Foram-green algae pack/grainstone with dasycladacean algae, thaumatoporellids and small benthic foraminifers (Fokianos).

tinental margin. The following sedimentological features characterize the carbonate sediments exposed in the Dhidymi section:

Subtidal facies — The shallow subtidal/back-reef lagoon facies (Fig. 4a) are composed of prevailing wackestones, packstones and packstones/grainstones with an abundant and diverse marine fauna (Megalodontids, Aulotortinae, Dacycladaceans). The non-skeletal material is mainly represented by peloids.

Inter-supratidal facies — The inter-supratidal facies generally consist of laminated dolomitic and fenestral dolomitic mudstones. They are characterized by well-developed laminations, probably of microbial origin, small fenestrae with geopetal filling and a variety of desiccation structures (Fig. 5a). Bird's eyes and desiccation cracks indicate a tidal/supratidal setting.

Subaerial exposure-related facies — The Late Triassic neritic carbonates contain emergence-related diagenetic features (e.g. glaebules, laminar dolocrete crusts, filled small-sized palaeokarstic cavities, geopetal filling) (Fig. 6a, b), which reflect emersion events of limited duration and weak subsequent early meteoric modification under a slightly wetter climate regime (Esteban and Klappa, 1983; Wright and Tucker, 1991; Jimenez de Cisneros et al., 1993).

Fokianos section — The studied Fokianos section (13 Km SE of Leonidion) is ca. 30m thick and shows a succession of Early-Middle Liassic neritic carbonate sediments that forms part of the Triassic-Jurassic thick platform carbonates which crop out along the eastern coasts of Peloponnesus and geotectonically belongs to the Gavrovo-Tripolitza zone. The carbonate sediments exposed in the Fokianos section are characterized by the following sedimentological features:

Subtidal facies — The subtidal facies (Fig. 4b) are mostly composed of fossiliferous packstones/grainstones. The most important biogenic components are Dacycladaceans (*Palaeodasycladus mediterraneus)* and Thaumatoporellids. A few shell-fragments of molluscan debris (megalodonts, gastropods) and not abundant small benthic foraminifera (Valvulinidae, Ammodiscidae, Textulariidae*)* are also found. Peloids, aggregate grains, cortoids and small intraclasts are included in the observed non-skeletal particles.

Inter-supratidal facies — The peritidal sediments (Fig. 5b) comprise mainly unfossiliferous dolomitized mudstones and rare fenestral bindstones. Neomorphism commonly has affected the original texture (supratidal settings). The occurrence of saddle dolomite crystals, interpreted as pseudomorphs after evaporite minerals, imply hypersaline conditions. The presence of authigenic idiomorphic quartz crystals and the faunal absence suggest elevated salinities, as well (Flügel, 1982).

Subaerial exposure-related facies — The well-developed diagenetic in origin facies preserved in these Early Jurasssic peritidal strata are mainly represented by laminated, fenestral and massive ley-

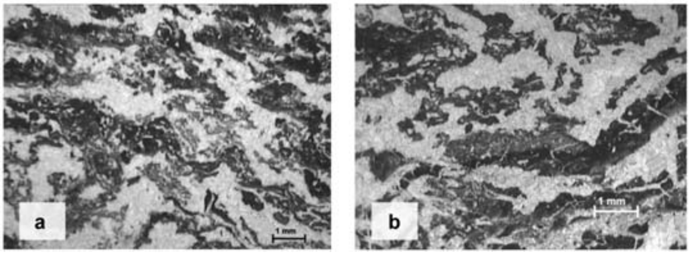

Fig. 5: Inter/supratidal environment – a. Fenestral laminated mudstone desiccated and fragmented (Dhidymi). b. Fenestral laminated mudstone desiccated and fragmented (Fokianos).

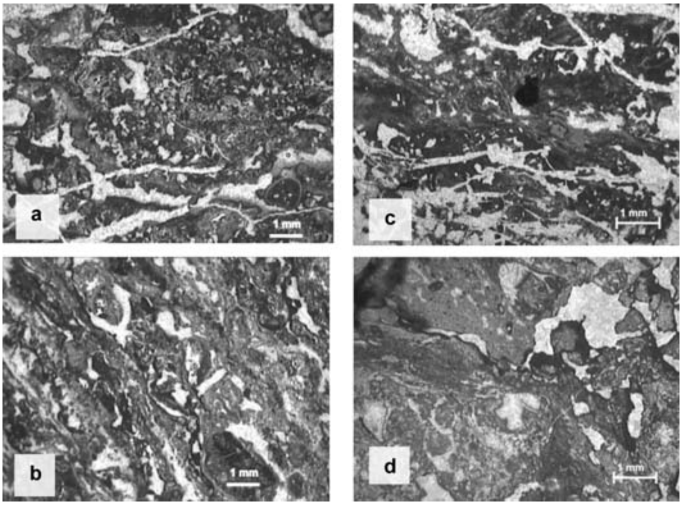

Fig. 6: Vadose environment, subaerial exposure – a. Laminar dolocrete with spar-filled interconnecting elongated cavities (Dhidymi). b. Glaebules. Spar-filled voids and cracks (Dhidymi). c. Microlaminated black micritic layers of pedogenic origin. Spar-filled interconnecting elongated cavities (Fokianos). d. Glaebules. Spar-filled voids and cracks (Fokianos).

ers which display several diagenetic textures (e.g. microlaminated black micritic layers, root structures, glaebules, circum-granular cracking) (Fig. 6c, d) that considered to be indicative of former plant-roots and of intense meteoric influence. They testify long-lasting emersion episodes and provide indices of pedogenesis and palaeosol formation under semi-arid to arid climate (Esteban and Klappa, 1983; Wright and Tucker, 1991; Jimenez de Cisneros et al., 1993).

In summary, the recognized facies associations of both selected outcrop sections include shallow subtidal-lagoonal and inter-supratidal facies. The depositional environment corresponds to the inner restricted platform–tidal flat system (Fig. 7). Several subaerial exposure-related evidencies pointing to emersion events and related to climate are preserved in both successions.

3.2 Microfacies correlation

By the comparison of the subtidal facies, a differentiation consisting primarily in the skeletal con-

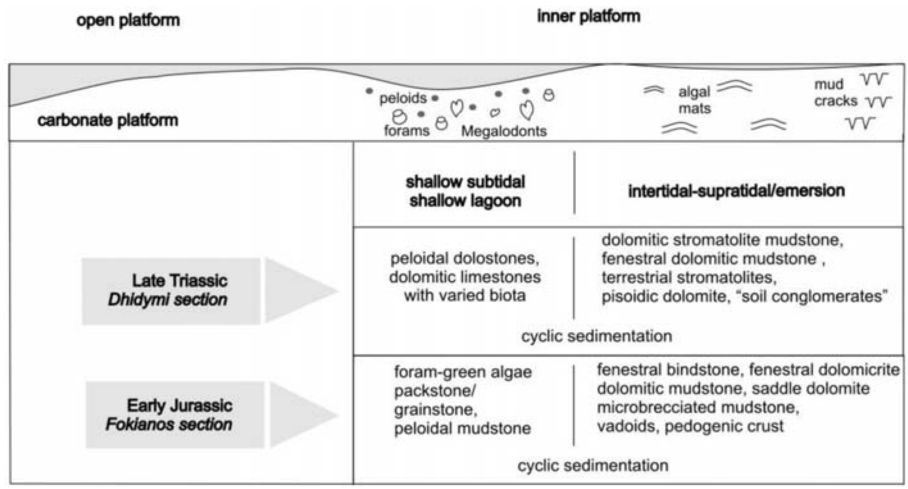

Fig. 7: Depositional settings of the Dhidymi and Fokianos sections.

tribution has been dedected. Late Triassic deposits are characterized by a rather good and rich amount of macro- and microfossil skeletal grains, reflecting a warm, lagoonal and productive environment with low water energy. Regarding to the Early Jurasssic facies, the biogenic contribution is less abundant and suggestive of more restricted and protected very shallow water conditions (transitional from a restricted lagoonal to a tidal-flat domain).

In both analyzed areas, a relative abundance of the inter-supratidal facies in respect to the subtidal ones, is noticed. However, the prevalence of supratidal deposits is more pronounced in the Early Jurasssic carbonate succession.

Early palaeoexposure surfaces and pedogenetic levels (palaeosols) are detected in both carbonate successions. The well-developed pedogenic features observed in the Early Jurassic platform carbonates indicate long-lasting subaerial exposure intervals and semi-arid to arid climate. Instead, the Late Triassic strata preserve vadose diagenetic indices which point to shorter exposure events, weaker meteoric alteration and slightly wetter climatic conditions (Pomoni-Papaioannou, 2009).

3.3 Vertical facies distribution and Lofer-type development

Considering the vertical evolution of various microfacies types/ facies associations defined, their arrangement reflects: (i) a general regressive trend from shallow subtidal-lagoonal to tidal-flat and subaerial exposure conditions and (ii) a general development of small-scaled peritidal cycles with a similar shallowing-upward trend.

The investigated platform carbonate successions, in both localities, consist of lagoonal-peritidal cycles. The basic facies pattern and the meter-scale cyclicity detected show close similarity with the Alpine Dachstein Lofer cycles. The indentified cyclothems are mostly incomplete, show a general regressive upward-shallowing trend and their topmost parts always preserve subaerial exposure evidences. Moreover, pedogenetic features suggesting sea-level lowering and periodic emersions episodes (Strasser, 1991) often overprint subtidal deposits. The subtidal carbonate facies with varied marine biota (e.g. Megalodont dolostones, foram-green algae grainstones) correspond to Member C of the typical Dachstein Lofer cycle. The recognized tidal-flat facies (e.g. loferites with fenestral structure) and the diagenetic-pedogenetic in origin layers (e.g. loferitic breccias, laminar dolocretes) correspond to the Member B and Member A of the classic Lofer cycle, respectively. However, the affected by intense diagenesis studied Early Jurassic peritidal carbonate platform cycles differs from the real Dachstein Lofer cyclothems showing a general regressive shallowing-upward asymmetric pattern. Instead, in the Dhidymi area, some of the cycles appear to be symmetric and the subtidal facies mark a clear deepening–upward trend. The commonly developed on tops of the peritidal cycles and/or directly superimposed upon the subtidal deposits pedogenic surfaces, support an allocyclic/eustatic control on their formation (Strasser, 1991; Haas et al., 2007, 2009). However, the contribution of autocyclic processes cannot be excluded.

The recognized sedimentological features suggest the occurrence of vast, Dachstein-type carbonate platform depositional systems, during the Late Triassic and Early Jurassic, eastern and western of the Pindos basin, respectively. Furthermore, the detected Early-Middle Liassic Lofer cycles support that in the Hellenides the Dachstein-type platform systems evolved till Early-Middle Liassic (GTz), under similar conditions. Additionally, the Liassic cyclic peritidal sediments of the Gavrovo-Tripolitza zone are comparable with similar coeval peritidal cycles distinguisted in the western peri-Mediterranean area (e.g. Bosence et al., 2000) denoting the development of analogous carbonate platform depositional systems within the western Tethys, during the Early Jurassic times.

4. Concluding remarks

Sedimentological analysis of the Late Triassic carbonates formed at the passive Pelagonian margin (Dhidymi) and of the Early-Middle Liassic successions of the Gavrovo-Tripolitza zone (SE of Leonidion) reveals:

- The recognized facies of both selected outcrop sections can be organized into three major groups/associations; shallow subtidal-lagoonal, peritidal (inter/supratidal) and subaerial exposure/pedogenic deposits.
- The deposition of the studied carbonate formations in analogous warm, quiet, very shallow marine environment (restricted, protected lagoon-tidal-flat settings) suggesting the occurrence of extensive, lagoonal-peritidal environments, during the Late Triassic and Early Jurassic, eastern and western of the Pindos basin, respectively.
- Sediments were repeatedly subaerially exposed and affected by meteoric diagenesis. They were completely or partially dolomitized. Well-developed subaerial exposure/emersion surfaces that dislpay strong evidence of early vadose diagenesis and terrestrial conditions have been observed.
- The pedogenic features detected in the Early Jurassic platform carbonates indicate long-lasting subaerial exposure intervals and semi-arid to arid climate. Instead, the Late Triassic strata preserve vadose diagenetic indices, which reveal shorter emersion episodes, minor meteoric influence and less arid climatic conditions.
- The vertical distribution of the defined microfacies associations and of the subaerial exposure related features show a characteristic repetitive pattern and organization in small-scaled cycles/units. The basic facies pattern and the meter-scale cyclicity, detected in both examinated localities, resemble closely the Alpine Dachstein Lofer cycles, supporting that in the Hellenides the Dachstein-type platform systems evolved till Early-Middle Liassic (Gavrovo-Tripolitza zone).

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ASSESSMENT OF THE QUANTITY OF THE MATERIAL TRANSPORTED DOWNSTREAM OF SPERCHIOS RIVER, CENTRAL GREECE

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Abstract

It is well known that streams are an integral part of a natural ecosystem. The Sperchios valley is crossed by a large number of seasonal or permanent flow streams and rivers, out of which the Sperchios river can be distinguished, not only for its length but also for the area surrounded by the boundaries of its drainage system. The present study is aimed to estimate the quantity of the transported material at the mouth of Sperchios River. For this purpose we applied the Revised Universal Soil Loss Equation (RUSLE) model to the Sperchios drainage network in a Geographical Information Systems (GIS) environment. We estimated that approximately 2,308,000 tons per year are flooded mainly down the Sperchios drainage system, supporting the Malian delta.

Key Words: *Sperchios River, soil loss, RUSLE, GIS.*

1. Introduction

It is well known that soil erosion, usually due to rainwater runoff, is a process by which the soil epidermis of the soil surface is washed away from the land. Soil erosion is a worldwide environmental problem that affects not only the natural environment, leading to sediment deposition, soil degradation, water quality degradation etc, but human activities as well, such as agriculture productivity regression. Soil loss can be one of the most important and still unknown natural processes leading to serious natural hazards, such as floods.

Research on soil loss has started quit early (in the 1930s), mainly emphasizing on its impact on agricultural productivity. During 1940 and 1956, USA research scientists began to develop a quantitative method for estimating soil loss. Several factors were introduced to an early soil loss equation, in which slope and agricultural practice were primarily considered. Based on the data collected for almost a decade at the National Runoff and Soil Loss Data Center at Purdue University, as well as previous studies, Wischmeier & Smith (Wischmeier and Smith, 1978) developed the Universal Soil Loss Equation (USLE), a widely accepted mathematical model that estimates the average annual soil loss of a study area. Additional research, experiments and data collection in the years after (Renard K.G et al., 1997) led to the development of the Revised Universal Soil Loss Equation (RUSLE), an improved mathematical model, that takes into consideration not only morphological factors but conservation practices as well. It has been used since in developing conservation planning and land-use decision making.

2. Study Area

The study area of this paper (Fig. 1) is located in the prefecture of Fthiotis, Central Greece, covering a region of approximately 1,875 km^2, out of which almost 88%, that is 1,645 km^2, correspond to the watershed of Sperchios River basin, while the rest of the area belongs to the nearby watersheds of several other minor rivers.

The Sperchios River basin can be outlined by the Tymfistos, Vardoussia, Iti and Kallidromo mountains. It has an elongated shape along the E-W direction and is open to the sea on the east side. It is covered both by alpine and post-alpine formations, the former outcropping of the basin and usually forming the nearby mountains while the latter covering the flattened areas at the centre of the basin. Alpine formations consist primarily of limestones and dolomites of Lower Triassic – Upper Jurassic, Cretaceous or even Eocene age, schists of Jurassic age, ophiolites, flysch of Upper Cretaceous or Eocene age, sandstones and conglomerates of Cretaceous age etc. Post-alpine sediments consist of sandstones, conglomerates, clay and mudstones of Eocene age, marls of Pleiocene age, breccia and alluvial deposits. The presence of bedrock lithology is quit extensive, affecting not only the morphology of the area or the size of individual watersheds, but also the amount of sediment that can be transported throughout the years.

The Sperchios River is considered to be one of the longest rivers in Greece, having a length of approximately 85 km, of which 80 km alone correspond to the central axis of the stream. The river springs from the Panaitoliko Mountain (Evritania prefecture), flows northeast of the Vardousia and Tymfistos mountains, crosses the large plain south of Lamia and flows into the Malian Gulf. It is also considered to have one of the most extensive delta formations, not only in Greece, but in the Eastern Mediterranean as well. Indeed, its delta comprises a region of approximately 196 km^2, which can give an idea of the amount of sediment that has been transported up to the river mouth.

Hundreds of major or minor rivers contribute to each other creating the large drainage network of Sperchios. Detailed drainage network studies have revealed that drainage is highly organised in the basin and primarily controlled by neo-tectonic movements. These recent movements seem to have also affected the morphology of the region. The area is characterised by steep morphological slopes, usually varying from 20% to 40% and sometimes reaching almost up to 70% especially at the borders of the Sperchios watershed, while the regions near the Sperchios River centerline remain almost flat. The average slope of the area is estimated to be 33%.

Agriculture plays an important role in the economic development of the study area. Almost 35% of the study area is dedicated to cultivations, another 35% to state, municipal or private pasture, while only 23% is covered by forestry. A small portion (5%) corresponds to wetlands and swamps. The remaining 2% is occupied by human infrastructure, that is settlement, road network etc.

3. Data Used

In order to carry out this work a primary database was created via digitising the cartographic background (topography, hydrographic network, geology) of the topographic maps "Amfikleia", "Amfissa", "Domokos", "Efxinoupolis", "Fourna", "Karpenision", "Lamia", "Leontarion", "Lidorikion", "Spercheias" and "Stylis"of the H.M.G.S. at a scale of 1:50.000, as well as of the homonymous geological maps of I.G.M.E., also at a scale of 1:50.000. Data concerning land cover information were extracted from the Corine Land Cover project (CLC2000) carried out by the European Environmental Agency (European Topic Centre on Land and Spatial Information, 2000). Data regarding

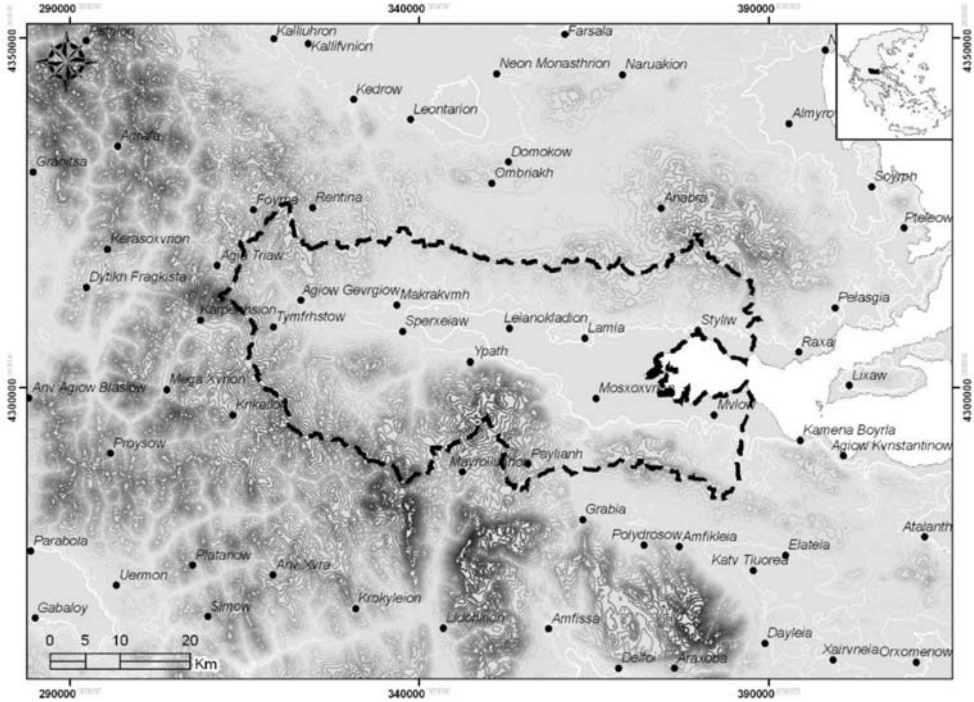

Fig. 1: Study area.

rainfall amounts were collected from the Hellenic National Meteorological Service. All data were transformed, edited and inserted in a spatial database. Enriched by field investigations as well as literature, this primitive database allowed us to analyse the factors that control soil loss.

The use of Geographic Information Systems (GIS), applied in this work, provides us with an important geographic database that can be used either directly for estimations regarding the present state or under assessment models used for predictions of the future state and estimations of possible conditions.

4. Methodology – Data Analysis

In order to estimate the soil loss in the basin, the Revised Universal Soil Loss Equation (RUSLE) model was used in a Geographic Information System environment. The RUSLE equation computes the average annual erosion by using a functional relationship of several other factors as:

$$A = R * K * LS * C * P \qquad (1)$$

where: (A) is the computed average soil loss per unit of area. Usually, A is expressed in tons/acre/year.

(R) is the rainfall - runoff erosivity factor, expresswed in MJ*mm / ha*h,

(K) is the soil erodibility factor (in t*h / MJ*mm),

(L) is the slope length factor,

(S) is the slope steepness factor,

(C) is the cover and management factor and

(P) is the support practice factor.

Factor R: It is the average annual summation values in a normal year's rainfall. In literature, the only equation relating the R factor with the mean annual precipitation, adapted to the greek climate characteristics, is provided by Flambouris (Flambouris, 2008) and has the following form:

$$R = \alpha * Pi \qquad (2),$$

where: (a) is precipitation coefficient and
(Pi) is the mean annual precipitation, measured in mm.

In his work, Flambouris also provides the value of the coefficient a, corresponding to the study area, which, according to him, should be equal to 0.7 (a = 0.7), depending not only on the meteorologic, but on the morphologic characteristics of the Lamia weather station. We disagree, since the Lamia weather station does not reflect the meteorological characteristics of the whole of the study area, especially the highlands, whose mean annual precipitation is expected to be much higher. Therefore we apply the value of 1.3 (a = 1.3) to our estimations, which we consider the most suitable for the study area, based on research conducted in Greece (Zarris et al., 2001), as well as in Italy (Van der Knijff et al., 2000). The equation (2) has the following form now:

$$R = 1.3 * Pi \qquad (2),$$

Factor K: Is soil erodibility factor which represents susceptibility of soil to erosion and the rate of runoff, taking into account the % portion of silt, sand or organic matter, soil texture, soil structure and permeability (Wischmeier et al., 1971). Since the K factor can easily be related to geological formations' susceptibility to erosion (Koutsoyiannis and Tarla, 1987; Lykoudi and Zarris, 2004), each rock formation of the study area was given a K factor value, based not only on the rock type, but on the age, the geotectonic unit etc. The following figure represents the classification of rock formations based on the proposed by the bibliography K values.

Factors L and S: Slope length is the distance from the origin of overland flow along its flow path to the location of either concentrated flow or deposition. Fortunately, computed soil loss values are not especially sensitive to slope length and differences of ±10% in slope length are not important, especially on flat landscapes. On the other hand, slope steepness is the ratio of soil loss from the field gradient to that from a 9 percent slope under otherwise identical conditions. Soil loss increases more rapidly due to slope steepness than due to slope length.

Table 1. K factor values.

Geological formations	*K factor value*
ophiolites	0.0005
limestones/dolomites	0.00055 to 0.00085
conglomerates	0.003
alluvia	0.0035
sandstone	0.015
flysh	0.02 to 0.03
schist	0.025
breccia	0.045

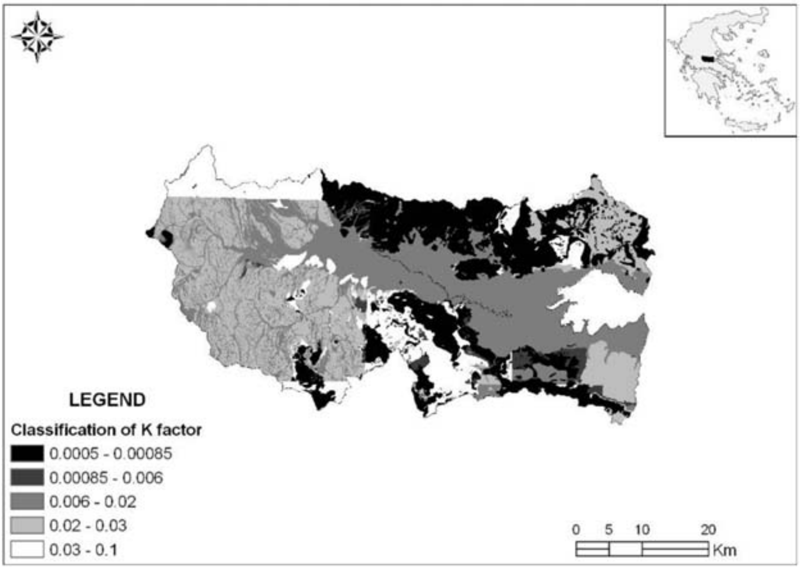

Fig. 2: Classification of K factor values.

Among these factors, the slope length factor (L) is the most difficult to compute. This is why it is widely estimated together with the slope steepness factor (S) through the Digital Elevation Model (DEM) of the study area. The combined result of L*S reflects the morphology of the study area. For this purpose several methods have been developed (Moore et al., 1986; Moore et al., 1993; McCool et al., 1997). For the aim of this paper the method developed by Mitasova and Mitas (2001) is adopted. The combined LS factor can then be calculated via the following equation:

$$LS = (m+1) * [(As / 22.13)\ m] * [(\sin\beta / 0.09)\ n] \quad (3)$$

where: LS is the computed L*S product,

As is the upslope contributing area per unit width of contour,

β is the slope angle in degrees,

m is an exponent varying from 0.4 to 0.6 and

n is an exponent varying from 1.2 to 1.3.

The upslope contributing area can be calculated in an ArcInfo environment using the "Flow Accumulation" routine multiplied by the squared cell size and divided by the cell size, while the slope angle can be calculated using the "Slope" algorithm and the "Atan" function in ArcInfo (that is, $\beta = \text{Atan}(\text{Tan}\ \beta) = \text{Atan}\ [(\text{Slope grid in } \%) / 100]$). Computing the equation (3) led to the estimation of LS values for the entire study area, as follows:

Factor C: It reflects the effect of cropping and management practices on soil erosion rates. Since the C factor represents the effect of plants, soil cover, soil biomass and soil disturbing activities to erosion, soil loss ratios vary with time as canopy, ground cover, roughness, soil biomass and consolidation change. On the other hand, each land cover type can correspond to an estimated C value, thus the following figure pictures the C-factor values for the different land use categories.

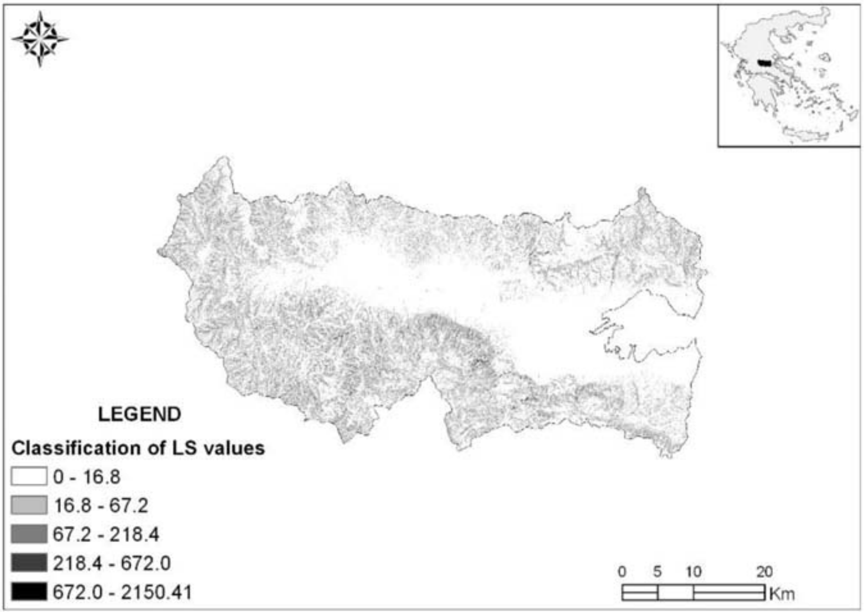

Fig. 3: Classification of LS factor values.

Table 2. C factor values.

Corine Type	*C factor value*	*Corine Type*	*C factor value*	*Corine Type*	*C factor value*
111	0.001	**221**	0.2	**322**	0.2
112	0.001	**223**	0.1	**323**	0.03
121	0.01	**231**	0.1	**324**	0.02
124	0.003	**242**	0.18	**331**	0.06
131	0.36	**243**	0.1	**332**	0.0001
133	0.36	**311**	0.001	**333**	0.001
211	0.3	**312**	0.001	**421**	0.18
212	0.15	**313**	0.001	**511**	0.00001
213	0.001	**321**	0.3		

Factor P: It reflects the impact of support practices on the average annual erosion rate. As with the other factors, the P-factor differentiates between cropland and rangeland or permanent pasture.

5. Results

By processing the gathered data according to the previously described model the following map was derived. It corresponds to the estimation of the annual soil loss, based on the rainfall, soil, to-

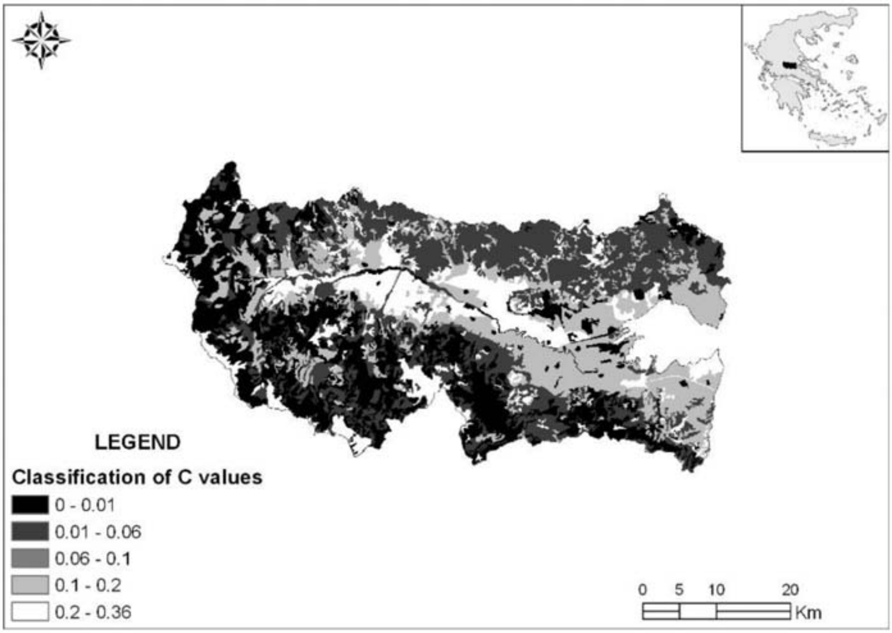

Fig. 4: Classification of C factor values.

pography, cover and management erodibility, as well as the support practice factor for the study area. According to the RUSLE model, the annual soil loss of the study area is estimated at approximately 2,308,000 tones per year, the vast majority of which corresponds to bedrock formations of the mountainous regions of the Sperchios watershed.

This result approaches soil loss older estimations for the same study area, such as the results announced by the Aristotle University of Thessaloniki (approximately 2,500,000 tones per year), while it differentiates from others, such as those announced by Poulos and Chronis (1997), who estimated the soil loss at approximately 1,500,000 tones per year. The differences between results, obtained from the application of empirical models like the present one, are due to different assumptions, estimations of the research variables and approach methods.

The annual soil loss rate of the study area is estimated at 11.5 tones per year. This rate is quite low, compared with soil loss rates for other regions, such as Acheloos basin, where the mean A was estimates at 47.26 t/ha, or Cephalonia island (Zarris et al., 2001), where the mean A was estimated at 47.26 t/ha (Lykoudi and Zarris, 2004). This is due to the fact that the majority of the study region corresponds to flat areas, having a LS factor of approximately zero.

It should be noted that the accuracy of the results, derived from the application of empirical models, such as in this work, depends on the quantification of the parameters involved and will never be absolute (Brazier et al., 2000). But, even though the quantitative estimatations are questionable, the qualitative results regarding the spatial distribution of erosion risk between different areas of interest value the most (Zarris et al., 2001; Saavedra, 2005). Therefore, the application of this model cannot replace other methods of collecting data or conducting experiments, though it can increase their effectiveness.

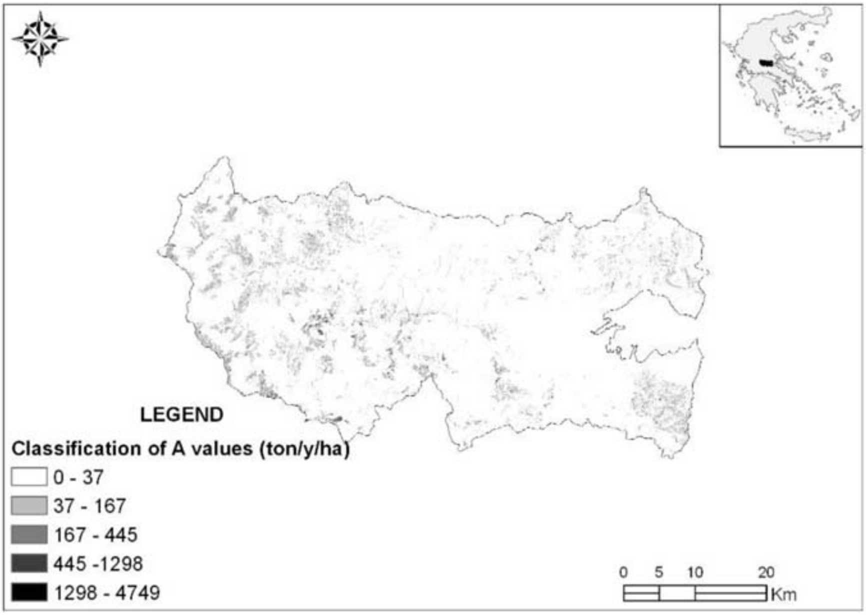

Fig. 5: Classification of A factor values.

6. Conclusions

The processes of weathering, erosion and deposition of sediment in river basins can vary, depending on a variety of biophysical and human factors. The intensity of these processes differentiates also not only in space, but in time as well, which makes the study conducted difficult and the results even more uncertain.

The importance of soil erosion assessment is great and associated with:

- a range of environmental impacts, including loss of organic matter and soil nutrients, reducing crop productivity etc,
- the management of natural resources and the approach to sustainable agriculture,
- a better understanding and assessment of erosion processes, compared with the current situation, as well as any changes in the present conditions, in a watershed or in a broader regional scale.

This paper shows that the combination of modern tools, such as Geographic Information Systems (GIS), methods and prediction models, gives us spatial and quantitative information of great importance and usefulness, if used properly. The spatial and quantitative assessment of soil loss gives us information which can stand as a guide, in order to take appropriate measures targeting to the control of the problems arising and to the rational environmental management of natural resources. The method may find practical use and application of local, regional or national level:

- the environmental impact assessment (e.g. desertification and climate change),
- the identification of new data involved in the effect of changes in the natural environment (e.g. destruction of plant cover due to fire),
- the risk assessment associated with economic and social impacts caused by soil erosion,
- the rational design of infrastructure and technical measures, which can be taken to avoid negative situations and to protect areas,
- and in general, spatial and environmental planning and management of land and natural resources.

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NEW SIRENIAN FINDINGS FROM CRETE ISLAND

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Abstract

In the last five years, the discovery of several new localities of fossil Sirenians found in the Neogene sediments of Crete has increased drastically the number of sirenian localities on the island. Some of the most important findings consist of almost complete post cranial skeletons (localities of Stilos, Panassos near Zaros and Tripitos in Agia Fotia near Siteia). Furthermore, the locality Kotsiana near Chania, where in 1973 Symeonidis and Schultz reported the first sirenian findings from Crete, was revisited and several new sites were recorded. The most recent findings not thoroughly studied yet, are situated in three new fossiliferous sites near Panassos village (Ampelouzos, Panasos 2 and Kefala), and in Afrata at Rodopou peninsula. The preliminary morphological and metrical study of the remains from Panassos and Tripitos, and their comparison with other findings from Crete, as well as with Sirenian material from European localities, has shown that all studied individuals belong to the species Metaxytherium cf. medium (Desmarest 1822). The age of the studied Cretan Sirenian material has been determined as Late Miocene (Tortonian) and the presence of Sirenia in Crete indicates the prevalence of shallow and warm marine environments in coastal areas, rich in sea weeds.

Key words: *Sirenia, Metaxytherium medium, marine mammals, Late Miocene, Crete.*

1. Introduction

During the Neogene, Sirenians were abundant shallow water dwellers of the Tethys Ocean. Particularly the genus *Metaxytherium* (Dugongidae) is considered a very common Dugongid representative found in Miocene or Pliocene sediments across Europe and the Mediterranean basin. Several significant fossiliferous sites with Miocene and Pliocene Sirenian findings in the Mediterranean basin have been documented in Italy, France, Catalonia, Majorca, Hungary, Slovakia, Germany and of course in Crete, which until today is considered as the only region of Greece with documented Sirenian fossil findings (Symeonidis and Schultz, 1973; Markopoulou-Diacantoni, 2001; Markopoulou-Diacantoni and Logos 2004; Kroeger, 2004).

The genus *Metaxytherium* is a common finding from the European Miocene and Pliocene (Landini et al., 2005), and is generally regarded as the descendent of the Oligocene *Halitherium* which was identified by the species *H. schinzii* from the Rupelian of Germany, France and Belgium. Domning (1982) presented a phylogenetic analysis and proposed that *M. krahuletzi* and subsequently *M. medium, M. serresii* and *M. subapeninum* form an ancestor-descendant sequence (monophyletic clade), although *M. serresii* is clearly smaller than the rest. The reduction in size (dwarfism) of *M. serresii* is considered an adaptation to the changing environment in the Messinian Mediterranean and more specifically as a consequence of malnourishment due to the reduced diversity, quality and probably quantity of sea

Fig. 1: Map of Crete Island that shows the localities where Sirenian fossil remains have been found todate. The shaded areas indicate the exposures of Neogene rocks on the Island.

grasses and the confined habitats in which the taxon survived during and after the "Messinian salinity crisis" sea (Domning and Thomas, 1987; Bianucci et al., 2004).

The first members of the order Sirenia appeared at the beginning of the Cenozoic at about 50 Ma, in the middle Eocene. The order Sirenia (Illiger 1811) is closely related with the group Tethytheria (a group of ungulate, hoofed mammals) that includes the extinct orders Desmostylia and Embrithopoda. The genus *Paleoparadoxia* is considered to be the ancestral line to all of them.The Sirenians probably were separated from their ancestral group during the Palaeocene (65-54 Ma) and very soon they entered the water fully adapting to aquatic life and dispersed to the New World (Barnes et al., 1985, Domning, 1978, 1999). The order Sirenia contains four families: Prorastomidae, Protosirenidae, Dugongidae and Trichechidae. Today, there are four extant species belonging to the families Dugongidae (*Dugong dugong*) and Trichechidae (*Trichechus manatus, Trichechus inunguis, Trichechus senegalensis*) and another species (Steller's cow – *Hydrodamalis gigas*) that went extinct in the 18^{th} century (Domning, 1988, 1997).

Characteristic Sirenian anatomical features are: the pachyostic bones, the lumbar vertebrae with the very long transverse processes, and the vestigial pelvic bone which is used in sex determination. In addition, the cranium is characterized by a long snout and two distinctive tusks in the front.

Significant Sirenian fossil remains have been found on the island of Crete (Greece) in Late Miocene deposits. A large portion of Crete is covered with Neogene sediments (marls, sands, clays and limestones) most of which are of marine origin, deposited during the Late Miocene from 11.5 Ma and until the Messinian salinity crisis 5 Ma. During the last 30 years, four Late Miocene localities with Sirenian fossil remains have been found on the island of Crete: Kotsiana in Kissamos (Symeonidis and Schultz, 1973), 2 localities, Timpana and Kefala, in the wider area of Sitia (Markopoulou-Diakantoni and Logos, 2004) and also the locality Machairidi near the village Gdochia in Ierapetra (Markopoulou-Diakantoni, 2001) (Fig. 1). In recent years new significant Sirenian findings have been discovered on the island (Svana, 2007). Systematic surveys on the island were performed by the Palaeontology group of the Natural History Museum of Crete, University of Crete (NHMC), which revealed 14 new localities across Crete.

2. Geographical and palaeoecological settings

The new localities are the localities of Stylos, Afrata and seven more around the village Kotsiana in western Crete, Panassos, Panassos 2, Ampelouzos and Kefala Gergeri in central Crete, and Tripitos site near Siteia (Fig. 1). In some of the localities the findings consisted of almost complete post-cranial remains. In addition five more new localities have been recently traced on the island by other researchers. These are the localities of Filippoi (Koskeridou, personal communication), Psalida, Apomarma, Vassiliki 1 and Vassiliki 2 (Reuter et al., 2005) all of them found in central Crete (Fig. 1). The recovered fossils have been found in sediments belonging to the geological formations of: Roka (Kotsiana sites and Afrata), Akrotiri (Stylos), Ampelouzos (Panassos, Panassos 2, Ampelouzos, Kefala Gergeri), Achladia (Tripitos). All these formations belong to the Late Miocene and more precisely their age is Tortonian (Freudenthal, 1969, Meulenkamp et al., 1979).

In complete contrast to recent shallow marine environments, during the Late Miocene, coral reefs were widely distributed along the Mediterranean region, except from northern regions (Reuter et al., 2006). This biogeographical pattern is generally considered to reflect a warmer than today's climate for the Mediterranean region. During the Late Miocene, in the area of Crete there were multiple periods where extensive regions with shallow warm waters existed, providing favourable conditions for the development of coral reefs. This is also documented by the extensive descriptions of Markopoulou-Diacantoni (2001) for the coral reef system (*Porites*) in the Ierapetra region and by Reuter's et al. (2005) report for the corals in the basin of Iraklion during the Tortonian.

3. Material and local geology

The skeletal elements that have been collected all these years through excavations by NHMC, are basically ribs, cervical, thoracic and lumbar vertebrae and in one case an incisor, the only cranial material found todate. The used reference material for this study belongs to the Palaeontological collection and the Comparative Anatomy collection of the National Museum of Natural History in Paris (MNHN), France and included the species: *Metaxytherium medium* (*Metaxytherium* sp., *Halianassa cuvieri*), *Halitherium serresii, Dugon dugong*. Also, the two skulls from the Sitia area (localities of Timpana and Kefala) described by Markopoulou-Diakantoni et al. (2004), stored at the Athens Historical Geology and Palaeontology Museum of the University of Athens, were examined.

3.1 *The locality of Stylos*

The studied specimen (Fig. 2) consists of a marly limestone block with embedded Sirenian remains. The specimen was originally found several years ago during the construction of a new road near the village of Stylos (east of Chania), and later the local people placed it in the courtyard of an old church in the village. The material consists of an almost complete and articulated skeleton in the correct anatomical position (Fig. 2). The head and some body parts were secondarily removed and the rest of the remains present considerable weathering. Taphonomical analysis of the skeletal remains shows that after death and due to bloating caused by decay processes, the animal's body was placed at the bottom of the sea in an upside down ventral position, and due to post-burial compression by the sediment burden the ribs were separated into 2 directions. The animal is probably a young individual since the measured skeletal elements have relatively smaller dimensions than the dimensions of the reference material.

3.2 *The locality of Panassos*

The remains were found in an excavation conducted in the outskirts of the village of Panassos, south of Heraklion, in 2002. The material consists of scattered skeletal elements and more specifically of cervical, thoracic and lumbar vertebrae, an incisor and several bone fragments. The bone bearing sediments were shallow deposited marine sandstones that belong to the Ampelouzos formation.

3.3 *The locality of Kotsiana*

Sirenian remains were recently discovered nearby the village Kotsiana, SW of Chania, following a

Fig. 2: (left): Photo of the fossil post-cranial skeleton found in the marly limestone block at Stylos; (right): Direct sketch of the skeleton found in Stylos with all present ribs and vertebrae identified and numbered.

previous report by Symeonidis and Schultz (1973). The exact position of the original locality of Symeonidis and Schultz (1973) was traced; nevertheless, since 1973 the described remains (Symeonidis and Schultz, 1973) have been significantly weathered. After surveying the wider area of Kotsiana, the fossiliferous layer that consists of sandy limestones which belong to the Roka formation, was traced and seven more localities with abundant but scattered Sirenian remains were found. Most of them were weathered and fragmentary but some complete specimens have been also found. The collection of various marine invertebrates (bivalves, brachiopods, corals and gastropods) from the same fossiliferous layer, allowed the age determination of the layer as Upper Miocene (Tortonian).

3.4 *The locality of Tripitos in Siteia*

Recently, excavations conducted in deltaic deposits in the locality of Tripitos in Siteia have yielded the remains of an almost complete skeleton that consists of several partly articulated ribs and thoracic vertebrae that seem to belong to an (young) adult. The localities of Timpana and Kefala are found in the wider area of Sitia (Markopoulou-Diakantoni and Logos, 2004). These localities have yielded two important findings, two Sirenian skulls that confirm the species determination and its age (Markopoulou-Diakantoni and Logos, 2004). These remarkable findings lie in the same sedimentary layers that belong to the Achladia formation, as the bone bearing layer from Tripitos.

The material from the other localities, Panassos 2, Ampelouzos, Kefala Gergeri, and Afrata has not been studied yet as the excavations in these localities are still at a preliminary stage, and sufficient financial support has not been available yet.

4. Systematic palaeontology

Order: Sirenia (Illiger, 1811)

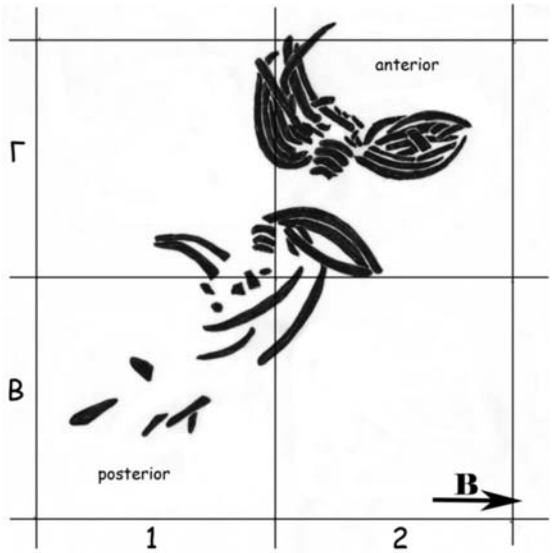

Fig. 3: Actual plan-view of the Sirenian fossil remains from Tripitos. Articulated and associated vertebrae and ribs are clear, indicating that the remains belong to one individual.

Family: Dugongidae (Gray, 1821)

Subfamily: Halitheriinae (Kaup, 1838)

Genus: Metaxytherium (de Christol, 1840)

Species: *Metaxytherium medium* (Desmarest, 1822) Hoijer, 1952

Synonynms: *Metaxytherium cuvieri* (de Christol), Markopoulou-Diakantoni and Logos (2004)

Holotype: MNHN Fs 2706, partial left mandible with $M_{2\ 3}$ and roots of M_1 (the «Moyen hippopotame» of Cuvier, 1821).

Type Locality: Saint-Michel en Chaisine, Maine-et-Loire, France.

Formation: Calcareous tuff.

Age: Middle to Late Miocene (Serravallian-Tortonian) (Domning, 1996).

Description: The finding of an incisor (tusk) in Panassos locality (Fig. 4 left) is very crucial for the study and the determination of the Sirenian fossil remains, as it can be used as a confirmation of the above species classification. It is an incisor worn a little at the edge of the crown, a fact that along with its size it confers that the individual was an adult. The root of the incisor is transversely elliptical (laterally flattened) and with distinct folding along its length and with a slight curve on the dorsal side. The total length of the incisor is 114.54 mm and the length of the crown is 15.2 mm, with base dimensions of 11.02x13.10 mm. The ratio of total incisor length to crown length is about 7.5.

Sirenian vertebrae and ribs present very characteristic morphological features which are clearly present in the fossil findings from all the Cretan localities. Firstly, the typical pachyostosis and osteosclerosis of the Sirenian ribs are evident in the studied material, a feature that has developed in order to facilitate their aquatic mode of life. Moreover, the fairly elongated and thick lateral apophyses of the lumbar vertebrae are further characteristic Sirenian features (Fig. 4 right).

Fig. 4: (left): The incisor tooth found in locality Panassos; (right): A lumbar vertebra with the distinctive long lateral apophyses.

5. Discussion and Conclusions

During the Late Miocene, the species *M. medium* was found in abundance all over (i.e. France, Spain, Italy) the Mediterranean basin and some of the findings are believed to belong to young individuals. Our data seem to verify this statement and are also in accordance with the report of Markopoulou-Diacantoni and Logos (2004) where the two fossil Sirenian skulls found in Timpana and Kefala (Sitia) are identified as *Metaxytherium cuvieri* de Christol, 1840. In the present study this report is confirmed, nevertheless the species name determination is considered erroneous and therefore it is corrected and synonimased to *Metaxytherium* cf. *medium* (Desmarest, 1822) Hoijer, 1952, as this is the valid species name according to the latest accepted Sirenian systematics presented by Domning in 1996. Furthermore, additional evidence for our determinations is the fact that the species *M. medium* is the only *Metaxytherium* taxon found in the fossil record of the Mediterranean basin during the Tortonian (Bianucci & Landini, 2003a, b). As mentioned above, the European (or Mediterranean) *Metaxytherium* clade of the genus is monophyletic and thus all other species can be excluded with safety. These conclusions support the confirmation of the hypothesis that all Sirenian fossils found in Crete are of Tortonian age and belong to the species *Metaxytherium* cf. *medium*.

Extant Sirenia are herbivores and dwell in tropical coastal and river environments where they feed on seagrasses (marine angiorperms). Therefore, the presence of Sirenian remains in several localities all over Crete indicates that during the Tortonian, extensive shallow and warm marine environments, rich in marine angiosperms were common.

In conclusion, it can be said that until today Crete is the only region in Greece, where fossil Sirenian findings have been documented. The reason for this could be assigned to the lack of systematic field work, but also to the fact that probably during the Tortonian in this southern region of the Mediterranean the climate was warmer, facilitating the survival of sea cows. Therefore, it is suggested that in Crete there were extensive regions with warm and shallow waters rich in coral reefs and seagrasses, where of course Sirenians were abundant.

6. Acknowledgments

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CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY OF LANGHIAN DEPOSITS IN LEFKAS (IONIAN ISLANDS)

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Abstract

Spanochorion composite section (NE Lefkas) and Aghios Vassilios section (W Lefkas) have been studied semiquantitatively for their calcareous nannofossil content. The calcareous nannofossil biostratigraphy, performed at the Paxos unit atypical flysch sediments of Aghios Vassilios section, permits their biostratigraphic correlation with the uppermost part of NN4 biozone and the lower part of NN5 biozones (Martini, 1971) or MNN4b and MNN5a (Fornaciari and Rio, 1996), which chronostratigraphically point to Early Langhian age and range between 15.974 and 14.53 Ma. The most interesting biostratigraphic result is the detection of the Sphenolithus heteromorphus Paracme End at the base of Aghios Vassilios section, a biohorizon that marks the basal Langhian deposits in the Mediterranean region. The mollasic sediments of Spanochorion section are more or less of the same age, ranging between 15.5 and 14.53 Ma. The biostratigraphic results of the present study reinforce the hypothesis that the molassic sediments of NE Lefkas Island behind the Ionian thrust were isochronously deposited with Paxos atypical flysch sequences deposited in front of Ionian thrust, at least until Early Langhian times.

Key words: *calcareous nannofossils, Langhian, Sphenolithus heteromorphus Paracme Zone.*

1. Introduction

The geology of Lefkas Island comprises carbonate and clastic sediments which belong to the external geotectonic units of the Hellenic arc; Paxos (Pre-Apulian) and Ionian, ranging between Triassic-Tortonian and Triassic-Aquitanian respectively (Renz, 1955; Bornovas, 1964). These two units are separated by a major west-directed thrust fault (Aubouin, 1959; Jacobshagen, 1986), marked by evaporate intrusion (Karakitsios and Rigakis, 2007). The current geodynamic regime is expressed by a dense fault network, striking to the NNE-SSW or E-W direction that has overprinted the pre-existing thrust-related features and has been dominant throughout the Plio-Quaternary, breaking up the island in a multitude of independent fault blocks (Lekkas et al., 2001).

In particular Lefkas Island consists mainly of the carbonate sequence of the Ionian unit that forms the major part of the island and the limestones of Paxos (Pre-Apulian) unit, at the southwestern part (Lefkata peninsula). The Ionian unit contains (Permo)-Triassic gypsum, Triassic to Jurassic platform carbonates and deep-marine well-bedded limestones that overthrusted the (pre)-Apulian unit. The stratigraphy of the Ionian unit exhibits three distinct sequences (Karakitsios, 1992, 1995); a prerift, a synrift and a postrift sequence. The latter one consists of the Vigla limestones and overlying Alpine formations and is defined by an Early Berriasian breakup at the base. The postrift sequence contin-

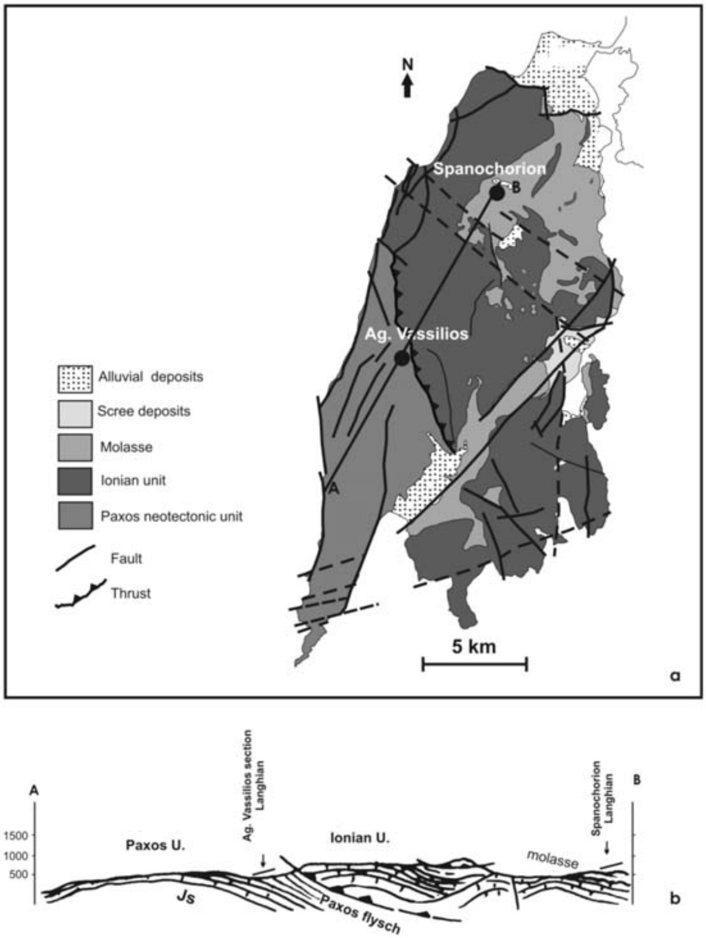


Fig. 1: a. Simplified geological and neotectonic map of Lefkas Island (after Bornovas, 1964, Rondoyanni- Tsiambaou, 1997, Lekkas et al., 2001). Position of the studied sections is indicated by black circles. b. Geological section (AB on map) showing the geological position of the studied sections.

ued till the end of the Eocene, followed by the deposition of flysch sediments (Karakitsios, 1992, 1995; Sotiropoulos et al., 2003). The depositional sequence of the Paxos unit in Lefkas Island begins with Lower Jurassic dolomites and Middle Jurassic cherts and bituminous shales (Bornovas, 1964; BP, 1971). During the Campanian-Maestrichtian intra-platform basins characterised the slope between the Apulian platform and the Ionian basin (Nikolaou, 1986; Karakitsios and Rigakis, 2007). Sporadic hiatuses in between Paleocene and Late Cretaceous have been described by Mirkou (1974), suggesting intense tectonic activity, that persisted throughout the Oligocene, suggesting the presence of flexural subsiding foreland basins (Karakitsios and Rigakis, 2007). The Paxos unit exposes Oligocene to Lower Miocene deep-marine carbonate successions, with a transition to terrigenous clastics in the course of the late Burdigalian (late Early Miocene) to early Langhian (early Middle Miocene), (De Mulder, 1975). It has so far been generally accepted that the Paxos (Pre-Apulian) zone lacks typical flysch sediments. However, the observed progressive passage from the Ionian typical flysch to the more calcareous, age-equivalent, facies in the Pre-Apulian zone (BP, 1971) indicates that post- Oligocene Pre-Apulian sediments correspond to an atypical distal flysch unit (Karakitsios & Rigakis 2007). It's partial or complete absence from some areas corresponding to the most external part of the forebulge depozone in the Hellenide foreland basin system (sensu DeCelles & Giles 1996), can be associated with erosional phaenomena (Karakitsios & Rigakis 2007).

On Lefkas Island, molassic formations of mostly marine Aquitanian-Tortonian (Bornovas, 1964; Lekkas et al., 2001) marls, bioclastic limestones conglomerates and sandstones are unconformably overlying the Ionian sequence and few outcrops of Ionian flysch turbidites (Cushing, 1985; Rondoyanni- Tsiambaou, 1997). The lower parts of the Paxos atypical flysch sequence at western Lefkas, are considered isochronous to the mollasic deposits (Bornovas, 1964; IGRS-IFP, 1966; BP, 1971; Cushing, 1985; Lekkas et al., 2001). Neogene clastic sediments and quaternary coastal deposists consist the post-alpine formations (Bornovas, 1964; IGRS-IFP, 1966; Cushing, 1985).

Little biostratigraphic work has been done in respect to the above mentioned atypical flysch and molassic deposits on Lefkas Island, and their biostratigraphic assignment. De Mulder (1975) provided some constraints on the age of several Oligocene-Miocene outcrops of Lefkas, based mainly on the planktonic foraminiferal biostratigraphy, and suggested that they were extending at least up to Serravallian. Recently, Drinia et al. (2007) have studied the paleobathymetric evolution of the Manassi section at the southwestern part of Lefkas Island. They identified turbidite beds intercalated with in-situ marly sediments and dated these atypical Paxos (Pre-Apulian) flysch deposits as of early Tortonian age, between 11.54-11.2 Ma.

The main scope of the present study is to evaluate by means of calcareous nannofossil biostratigraphy the age of parts of Paxos atypical flysch sediments and molassic deposits on Lefkas Island, and inquire whether their deposition is at least partly isochronous.

2. Materials and methods

Ag. Vassilios section in the southwestern part of Lefkas Island (Fig. 1a), about 400 m in thickness, is located on the eastern slope of a N-S running valley (De Mulder, 1975) and consists of fine grained clayey and marly sediments with some sandy intercalations, assigned to the atypical flysch marly deposits of Paxos unit (Bornovas, 1964; Lekkas et al., 2001). Twenty samples from the lower approximately 100 m of the section have been investigated for their nannofossil content (Figs 2a, 3).

Section Spanochorion is located along the road to Lazarata village at the northeastern part of the island (Fig. 1a) and represents part of the Spanochorion section described by De Mulder (1975). It consists of about 50 m of marls alternating with coarse breccious beds and marly limestones. Thirty-three samples have been collected from the fine grained intercalations and studied by the means of calcareous nannofossils (Figs 2b, 4).

Calcareous nannofossil biostratigraphy, mainly based on the appearance/disappearance and relative abundance patterns of selected species, provided high time resolution and accurate correlation with regional and global stratigraphy and time scale for the Miocene marine successions (Fornaciari and Rio, 1996; Lourens et al., 2004; Raffi et al., 2006).

Smear slides for calcareous nannofossil analysis have been prepared following the standard preparation technique of Perch Nielsen (1985). To obtain accurate biostratigraphic estimations, up to 100 fields of view have been investigated per slide, counting at least 500 specimens, with a Leica DMLSP optical polarising light microscope at 1250x. Nannofossil state of preservation was overall very

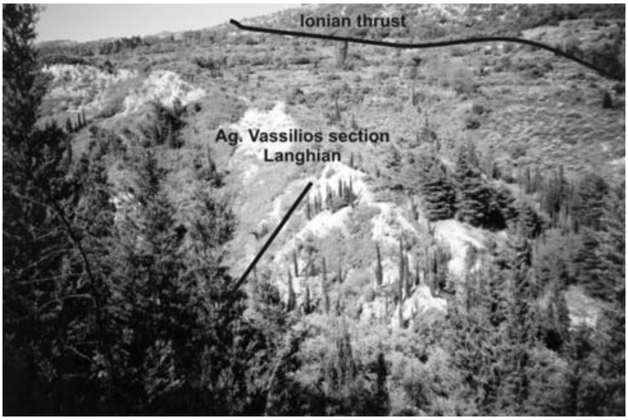


Fig. 2a: Panoramic view of Ag. Vassilios section (Paxos atypical flysch sequence).

good. Semiquantitative abundances of the taxa encountered were recorded as follows: A, abundant: more than one specimen every field of view; C, common: 1 specimen/10 fields of view; R, rare: 1 specimen/ 50 fields of view; P, present: 1 specimen/ >100 fields of view; RW, reworked specimens. The taxonomy of the determined calcareous nannofossil species has been based on Aubry (1984, 1988, 1989, 1990); Perch-Nielsen (1985). The determination of the biostratigraphic events has followed Martini (1971), Fornaciari and Rio (1996), Raffi et al. (2006). Numerical ages of biozone boundaries are given according to Lourens et al. (2004) and Iaccarino et al. (2005).

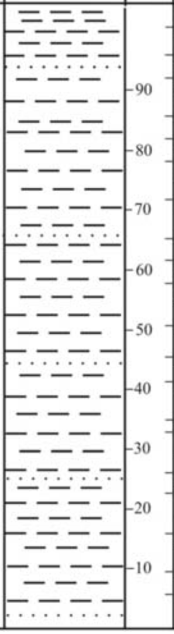
Fig. 2b: The upper part of Spanochorion composite section (molassic deposits).

3. Biostratigraphic results

Calcareous nannofossils are abundant throughout the studied sections and were generally well-preserved in all samples. Semiquantitative results of representative taxa are shown in Figs 3, 4.

3.1 Ag. Vassilios section

In Ag. Vassilios section, the nannoflora assemblage is dominated by discoasterids and sphenoliths, which provide important biostratigraphic markers in the Miocene. Discoasters mainly contain *Dis-*



Age	Samples	Biozones	C.miopelagicus	C.pelagicus	C.floridanus	D.variabilis	D.exilis	D.adamanteus	H.carteri	H.intermedia	H.walberdorfensis	S.heteromorphus	S.moriformis	Rhabdosphaera spp
MIDDLE MIOCENE (LANGHIAN)	Av20	MNN5a	R	C					R	R		C	A	
	Av19		P	C	C	P	C		C			C	C	
	Av18		R	R					R	R		A	A	
	Av17		C	P	C	R	C	P	C			A	A	
	Av16				C	C		P	R	P		A	A	R
	Av15		R	P	R	R	R	R	C	R		A	C	R
	Av14		R					P	C	P	P	A	A	
	Av13		R	R	C	C	C	R	C			C	C	P
	Av12			R				P	R			C	A	
	Av11			C	C				R	R		R	A	P
	Av10	PE S.heteromorphus	R		R	R	R	R	R	P		P	A	R
	Av9	MNN4b	C		C	C	C		C				C	
	Av8		R		R	R	R	R	R	R			C	R
	Av7			R		C		R	C	R			C	P
	Av6			R	R	R			R	R			C	
	Av5			R	R							P	C	R
	Av4		C	R		C		R	C	P			A	
	Av3		C		R				R	R			C	
	Av2		R		R	R			R	R			C	P
	Av1			R	P	R			C				A	

CALCAREOUS NANNOFOSSILS

Fig. 3: Lithology, sample location and calcareous nannofossil biostratigraphy of Ag. Vassilios section.

coaster variabilis, D. exilis and *D. adamanteus,* whereas *D. deflandrei* is very rare. *Sphenolithus* spp. include *S. heteromorphus* and *S. moriformis*.

Placoliths are represented mainly by *Coccolithus pelagicus, C. miopelagicus* and *Cyclicargolithus floridanus*. *Helicosphaera carteri* is also well represented, whereas *H. intermedia* is scattered and *H. ampliaperta* and *H. walbersdorfensis* are totally absent.

The results reveal the absence of *S. heteromorphus* at the lower part of the studied section (Fig.3) along with the contemporaneous absence of *H. ampliaperta* and *H. walbersdorfensis*. This indicates the interval of absence or strong reduction of *S. heteromorphus* above the Last Common Occurrence (LCO) of *H. ampliaperta* and below the First Common Occurrence (FCO) of *H. walbersdorfensis*, that has been determined by Fornaciari et al. (1996) as *Sphenolithus heteromorphus* Absence Interval (Paracme) Zone MNN4b, and is correlated with the uppermost part of NN4 (Martini, 1971).

The rest part of the section displays abundant-common *S. heteromorphus* but no trace of *H. walbersdorfensis*, allowing the correlation with the interval between the paracme end of *S. heteromorphus* and the FCO of *H. walbersdorfensis*. This verifies the recognition of *Sphenolithus heteromorphus- Helicosphaera walbersdorfensis* Interval Subzone MNN5a (Fornaciari et al., 1996) and the lower part of NN5 (Martini, 1971).

The available nannofossil biostratigraphic data enable the dating of Ag. Vassilios section between

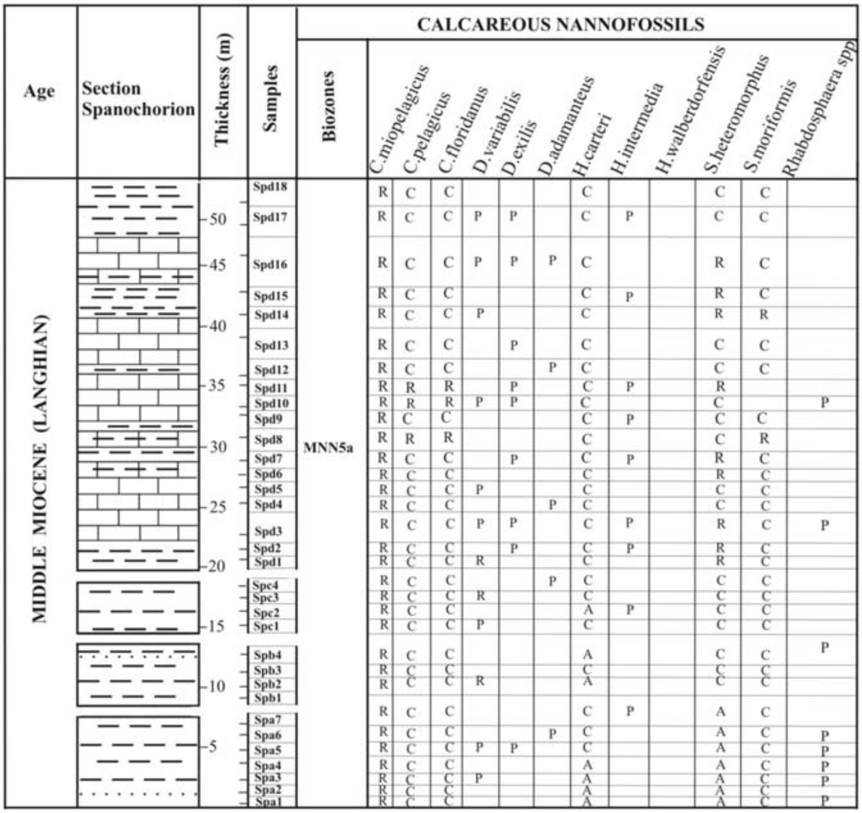


Fig. 4: Lithology, sample location and calcareous nannofossil biostratigraphy of Spanochorion section.

15.974 Ma (PB *S. heteromorphus*, Iaccarino et al., 2005) and 14.53 Ma (FCO *H. walbersdorfensis*, Iaccarino et al., 2005). The Paracme End (PE) of *S. heteromorphus* at 15.5 Ma, is located at approximately 55m from the base of the section (Fig. 3).

3.2 Spanochorion section

The nannoflora assemblage of Spanochorion section is marked by the abundant-common presence of *S. heteromorphus* and the absence of *H. ampliaperta* and *H. walbersdorfensis* (Fig. 4). This verifies the recognition of *Sphenolithus heteromorphus- Helicosphaera walbersdorfensis* Interval Subzone MNN5a (Fornaciari et al., 1996) and the lower part of NN5 (Martini, 1971) that ranges between 15.5 and 14.53 Ma (Iaccarino et al., 2005).

4. Discussion and conclusions

Previous stratigraphic data concerning the base of Ag. Vassilios section, were proposed by De Mulder (1975) who dated the turbiditic deposits as Early Miocene (Burdigalian) on the basis of the presence of *Globigerinoides altiaperturus, G. trilobus*, *Globoquadrina dehiscens, Globorotalia peripheroronda* and *G. praescitula* that are associated with N6-N7 planktonic foraminiferal biozones. De Mulder (1975) did not provide any data concerning the biostratigraphic assignment of the top of the section.

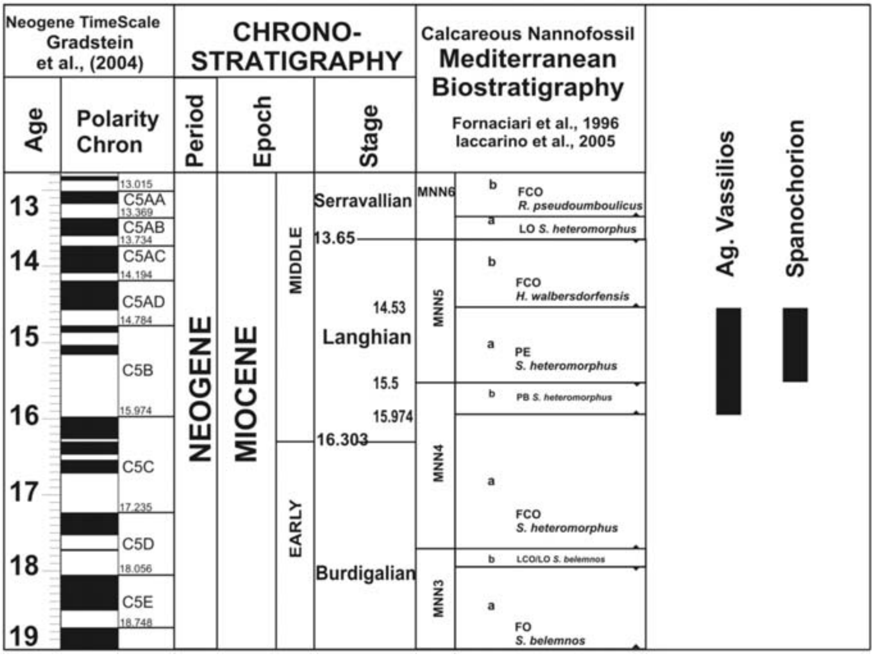


Fig. 5: Biostratigraphic-Chronostratigraphic assignment and age control of Ag. Vassilios and Spanochorion sections on Lefkas Island (ages provided are based on Lourens et al. 2004, Iaccarino et al. 2005).

However IGRS-IFP (1966) and Bizon (1967) suggested that the section may reach as high as the Late Miocene. Our results provide an Early Langhian age (15.974 -14.53 Ma) to the studied Paxos atypical flysch deposits of Ag. Vassilios section.

Overall it seems likely that the duration of Paxos atypical flysch deposition on Lefkas Island spanned the Aquitanian, Bourdigalian (sections Komilio, basal Ag. Vassilios; De Mulder, 1975), Early Langhian (upper Ag. Vassilios section; 15.974 -14.53 Ma, present study), Late Langhian (section Roupakias; Antonarakou et al, 2006), Serravallian (section Kalamitsi; De Mulder, 1975) and ranged at least till the Early Tortonian (section Manassi; 11.54-11.2 Ma, Drinia et al., 2007).

The molassic sediments of NE Lefkas do not reach the Late Miocene. De Mulder (1975) provided evidence for Burdigalian-Langhian dating of several deposits in this area. In particular, Spanochorion section has been assigned to N8 planktonic foraminiferal zone (Late Bourdigalian-Early Langhian) by De Mulder (1975). The present study refined this dating to Early Langhian (15.5 -14.53 Ma). Similar results have been provided from the nearby Asprogerakata section (Antonarakou et al., 2006).

The biostratigraphic results of the present study (Fig. 5) support the hypothesis that the deposition of both the molassic sediments of NE Lefkas Island behind the Ionian thrust and Paxos atypical flysch sequences deposited in front of Ionian thrust, was taking place until at least the Early Langhian times (Fig. 1b).

5. Acknowledgements

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HIGH RESOLUTION BIOSTRATIGRAPHY AND PALEOECOLOGY OF THE EARLY PLIOCENE SUCCESSION OF PISSOURI BASIN (CYPRUS ISLAND)

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Abstract

The Pissouri basin (Cyprus Island) corresponds to a small tectonically controlled depression elongated NNW-SSE and widening southward in the direction of the deep Mediterranean domain. In the centre of the basin, the section Pissouri South, about 100 m thick, consists of well-preserved cyclic marine sediments including laminated brownish layers alternating with grey homogeneous marls. Plankton biostratigraphy (calcareous nannofossil and planktonic foraminifera) revealed a remarkable number of biovents bracketing the Zanclean-Piacenzian boundary.

In particular the Highest Occurrence (HO) of Reticulofenestra pseudoumbilicus suggests the presence of NN14/15-NN16 nannofossil biozone boundary, dated at 3.84 Ma. Additionally the defined planktonic foraminiferal MPL3-MPL4a and MPL4a-MPL4b zone boundaries point to ages between 3.81 and 3.57 Ma, in Pissouri North section. Zanclean/Piacenzian boundary (3.6 Ma) is placed at 75.8 m from the base of the section, considering Discoaster pentaradiatus top paracme (3.61 Ma) and Globorotalia crassaformis first influx (3.6 Ma) bioevents.

The cyclically developed sapropelic layers around the Zanclean – Piacenzian boundary suggest a climate characterized by a period of warm temperate conditions and a highly stratified water column that occurred at times of precession minima.

Key words: *calcareous nannofossil, foraminifera, fossil Pissouri Basin, Zanclean-Piacenzian.*

1. Introduction

The Neogene-Quaternary marine stratigraphy exposed on land in the Mediterranean region has been of interest to Earth scientists and has become the reference standard for the chronostratigraphy of this time interval (Berggren, 1971; Rio et al., 1984, 1991, 1997). Calcareous plankton biostratigraphy, mainly based on the appearance/disappearance and relative abundance patterns of selected species of planktonic foraminifera and calcareous nannofossils, provides high time resolution and accurate correlation at regional and global scale and is widely used for a first-order age control in many Mediterranean Neogene and Quaternary marine successions (Cita, 1973,1975; Cita & Gartner, 1973; Rio et al., 1988, 1990; Hilgen, 1991; Sprovieri, 1992, 1993; Cita et al., 1996; Di Stefano et al., 1996; Lourens et al., 1996; Di Stefano, 1998; Raffi et al., 2006).

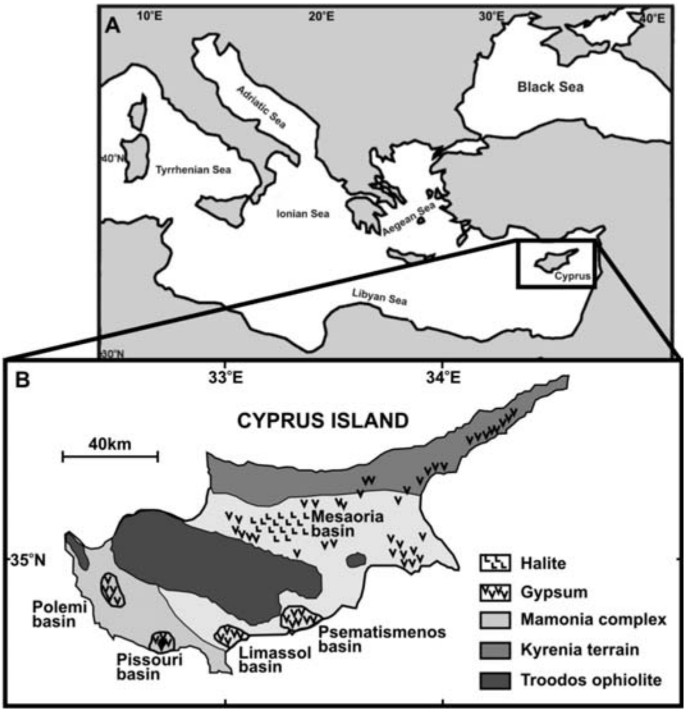

Fig. 1: a) Generalized map of the Mediterranean Sea. Cyprus is located in the eastern Mediterranean Sea. B) Simplified geological sketch map of the Cyprus Island (modified after Robertson et al., 1991; Stow et al., 1995; Krijgsman et al., 2002 and Kouwenhoven et al., 2006).

Simultaneously, the dynamics of calcareous planktonic communities are of paramount significance in palaeoenvironmental studies because they quickly respond to oceanographic changes (primary production, water stratification, temperature, salinity, etc.).

Cyprus is located in the eastern Mediterranean Sea (Fig. 1). The island is built up from three major tectonostratigraphic terrains namely Troodos, Kyrenia and Mamonia (Robertson et al., 1991). The Neogene and Quaternary marine succession of the island have been recognized in five main sedimentary sub-basins (Fig. 1). The Pissouri basin is one of these, which is located on the SW of island. It corresponds to a small tectonically controlled depression elongated NNW-SSE and widening southward in the direction of the deep Mediterranean domain. Based on data from Robertson et al. (1991), five sedimentary formations have been recognized in the basin and adjacent regions: Plio-Pleistocene succession represented by Nicosia and Athalassa formations, Kalavassos Formation belongs to Messinian evaporites, whereas Eocene-Miocene limestone succession is distinguished in Lefkara and Pachna formations.

The Pissouri South section, about 100 m in thickness, is characterised by the deposits of Pissouri marlstone unit (Stow et al., 1995) which belongs to Nicosia formation. It is located in the centre of the Pissouri sub-basin and offers the opportunity to study the assemblage composition of calcareous plankton contents (calcareous nannofossil and planktonic foraminifera). In this study, we present the results of a tighter integrated calcareous plankton biostratigraphic examination of an early Pliocene marine succession outcropping in the section and evaluate the climate variability during this interval.

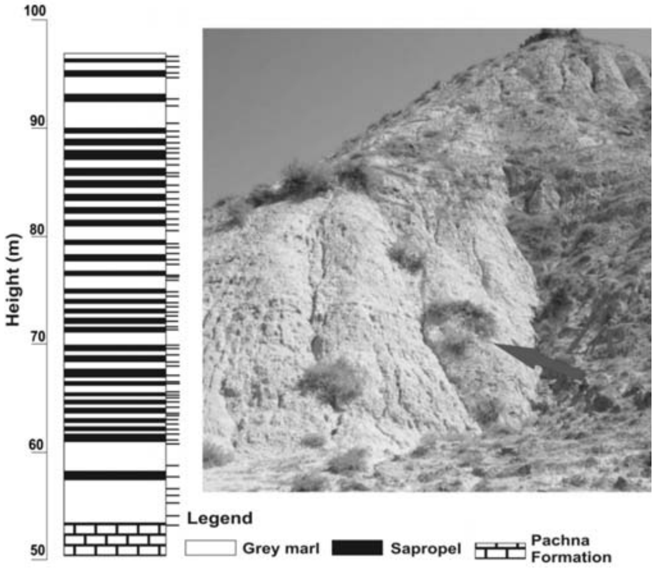

Fig. 2: Lithology and position of samples of the Pissouri South section.

2. Materials and methods

The studied Pissouri South section consists of well-preserved cyclic marine sediments including laminated brownish marly layers alternating with grey homogeneous marls. These sediments are overlying Pachna limestones. We focused our analyses in the part of the section between 50-100 m height, which was measured and sampled at 0.2 to 0.5 m intervals (Fig. 2). This high resolution sampling allowed us to perform detailed biostratigraphical studies.

Calcareous nannofossil analyses were carried out on 72 samples. Sample preparation followed standard "smear slide" techniques. Analyses were performed using a Leica DMSP polarising light microscope at 1250x magnification by counting the marker species at least 500 specimens per sample. Moreover, the frequencies of *Discoaser* species are established in a count of 50 discoasterids following the methods and determination of the biostratigraphic events described in Rio et al. (1990) and Raffi et al. (2006). Results were converted to relative frequencies (percentages). In order to evaluate primary production, the depth of the nutricline, and stratification in the water column we have used the ratio between *Florisphaera profunda* (F) and small gephyrocapsids (sG) abundances: S index = F/F+sG.

A quantitative study of the planktonic foraminiferal assemblages was performed on the same samples. Each sample was washed, sieved at 150μm and then dried at 60°C. Quantitative analysis was carried out on aliquots separated from each sample by means of a microsplitter, in order to obtain at least 300 specimens. Raw data were transformed into percentages over the total abundance of planktonic foraminifera. The palaeoclimatic curve inferred from the planktonic foraminiferal assemblages was obtained by the formula $(w–c)/(w + c) \times 100$, where w represents the warm-water indicators and c the cold-water indicators. The ratio *Neogloboquadrina* sp. (dex) / *Neogloboquadrina* sp. (dex) + *G. ruber* has been used to establish a valuable stratification index.

Twenty three samples were selected from the studied succession to assess the bottom-water condi-

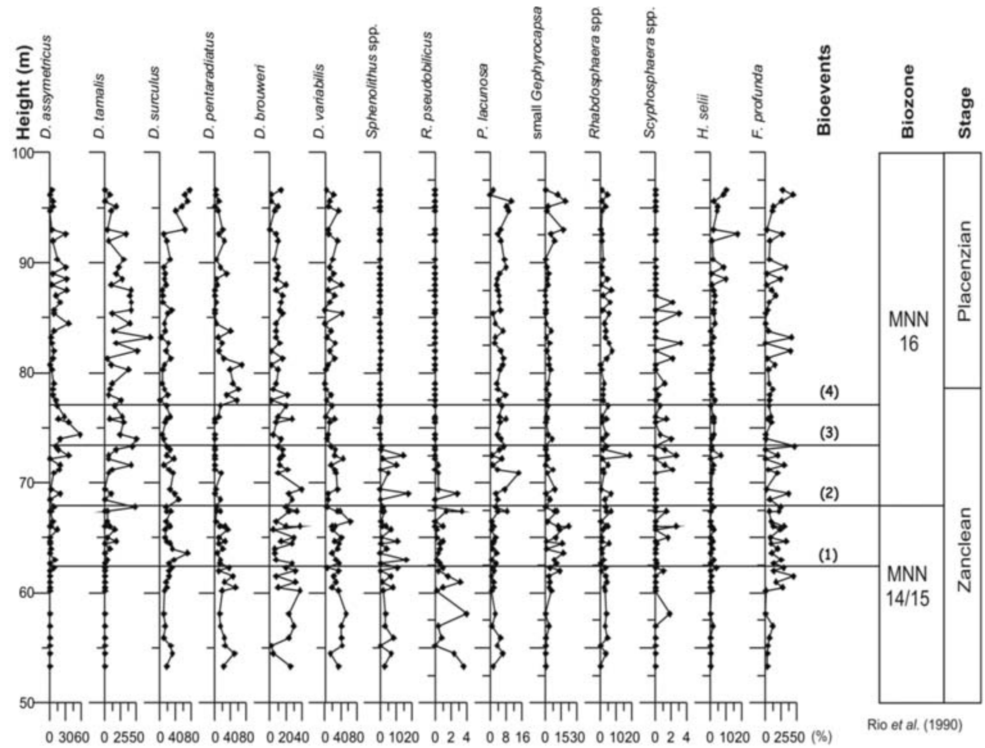

Fig. 3: Calcareous nannofossil biostratigraphy of the Pissouri south section. Quantitative distribution patterns of calcareous nannofossil marker species and the position of the main events.

tions. For the benthic quantitative analysis, the fraction larger than 150 μm of the washed residue was splitted with a microsplitter to a statistically significant size, which contained more than 250 specimens of benthic foraminifera. Reconstruction of bottom water conditions concerning oxygen content was based on the presence of the dysoxic indicators in the assemblage. For this purpose, the percentage occurrence of the well established redox front dwelling taxa (*Bulimina exilis, Bulimina costata, Globobulimina* spp., *Bolivina spathulata/dilatata*) which according to Rogerson et al. (2006) is related to disturbance and/or environmental stress was calculated.

3. Biostratigraphic results

3.1 Calcareous nannofossils

Calcareous nannofossils are abundant throughout the section and generally well-preserved in all samples. Trends of representative taxa are plotted in Fig. 3.

In Pissouri South section, the nannoflora assemblage is dominated by discoasterids and sphenoliths, which provide important biostratigraphic markers in the Pliocene. Discoasters are relatively well diversified and contain *Discoaster assymetricus, D. tamalis, D. surculus, D. pentaradiatus, D. brouweri* and *D. variabilis*. *Sphenolithus* spp. include *S. abies, S. neoabies* that are the only representatives of their genus in the Pliocene. Placoliths are represented mainly by small *Gephyrocapsa*, followed by *Reticulofenestra pseudoumbilicus* (>7micron) and *Pseudoemiliania lacunosa*. *Florisphaera profunda*, *Rhabdosphaera clavigera* and *Helicosphaera selli* are also well represented. *Scyphosphaera* spp. shows an insufficient occurrence with very low proportions.

The results reveal four important calcareous nannofossil events: (1) subbottom *Discoaster tamalis* (2) HO (Highest Occurrence) of *Reticulofenestra pseudoumbilicus*, (3) HO of *Sphenolithus* spp., (4) top paracme *Discoaster pentaradiatus*. The HOs of *R. pseudoumbilicus* and *Sphenolithus* spp. allow us to recognize the MNN14/15-MNN16 (Rio et al., 1990) nannofossil biostratigraphic boundary dated at 3.84 Ma.

The subbottom *D. tamalis* is recorded at 53.0 m, in the lower part of the section. The *D. tamalis* higher frequencies occur in the interval above 76.0 m with maximum value (72%) at 83.2 m. *R. pseudoumbilicus* presents maximum value (3.6%) at 53.3m. The highest occurrence of *R. pseudoumbilicus* marks the base of MNN16 at 67.8 m. The highest occurrence of *Sphenolithus* spp. occurs just above the disappearance of *R. pseudoumbilicus*, at 74.4 m, its stratigraphic position slightly above the base of MNN16. *D. pentaradiatus* is marked by high abundance and a continuous distribution, except in the interval between 71.2 to 76.0 m being completely absent. The identification of the top of the *D. pentaradiatus* paracme at 76.0 m allows the recognition of the lower part of the MNN16 zone, just above the extinction level of *Sphenolithus* spp. The age proposed for this event is 3.61 Ma (Lourens et al., 2004) and can be used to approximate in the Mediterranean the base of the Piacenzian Stage (3.60 Ma).

3.2 Planktonic foraminifera

Planktonic foraminifera are abundant throughout the section and well-preserved in all samples. The distribution pattern of the representative taxa is plotted in Fig. 4.

Planktonic foraminiferal assemblage is characterized by high abundances of *G. ruber, G. obliquus, G. apertura, G. trilobus* and *O. universa*. All these species are indicative of warm and oligotrophic conditions (Hemleben et al., 1989). Cool water species are represented by *G. scitula, T. quinueloba,* although in low percentages and *G. glutinata* (3-15%). High abundances are also recorded for *Neogloboquadrina* sp. dextral coiled specimens and *Sphaeroidinellopsis,* whereas the distribution pattern of *G. margaritae, G. puncticulata* and *G. crassaformis* is used to detect the biostratigraphic framework of the section following the zonation of Cita 1973, 1975b, emended by Sprovieri, 1992.

Six planktonic foraminiferal bioevents were recognized: (1) LCO (Last Common Occurrence) of *Globorotalia margaritae*, (2) LO (Last Occurrence) of *Globorotalia margaritae*, (3) FO (First Occurrence) of *Globorotalia crassaformis*, (4) disappearance of *Globorotalia puncticulata*, (5) reappearance of *G. crassaformis* and (6) reappearance of *G. puncticulata*.

The *G. margaritae* zone MPL3 is clearly identified at the base of the section characterized by the high abundance of *G. margaritae* (up to 20%), the occurrence of *G. puncticulata* (5-10%) and *Sphaeroidinellopsis* (2-5%). The LCO of *G. margaritae* (10%) is recorded at 61 m and its LO at 69 m of the section. The last bioevent has been dated by Lourens et al. (1996; 2004) at 3.81 Ma and marks the end of MPL3 biozone and the base of MPL4a. The FO of *G. crassaformis* is recorded at 76 m and marks the Zaclean/Placentian boundary at 3.60Ma (Lourens et al., 1996). The FO of *G. crassaformis* closely approximates the temporary disappearance of *G. puncticulata,* at 3.57 Ma, and also the transition to MPL4b at 78 m. Above this level and up to 87 m of the section, *G. crassaformis* is completely absent. The reappearance of this species has been dated at 3.35 Ma and predates the reappearance of *G. puncticulata* at 3.31 Ma recorded at 29 m.

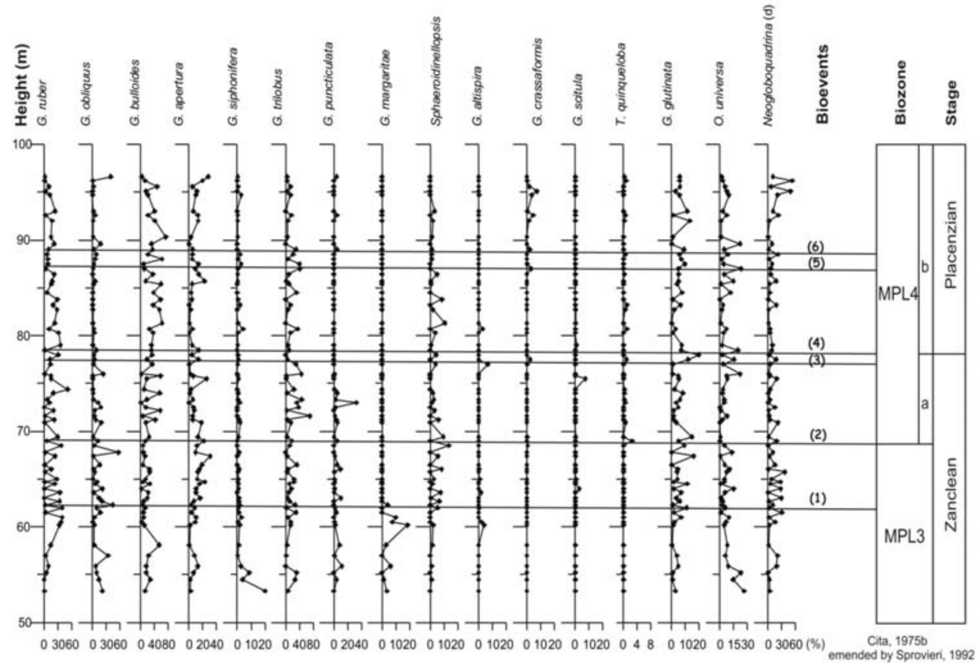

Fig. 4: Planktonic foraminiferal biostratigraphy of the Pissouri south section.

4. Sapropelic layers at Pissouri North Section

Micropaleontological analyses in this study also show direct relationships with lithological changes and confirm the presence of numerous cycles (Fig. 5). High relative abundant of TOC (Triantaphyllou et al., 2008) indicates that these layers can be associated with sapropelites. The marly levels of the Pissouri section can be correlated to grey and sapropelitic sediments in contemporaneous sections throughout the Mediterranean. Pliocene to Holocene Mediterranean sediments contain numerous sapropels (dark-coloured organic-rich sedimentary layers), which demonstrate that dramatically different conditions periodically occurred and coincided with changes in global and regional climate (Cita et al. 1977; Vergnaud-Grazzini et al., 1977). Detailed work in southern eastern Mediterranean sections (Jonkers, 1984; Verhallen, 1987, 1991; Hilgen, 1991) has shown that Pliocene sapropels are correlative and have a coherent and distinct cyclic pattern which correspond closely with minima in the precessional index (e.g. Rossignol-Strick, 1983; Hilgen, 1991; Lourens et al., 1992) when perihelion occurs in the Northern Hemisphere summer (Rossignol-Strick, 1983, 1985; Hilgen, 1991).

Florisphaera profunda (Fig. 5A) is a species restricted to the light-limited, lower euphotic zone (Winter et al., 1994) and has proven to be a very reliable proxy to locate the nutricline-thermocline level (Molfino & McIntyre, 1990) being important element of sapropel layers (Castradori, 1993). In order to trace stratification and nutricline fluctuations, we used the ratio between *Florisphaera profunda* (F) and small gephyrocapsids (sG)) abundances: S = F/F+sG. The increase of the nutricline proxy (Molfino & McIntyre, 1990) *F. profunda* vs the high nutrient indicator (Young, 1994) gephyrocapsids suggests high values of S index (Fig. 5E), that imply the gradual establishment of stratified conditions and the onset of a nutrient-rich environment in the deep photic zone during sapropel

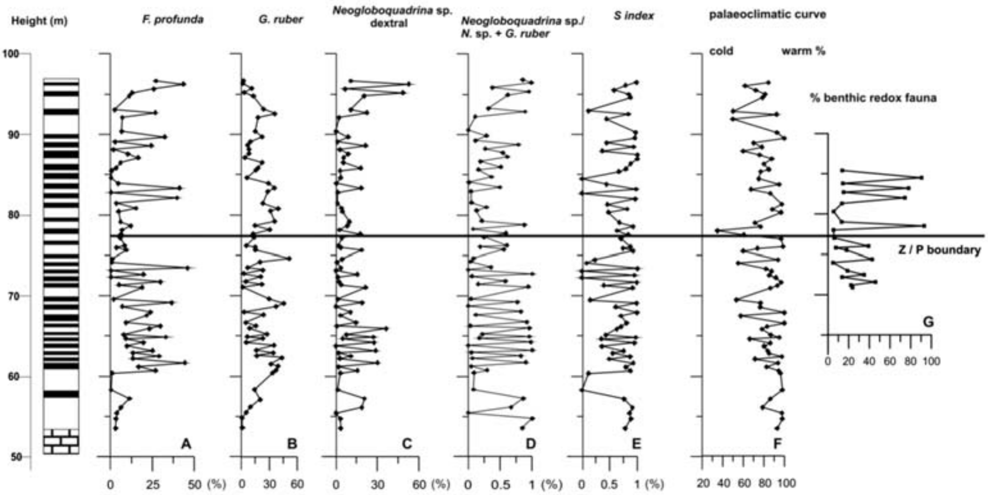

Fig. 5: Sapropelic layers at Pissouri South section.

formation. Higher abundance of *Rhabdosphaera* spp. at the same levels implies oligotrophic surface waters due to the increased stratification of the water column. Intervals of increased abundance of *F. profunda* and *Rhabdosphaera* spp. alternate with those of intense mixing of the surface waters that are featured by the intense presence of gephyrocapsids and anticorrelate to *F. profunda*.

The ratio *Neogloboquadrina* sp. (dex) / *Neogloboquadrina* sp. (dex) + *G. ruber* (Fig. 5D) has been used as additional stratification index that displays a similar trend (Fig. 5). *Neogloboquadrina* sp. (dex) is observed to be abundant in deep chlorophyll maxima (DCM) and, therefore, is assumed to proliferate under high productivity surface water masses and/or stratified surface water conditions. In the Mediterranean Sea, high abundance of *Neogloboquadrina* sp. (dex), (Fig. 5C) is often associated with sapropel layers (Rohling & Gieskes, 1989) and high abundance of *Globigerinoides ruber* (Fig. 5B), indicating intensive surface water stratification during relatively warm summers and a seasonal DCM (Lourens et al., 1992).

The continuous alternations in calcareous nannofossil and planktonic foraminiferal assemblages are reflected to the pronounced lithological cyclicity presented in the Pissouri South section. The sapropelites developed close to Zanclean/Piacenzian boundary suggest a climate characterised by a period of warm temperate conditions (Fig. 5F) and a highly stratified water column that occurred at times of precession minima.

These palaeoclimatic conditions enhanced palaeoproductivity and limited the availability of dissolved oxygen in bottom waters, temporarily establishing dysoxic conditions. At the same levels, an oligotypic benthic foraminiferal assemblage prevails. The fauna is entirely composed of the well-established redox-front taxa with *Bulimina exilis* making up to 94% of the total benthic assemblage (Fig. 5G). *Bulimina exilis* is often associated with sapropels formed under conditions of significant oxygen depletion (Jonkers 1984). Therefore, the high frequency values of this species may indicate a temporal reaction of benthic foraminifera to the input of fresh water organic matter. Hence, the shallowing of the redox front could be linked to the increase of food availability that leads to an increased consumption of oxygen (Jorissen et al., 1995).

5. Conclusions

Calcareous plankton biostratigraphy in this study confirm the presence of Zanclean/Piacenzian boundary of the early Pliocene marine succession in the Pissouri South section. Z/P boundary (3.6 Ma) is placed at 75.8 m from the base of the section, considering *Discoaster pentaradiatus* top paracme (3.61 Ma) and *Globorotalia crassaformis* first influx (3.6 Ma) bioevents.

Micropaleontological analysis revealed the presence of numerous cycles that resulted in the sapropelitic/homogeneous marl alternations. The sapropelites developed around the Zanclean – Piacenzian boundary suggest a climate characterised by fluctuations of warm – temperate to humid – subtropical conditions associated with a highly stratified water column at times of precession minima.

6. Acknowledgements

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ON THE OCCURRENCE OF PRIMITIVE *ORBITOIDES* SPECIES IN GAVROVO – TRIPOLITZA PLATFORM (MAINALON MOUNTAIN, PELOPONNESUS, GREECE)

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Abstract

Orbitoides genus is considered as a cosmopolitan one, with a worldwide distribution. It characterizes the open shelf sedimentation of late Cretaceous. Therefore, primitive species of the genus have not the same large paleogeographic distribution as the more evolved species. While evolved species of Orbitoides genus are frequently referred in Hellenids, primitive species are reported for the first time in Mainalon Mountain in central Peloponnessus (Zambetakis-Lekkas & Alexopoulos 2007). In this paper primitive Orbitoides species in the above area are studied and discussed. A new species seems to be identified.

Key words: *Primitive Orbitoides species, Campanian, Gavrovo-Tripolitza platform, Mainalon Mountain, Peloponnesus, Greece.*

1. Introduction

Orbitoides genus is considered as a cosmopolitan one, with a worldwide distribution. It characterizes the open shelf sedimentation of late Cretaceous. Therefore, primitive species of the genus have not the same large paleogeographic distribution as the more evolved species.

Primitive Orbitoidids were for the first time described in northern Spain (van Hinte 1966) and western France (Silvestri 1910, van Hinte 1968). Thenceforth, they are found in different localities of the Tethyan belt. While evolved species of *Orbitoides* genus are frequently referred in Hellenids, primitive species are found for the first time in Mainalon Mountain in central Peloponnessus (Zambetakis-Lekkas & Alexopoulos 2007).

Primitive species are differentiated from the more evolved ones by the absence or the sporadic presence of lateral chamberlets and by a different chambers arrangement in the juvenile stage of growth. The first “true” *Orbitoides* species developing lateral chamberlets from both sides of the equatorial plan of chambers, pierced by pillars is *Orbitoides tissoti*. Both *O. tissoti* and the younger species have a biconvex outline, due to the well developed lateral chamberlets. Primitive species are recognized by their plan, undulate, or concavo-convex shape of test. The definition of the different species of *Orbitoides* genus is based on the number and the arrangement of the embryonic and the juvenile chambers in the equatorial layer. In primitive species, contrary to the evolved ones, the equatorial chambers are not disposed in a plan.The undulation starts even from the embryonic and the juvenile stage of growth. This fact obstructs their observation in sections, thus leading to different opinions among several authors regarding the specific or generic attribution of the specimens. The primitive species stratigraphic range is from upper Santonian to lower Campanian, while the evolved ones is from upper Campanian to Maestrichtian.

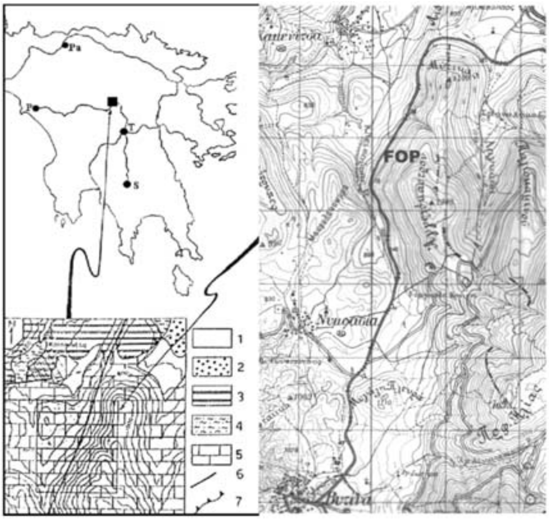

Fig. 1: Localization of the outcrop. Map showing the studied locality. Pa: Patras, P: Pyrgos, T: Tripolis, S: Sparti. 1: Alluvial, 2: Quaternary conglomerates, 3: Upper Cretaceous limestones of the Pindus series, 4: radiolarites, 5: Cretaceous limestones of the Tripolitza series, 6: fault, 7: overthrust (after Zambetakis et al 1988) FOP: Localization of primitive *Orbitoides* bearing limestones.

2. Geographical and Geological setting

Mainalon constitutes the main mountainous ridge of central Peloponnesus. Culminating up to 1867m altitude, it consists mainly of Jurassic up to Eocene carbonates of Tripolitza platform, followed by flysh. They are tectonically overlain by Pindus nappe.

Cretaceous carbonates of Tripolitza platform are the most represented in the Mainalon area. Whereas forests, intense tectonization and dolomitization obstruct the observation of continuous stratigraphic sequences, most cretaceous stratigraphic levels are recognized in different sections (Zambetakis-Lekkas 2006, Zambetakis-Lekkas & Alexopoulos 2007).

Primitive *Orbitoides* are found in the vicinity of Vitina, on the road Vitina – Tripolis. (Fig. 1)

3. Description of the outcrop

In the western flank of Mainalon mountain, NNE of Vitina village, a carbonate sequence of Aptian-Paleocene age is described along the national road Vitina – Tripolis (Zambetakis-Lekkas & Alexopoulos 2007). Primitive *Orbitoides* are found in a faulted block of dark, medium bedded limestones rich in rudist shells. Seventy four thin sections were obtained from seven samples. Primitive *Orbitoides* are recognized (see specific attribution below). They are associated with rotaliids, echinoids, *Cuneolina* sp., *Dicyclina schlumbergeri*, and *Calveziconus lecalvezae* (Fig. 4/2) dating Campanian age.

4. Discussion on primitive *Orbitoides* species

4.1 Previous works

The firstly described primitive *Orbitoides* species, *O. hottingeri* (Van Hinte 1966), is characterized by a circular test, with parallel sides, flat or folded rather irregularly, saucer-shaped or low conical. The periphery is lobulate and the surface is smooth. According to van Hinte's description, the diameter of the disc varies between 0.8 and 2mm, with most specimens measuring about 1.5mm. The thickness of the disc varies between 0.20 and 0.25mm. As van Hinte remarks, details of the central part of the test can only be studied in vertical and horizontal sections. Therefore, it is fairly impossible to obtain sections perfectly in the median layer due to the fact that the test is rarely flat. This lead to different interpretations of the arrangement of the equatorial chambers especially in the nepionic stage of growth (Neumann 1987; Caus et al. 1996) and as a consequence to a different general and specific attribution of the specimens. The spherical protoconque is followed by a deuteroconque of the same size. The third chamber possesses only one aperture, as well as some of the next chambers. Depending on the position of the aperture the arrangement of the initial chambers may be beserial or spiral. According to Drooger & Klerk (1985), the biserial or spiral initial stage of *O. hottingeri* reminds that of the microspheric specimens of all later *Orbitoides* and *Omphalocyclus*. According to Caus et al. (1996) the adult chambers have the same size as the nepionic ones. *O. hottingeri* has no lateral chamberlets, but the outer lamella covering the previously exposed shell thickens the lateral wall (Caus et al. 1996). *O. hottingeri* in the type-locality is included mainly in terrigenous facies and rarely in carbonate platforms. They are lithological related with beds containing planktic foraminifera of *Dicarinella asymetrica* zone (Caus & Gomez-Garrido 1989).

O. douvillei was determined as *Linderina? douvillei* by Silvestri (1910) in Aquitaine (southwestern France). Van Hinte (1968) restudied the topotypes and attributed the species to genus *Orbitoides*. The author differentiates *O. douvillei* from *O. hottingeri* by its H shaped embryonic apparatus formed by 4 chambers, contrary to the 3 chamber apparatus in *O. hottingeri*. The same author differentiates *O. tissoti* from *O. douvillei* by its biconvex test possessing buttons on the surface, and lateral chamberlets. *O. douvillei* is characterized by a smooth surface and the absence or rarity of lateral chambers. As Caus et al. (1996) mentioned, "true lateral chambers are not present in *O. douvillei*, but in some specimens the outer lamella seems to detach itself from the previous ones, leaving a small space, a so-called vacuole, between them". Drooger & Klerk (1985) mentioned that *O. douvillei* is the latest *Orbitoides* without lateral chambers, the embryonic apparatus of the species reminds that of *O. tissoti* but lacks the thickened wall that encloses the H-shaped, 4-chambered apparatus.

O. sanctae- pelagiae was determined as *Monolepidorbis sanctae-pelagiae* by Astre (1927) in Spanish Pyrenees in campanian marly carbonates. Astre differentiates *M. sanctae-pelagiae var. densa* without lateral vacuoles and a concavo-convex profile, from *M. sanctae-pelagiae var vacuolaris* possessing lateral vacuoles and a biconvex profile. Hottinger (1966) mentioned the differentiation of *M. sanctae-pelagiae* by the thickened wall of the embryonic apparatus. The protoconque is bigger than the deuteroconque, while they have the same size in *O. hottingeri*. The same author referred that a gradual transition is observed between the specimens of *M. sanctae-pelagiae* without lateral cavities and *M. douvillei* with lateral cavities. The author gets together to Astre's attribution of the species to Campanian, putting the Santonian/Campanian limit between the disappearance of *dordoniensis* (=*hottingeri*) and the apparition of *sanctae pelagiae*. Caus et al. (1996) attributed *M. sanctae-pelagiae var. densa* (Astre 1927) to *O. douvillei* (Silvestri 1910) of Lower Campanian age (*elevata* zone) and *M. sanctae-pelagiae var.vacuolaris* to *O. tissoti* (Sclumberger) of Middle Campanian age (lower part of *ventricosa* zone. The above authors gave a correlation of *Orbitoides* lineage zones with planktic foraminiferal zones (Fig. 2).

Summarizing the above, primitive species of *Orbitoides* genus are characterized by their plan, undulate,

m.y.	Stage	Planktonic Foraminiferal zones	*Orbitoides* zones
65	MAASTRICHTIAN	*Abathomphalus mayaroensis*	*Orbitoides apiculata*
		Gansserina gansseri	
		Globotruncana falsostuarti	*Orbitoides gruenbachensis*
74	CAMPANIAN	*Globotruncanita calcarata*	*Orbitoides megaloformis*
		Globotruncana ventricosa	*Orbitoides media*
			Orbitoides tissoti
		Globotruncanita elevata	*Orbitoides douvillei*
			"Gap in *Orbitoides* record"
83	SANTONIAN	*Dicarinella asymetrica*	*Orbitoides hottingeri*
		Dicarinella concavata	

Fig. 2: Correlation of *Orbitoides* lineage zones with planktic foraminiferal ones (according to Caus et al. 1996).

convex-concave shape of test. They have no or few lateral chamberlets. As Caus at al. (1996) mentioned, they are not true chamberelets but vacuoles formed by a detachment of the outer lamella of the lateral wall.

Concerning the embryonic apparatus, according to the concept of different authors, we conclude to the following criteria for the specific determination.

O. hottingeri: 2 chambered embryonic apparatus (P=D).

O. sanctae-pelagiae: 2chambered embryonic apparatus (P>D), with a thickened wall enveloping it (Hottinger 1966).

O. douvillei: 4chambered H shaped embryonic apparatus, without thickened wall (Drooger & Klerk 1985)

Apart from *O. sanctae pelagiae*, primitive *Orbitoides* species are characterized by the absence of thickened wall enveloping the embryonic apparatus that characterizes the first evolved species, *O. tissoti*. The later possess true lateral chambers, pierced by pillars, causing a biconvex shape of test.

4.2 Discussion on primitive Orbitoides species in Mainalon area

The studied material concerns to dark medium to thick bedded limestones, wackestones - pack-

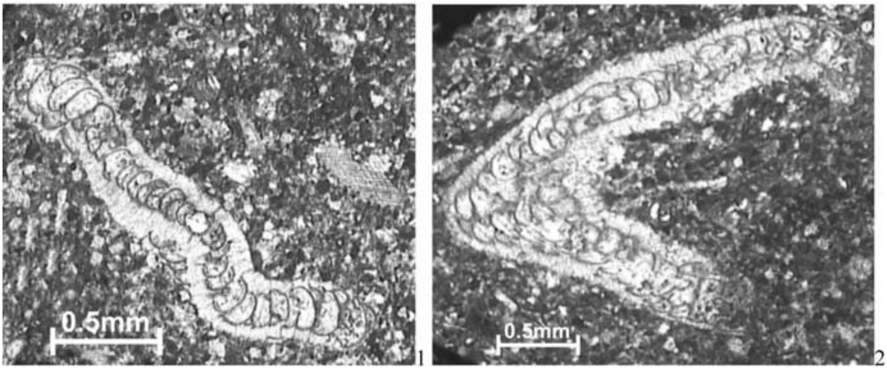

Fig. 3: Primitive *Orbitoides* species presenting undulate (1) or concavo-convex (2) shape of test.

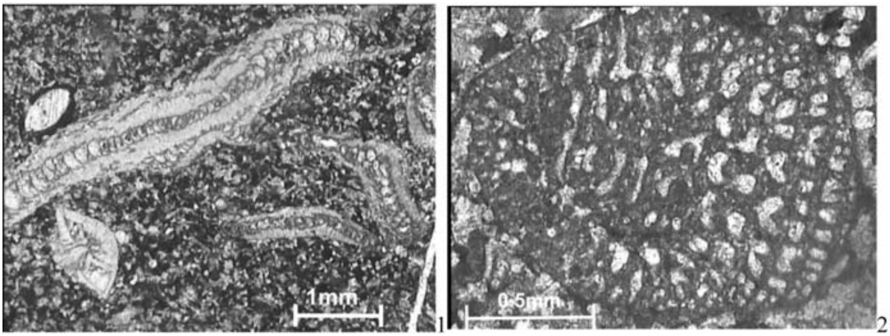

Fig. 4: 1: Primitive *Orbitoides* species presenting undulate test shape and few lateral chamberles 2: *Calvezi-conus lecalvezae* associated with primitive *Orbitoides* species.

stones. The observed specimens were studied in random thin sections. In these cases it is difficult to obtain oriented sections, necessary to determine the different species. Besides, as mentioned above, the chambers in the median layer of primitive species are not disposed in a plane, as happens in the case of the evolved species of the genus and the undulation starts by the embryonic and juvenile stage of growth. This implies incertitude if a 3 or 2chambered embryonic apparatus, observed in an axial, or even an equatorial section belongs actually to a specimen with a 2-, 3- or 4-chambered embryonic apparatus.

The specimens observed in the studied samples don't possess true lateral chambers, or a biconvex shape of test. They have a plan, undulate or concavo-convex test (Fig. 3). For this reason they are attributed to primitive, pre-*tissoti* species.

Axial and subaxial sections are mostly obtained. Embryonic and juvenile stage of growth is poorly represented in our sections. So, no measurements were obtained.

An equatorial section (Fig 5/1) presents a 4chambered H shaped embryonic apparatus, enveloped by a thickened wall. Thickened wall enveloping the embryonic apparatus is observed also in Fig. 5/2, in an oblique subequatorial section. The section cuts 3 of a 4chambered embryonic apparatus.

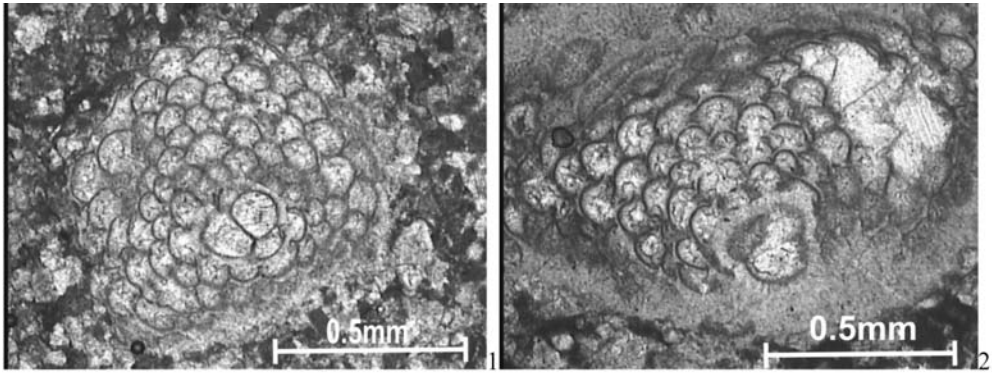

Fig. 5: 1: Equatorial section of specimen with a 4chambered embryonic apparatus enveloped by a thickened wall. 2: Oblique subequatorial section of a specimen possessing an embryonic apparatus enveloped by a thickened wall. The section cuts 3 of the 4 embryonic chambers.

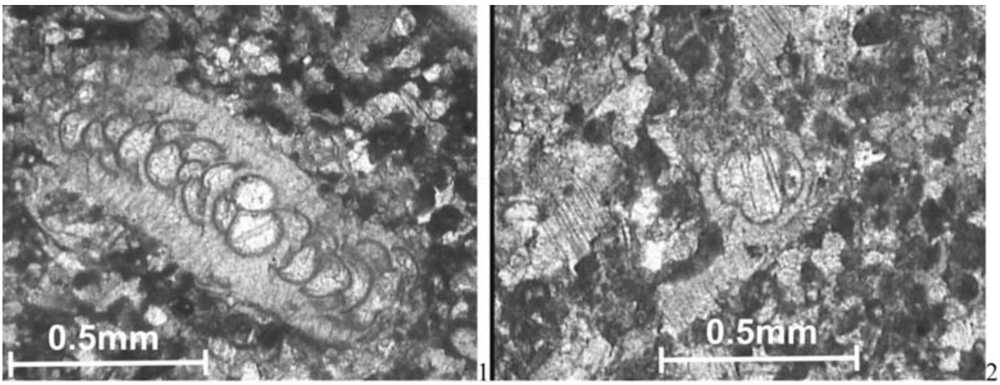

Fig. 6: 1: Axial section cutting 3 of the 4chambered embryonic apparatus, enveloped by a thickened wall. 2: Isolated 4chambered embryonic apparatus enveloped by a thickened wall.

An axial section cutting 3 of a 4 chambers of the apparatus enveloped by a thickened wall is presented in Fig 6/1, while Fig 6/2 shows an isolated typical *tissoti*-embryonic apparatus. Nevertheless no *tissoti* biconvex specimens, possessing true lateral chambers pierced by pillars were found in the studied material.

Specimens in Fig 7/1,2 show in axial sections a 2chambered embryonic apparatus with P>D, enveloped by a thickened wall. These specimens could be determined as *O. sanctae pelagiae* according to Hottinger (1966). Nevertheless, the axial sections could also be interpreted as cutting 2 of the 4 chambers of the embryonic apparatus.

The specimens owing a 4-chambered embryonic apparatus differ from *O. douvillei* species, by the thickened wall enveloping it. They could represent a new species, between the *douvillei* and *tissoti* evolutionary lineage. More equatorial sections allowing observation and measurements of the features of embryonic apparatus are necessary for the creation of a new species.

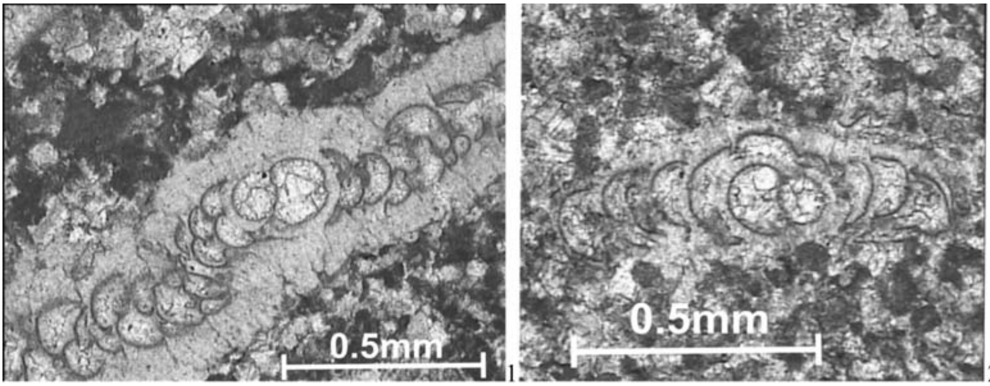

Fig. 7: 1, 2: Axial sections showing 2chambered embryonic apparatus with P>D, enveloped by a thickened wall.

5. Conclusions

Primitive *Orbitoides* species are described for the first time in Greece, in central Peloponnesus, in Mainalon Mountain. They occur in dark medium bedded limestones, wackestones - packstones, rich in rudist tests. They are associated with rotaliids, echinoids, *Cuneolina* sp., *Dicyclina schlumbergeri*, and *Calveziconus lecalvezae* dating Campanian age.

Orbitoides specimens were studied in random sections. They are characterized by a plan, undulate, concavo-convex shape of test. They lack true lateral chambers. Due to the undulation of the test even from the first embryonic and nepionic stage of growth, it is difficult to obtain good equatorial sections, necessary for the specific determination. Specimens showing a 2-chambered embryonic apparatus enveloped by a thickened wall could, with the above reserves, be determined as *O. sanctae pelagiae*. Specimens observed possessing a 4-chambered embryonic apparatus differ from *O. douvillei* by the existence of a thickened wall enveloping the embryonic apparatus. They could represent a new species, between the *douvillei* and *tissoti* evolutionary lineage. Nevertheless, more equatorial sections allowing observation and measurements of the features of the embryonic apparatus are necessary for the creation of a new species.

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A NEW LATE MIOCENE PLANT ASSEMBLAGE FROM MESSARA BASIN (CRETE, GREECE)

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Abstract

A rich terrigenous plant assemblage was recently excavated from early Tortonian deposits at Messara basin, southern Crete. The macro-remains are perfectly preserved as impressions or carbonized compressions in poorly lithified and locally laminated, blue-green clays with an age of at least 10.5 Ma and thus can be considered as the oldest plant assemblage found in Crete todate. Gymnosperms are represented by the families of Pinaceae (pine needles and winged seeds), Cupressaceae and Taxodiaceae (leafy twings of Taxodium). Besides, 19 different angiosperm taxa of trees and shrubs have been also determined. Fagaceae is the most diversified with foliage of beech and several deciduous and evergreen oaks, while Myricaceae contribute mainly as abundant leaf remains of Myrica lignitum. Accessory elements of evergreen Lauraceae (Daphnogene polymorpha), sclerophyllus shrubs of Buxaceae (Buxus pliocenica) and various deciduous dicotyledonous such as Populus crenata, Liquidambar europaea, Carya minor and Acer pseudomonspessulanum are well documented. Leguminosae is recorded by a significant number of various small leaflet imprints. Therefore, the recovered remains indicate swampy forest habitats dominated by hygrophilic woody plants of Taxodium and Myrica, while in the surrounding plains and slopes a mixed mesophytic forest with a relatively low proportion of evergreen plants occurred in early-Late Miocene times in Crete depicting a moderately humid, warm-temperate nature for the climate.

Key words: *plant fossils, palaeoflora, palaeovegetation, Miocene, Pitsidia, Crete, Messara.*

1. Introduction

The island of Crete is part of the Hellenic mountain chain formed during the late stages of Alpine orogenesis. During the middle Miocene the area was affected by intense crustal extension as a result of the retreatment of the African plate subduction and the lateral extrusion of the Anatolian plate (Angelier et al., 1979; Fassoulas, 2001; Meulenkamp, 1994). Fragmentation of landmasses resulted in the development of multi-oriented basins filled by Neogene and Quaternary sediments of various origins. For several decades, lignite deposits and other terrestrial sediments had addressed the possibility for the existence of terrestrial plant macro-remains in some of these basins; however, until recently these basins had not been extensively studied as in other places of Greece. Despite the local character of such fossil records and the doubtless inequitable representation of ancient vegetation, they provide invaluable information about the history and distribution of the floristic elements and offer a great potential for identifying past environmental signals. The first comprehensive reports on Cretan plant macro-fossils derive from the integrated study on the diversified late Tortonian plant assemblage of Makrilia sediments, in eastern Crete (Sachse & Mohr, 1996; Sachse et al., 1999;

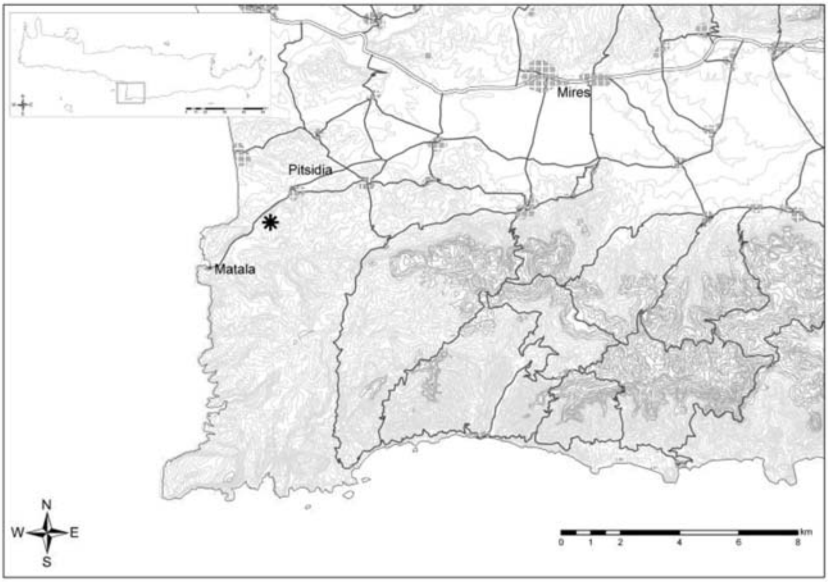

Fig. 1: Generalised topographical map of Eastern Messara basin. The black star indicates the exact position of the Pitsidia fossiliferous locality, southwest of the village Pitsidia.

Sachse, 2004). A few years later, Zidianakis et al. (2007) described a Late Tortonian-Early Messinian palaeoflora from the area of Vrysses in western Crete.

In this preliminary report we describe a new rich terrigenous plant assemblage, excavated recently in Messara basin, at the southern part of central Crete which consists mainly of foliage and diaspores. Terrestrial assemblages have been already found in the past at the eastern margin of the basin at the locality Kastelios hill near Kastelliana village. This locality is well known for its Valesian mammalian fauna (De Bruijn et al., 1971). Hitherto, data on the past plant cover of the basin had been extremely poor, limited exclusively to a few pollen spectra analyses (Benda et al., 1974; Van der Weerd, 1983; Sen et al., 1986). The plant bearing sediments of this study are located near the village Pitsidia in the southwest part of the basin (Fig. 1) and are considered to be early Tortonian or even late Serravallian in age (Kröger, 2004). If this dating is accurate, Pitsidia assemblage will constitute the oldest plant macro-remains that have been ever found on the island and thus can shed light to the palaeoenvironment of an unknown period of the geological history of the Island.

2. Geographical and stratigraphical settings

Messara basin, located at the southern part of central Crete, was originally formed during the Neogene as part of a larger basin extending northwards to the area of the present Heraklion basin. Tectonic processes during the early Pliocene separated these two basins with the development of the east-west central Heraklion Ridge (Fassoulas, 2001). Extending in an east-west orientation, Messara basin nowadays covers an area of about 360 km^2 bounded by the Psiloritis Mountains and the central Heraklion Ridge to the north, the Asteroussia Mountains to the south and the foothills of Dicti Mountains to the east. Westwards the basin expands into the Libyan sea.

The stratigraphic development of the Neogene sediments in Messara basin had been the subject of various studies in the past (e.g., Meulenkamp et al. 1979; ten Veen and Postma, 1999 and Kröger, 2004). According to these studies, the oldest sediments lie unconformably on the basement, Mesozoic to Paleogene, rocks composed mainly of limestone and flysch of the Tripolitza nappe (Creutzburg and Seidel, 1975, Bonneau, 1984). They comprise thick successions of siliciclastic, carbonate and marl deposits of terrigenous and mainly marine origin. These sediments have been separated into two formations, the Ambelouzos and Varvara formations (Meulenkamp, 1979; Meulenkamp et al., 1979; ten Veen and Postma, 1999).

The area, where the fossiliferous beds of Pitsidia are situated, is characterized by low hills dissected by ephemeral creeks. The studied outcrop constitutes a thick succession of terrigenous clastics, estuarine and shallow to open marine sediments which can be divided into 3 main lithostratigraphic units. The lower unit comprises mainly overbank river deposits and presents an alternation of conglomerates, sands, clays and silts that originated from the metamorphic rocks of the nearby mountains. The total thickness of this sequence remains unknown. The middle unit consists of successions of conglomerate and sand layers which indicate coastal, estuarine and shallow marine depositional environments. In the upper unit shallow marine bioclastic (mainly red algae) limestones are found. The first two units can be well correlated with Kröger's (2004) LFA1 unit, whereas the third one matches with his LFA2 unit.

In the lower unit a 5m thick layer of blue-green, poorly lithified and locally laminated clays and silty clays contains a large number of land plant macro-remains, while lack of marine fossils clearly indicates its terrigenous origin. This layer overlies fine sand, while at the top a thin coarse sand layer interrupts the low energy sedimentation which continues above it with a 30cm silty layer that also contains plant remains. The silt gradually turns into sand and for the next two meters a succession of conglomerates, sands and silts dominates.

Kröger (2004) using Sr isotope chronostratigraphy examined the bioclastic limestones of the area nearby the fossiliferous outcrop, southwest of Pitsidia village. The age of the base of these limestones which coincide with the limestone of our third unit was determined as early Tortonian (around 10.5 Ma). Consequently, the age of the fossiliferous layer can be presumed as older than 10.5 Ma, probably early Tortonian. Therefore, this determination supports the statement that the Pitsidia plant assemblage can be considered as the oldest recovered on the island, and in South Greece todate.

3. Material and methods

The terrigenous plant assemblage from Pitsidia is represented by at least 500 specimens that have been collected so far, comprising mainly of foliage (impressions, sporadically carbonized compressions) and less frequently of inflorescences, shoots, fruits and seeds. The material is quite damaged and is characterized by numerous, small in size, leaf fragments which are found scattered throughout the fossiliferous clays. The plant fossils are extremely abundant and in a few cases, the quality of preservation is excellent. Such specimens are exceptionally preserved, and thus cuticle remains are clearly detectable. The studied material is housed in the collections of the Natural History Museum of Crete, and hence the specimens are referred with the collection numbers of the Museum.

The taxonomic determinations established in this study are based exclusively on the gross morphological characters of the gathered specimens, whereas special attention is paid to the morphological details of lamina venation and margin outline of the leaves. The used morphological terminology is based on the descriptions of Hickey (1973), Dilcher (1974) and L.A.W.G. (1999), while the taxonomical arrangement of the angiosperms follows the system proposed by Takhtajan (1987).

4. Floristic composition

The Pitsidia assemblage, apart from the great number of specimens, is considered to be fairly diverse as more than 25 taxa have been identified at this preliminary stage, including two ferns or ferns allied, at least four gymnosperm and 19 angiosperm taxa (Table 1). Among them, the families of Myricaceae and Pinaceae are clearly the most abundant, while Fagaceae, Taxodiaceae, Salicaceae, Altingiaceae and Lauraceae are quite common. Other families like Cupressaceae, Sapindaceae, Leguminosae, Buxaceae, Juglandaceae, Poaceae vel. Cyperaceae and probably Ulmaceae have been also recognized although their occurrence is less frequent.

Pteridophyta are represented by a single fragment of a sterile front, deeply pinnatifid (Fig. 2a) which is attributed to the first occurrence of fern macro-fossils on the island and a jointed, unbranched, aerial stem assigned to the genus *Equisetum* L (Fig. 2b).

The presence of gymnosperms in the assemblage is demonstrated by both reproductive and vegetative organs. The genus *Pinus* L. is documented by well distinguishable needles in fascicles of three (Fig. 2c) that are particularly numerous in the fossiliferous layers, together with a few winged seeds (Fig. 2f). The needles are quite long and remarkably broad (10-20mm) with prominent basal leaf sheaths which are always persistent. In the Greek Neogene, almost identical needle fascicles have been reported by Unger in 1867 from the brown-coal bearing sediments of Kymi on Euboea Island. He classified this type of needles to the fossil species *Pinus holothana* Unger. Moreover, a large number of fragments of long, sterile shoot axes of cryptomerioid type along with some terminal parts of shoots with lanceolate bifacial leaves indicate the occurrence of Taxodiaceae family (Fig. 2d). We tend to believe that all these shoots correspond better with the genus *Taxodium* Rich.

Angiosperms, which apparently prevail, are documented either by numerous leaves and leaflets or less frequently by inflorescences and fruits. *Myrica lignitum* (Unger) Saporta is the floristic element that predominates by far the assemblage (Fig. 2g). The fossil leaves that correspond to this ancient species represent approximately 50 per cent of the total recovered plant material. However, at the moment it is difficult to judge to what extent this monotonous appearance is a result of taphonomic bias. Apart from the numerous records, it worth's noting as well the amazing variance in lamina shape, size, and type of margin demonstrated by the recovered foliage. It is generally accepted that although *Myrica lignitum* consists a very common and wide spread element of European Neogene floras, the evolutionary linage of this species and its relation to modern allies has not been fully resolved so far. Nevertheless, the majority of the authors agree that it should be considered as a typical swamp or riparian element which can survive periodical and long-lasting floods (Kovar-Eder et. al, 2001; Krenn, 1998; Kvaček et. al 2004). Besides *Myrica lignitum*, another component of the Myricaceae family is present: the well distinguishable *Comptonia difformis* (Sternberg) Berry with the typical deeply pinnately lobed leaves (Fig. 2h). Actually, the presence of this element in the Neogene of Crete is reported here for the first time.

The family Fagaceae is by far the most diversified in the assemblage. It comprises of at least one species of beech and four other different oak species. In particular the beech *Fagus* type *attenuata* (Fig. 2i) and the deciduous oak, *Quercus roburoides* Gaudin (Fig. 2j), are well documented. It worth's noting that this is also the first report for the presence of roburoid oaks as leaf macro-remains from the Neogene sediments of Crete and probably the earliest from the Greek Neogene. On the other hand, the evergreen sclerophyllous *Q. mediterranea* Unger (Fig. 2m) and *Q. drymeja* Unger (Fig. 2o) are less frequent. Unlike roburoid oaks, *Q. mediterranea* can be considered, with reasonable safety, as a widespread element in the Upper Miocene throughout Crete, since it has been also reported from Vrysses in the western and from Makrilia in the eastern part of the island.

Table 1. The floristic composition of Pitsidia plant assemblage.

Nr.	Family	Genus	Species	Type	No of specimens
Pteridophyta					
1	Equisetaceae	*Equisetum*	sp.	stem	1
2	fam. indet.	---	---	front	1
Gymnospermae					
3	Pinaceae	*Pinus*	sp.	needles in fasc. of 3	117
4		*Pinus*	sp.	winged seeds	4
5	Taxodiaceae	*Taxodium*	sp.	leafy shoots	10
6	Cupressaceae	*gen. indet.*	---	leafy shoots	3
Angiospermae					
7	Lauraceae	*Daphnogene*	*polymorpha*	leaves	8
8	Altingiaceae	*Liquidambar*	*europaea*	leaves	4
9		*Liquidambar*	*sp.*	infructescences	6
10	Fagaceae	*Fagus*	*type attenuata*	leaves	10
11		*Quercus*	*roburoides*	leaves	22
12		*Quercus*	*mediterranea*	leaves	5
13		*Quercus*	*drymeja*	leaves	3
14		*Quercus*	*?kubinyii*	leaves	3
15	Myricaceae	*Myrica*	*lignitum*	leaves	205
16		*Comptonia*	*difformis*	leaves	2
17	Juglandaceae	*Carya*	*minor*	leaflets	2
18	Salicaceae	*Salix*	*sp.*	leaves	3
19		*Populus*	*crenata*	leaves	5
20	Leguminosae	*Podocarpium*	*podocarpum*	leaflet	1
21		*gen. indet.*	---	leaflet	1
22	Buxaceae	*Buxus*	*pliocenica*	leaves	2
23	Sapindaceae	*Acer*	*pseudomonspessulanum*	leaf	*1*
24	Ulmaceae	*?Zelkova*	zelkovaefolia	leaf	*1*
25	Poaceae vel. Cyperaceae	*gen. indet*	---	leaves	2

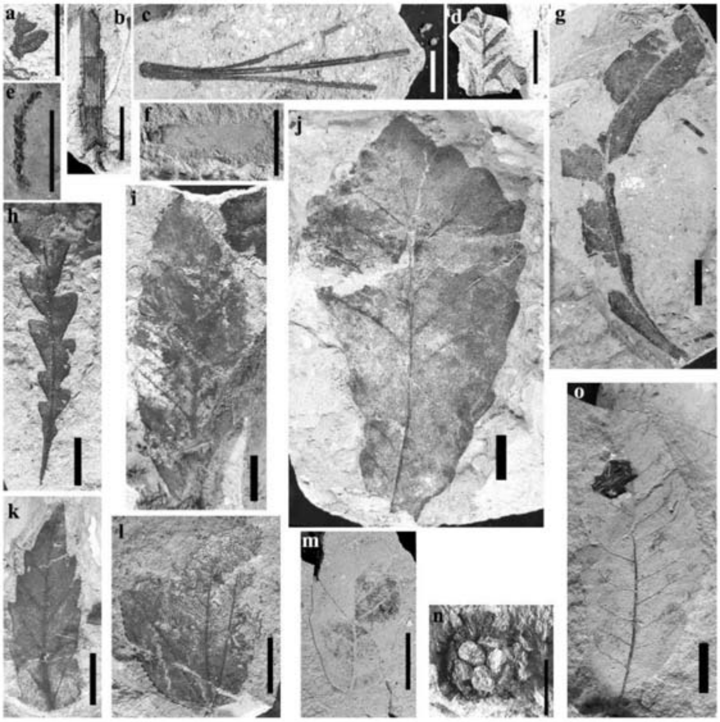

Fig. 2: Plant remains from Pitsidia outcrop: a) Fern no 31.4.2.109a; b) *Equisetum* sp. no 31.4.2.014; c) *Pinus* sp. (needles) no 31.4.2.472; d) *Taxodium* sp. no 31.4.2.219; e) Cupressaceae no 31.4.2.132; f) *Pinus* sp. (seed) no 31.4.2.322ii; g) *Myrica lignitum* no 31.4.2.060; h) *Comptonia difformis* no 31.4.2.105; i) *Fagus* type *attenuata* no 31.4.2.317; j) *Quercus roburoides* no 31.4.2.322i; k) *Quercus* cf. *kubinyii* no 31.4.2.323; l) *Liquidambar europaea* no 31.4.2.273; m) *Quercus mediterranea* no 31.4.2.272; n) *Liquidambar* (fruit) no 31.4.2.278; o) *Quercus drymeja* no 31.4.2.206. Scale bars 1 cm.

In the group of common floristic elements of the assemblage we can include another broad-leaved deciduous tree, *Liquidambar europaea* A. Braun. In general, the recovered population demonstrates foliage with exclusively three lobes (Fig. 2l). A thorough examination of macro-fossil records in numerous European localities has shown that three-lobed leaf forms predominated during the early Neogene, while this trend gradually changed in the Late Miocene and Pliocene as foliage with five or seven lobes became more frequent (Bůžek, 1971). In Pitsidia, the robust occurrence of the genus *Liquidambar* L is supported by the recovery of spherical fruiting heads which consist of dense clustered, elongate, wedge-shaped fruits (capsules). Their systematic position is positively confirmed by the characteristic honeycomp-like shape of the peripheral rim that one of the specimens displays (Fig. 2n). Actually, it can be concluded to a certain extent that these infructescences are related with the three-lobed leaves of *L. europaea* and probably they consist parts of the same species.

In this preliminary study, the occurrence of lauraceous elements is surprisingly rare. The morphospecies *Daphnogene polymorpha* (A. Braun.) Ettigshausen is the only component of the Lauraceae family identified till now (Fig. 3a). This weak representation can be ascribed either to the influence of an already well-established seasonal climate with a pronounced dry or cool period during the year, or perhaps to taphonomic bias.

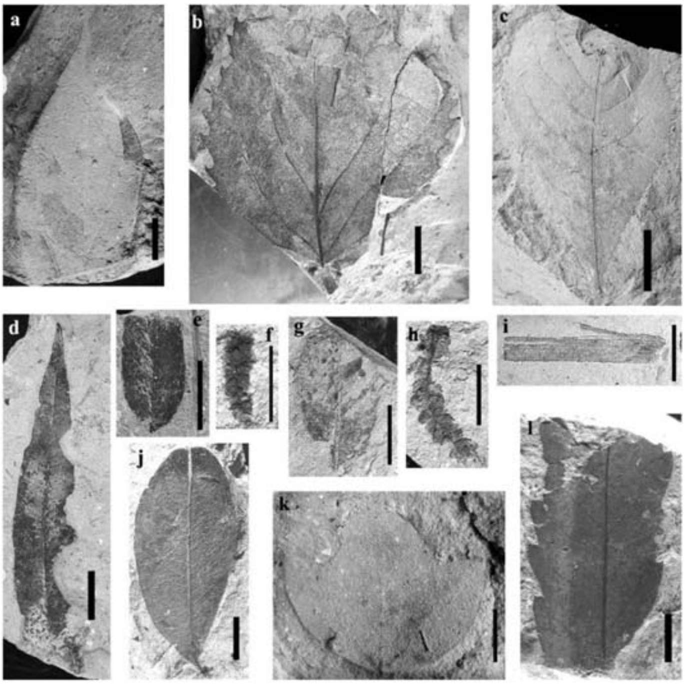

Fig. 3: Plant remains from Pitsidia outcrop: a) *Daphnogene polymorpha* no 31.4.2.263; b) *Populus crenata* no 31.4.2.349; c) *Carya minor* no 31.4.2.471; d) *Salix* sp. no 31.4.2.354; e) *Podocarpium podocarpum* no 31.4.2.229; f) Catkin probably of *Myrica* no 31.4.2.098; g) *Buxus pliocenica* no 31.4.2.269; h) Catkin probably of Betulaceae no 31.4.2.192; i) Poaceae vel. Cyperaceae no 31.4.2.312; j) Leguminosae leaflet no 31.4.2.207; k) *Acer pseudomonspessulanum* no 31.4.2.211; l) cf. *Zelkova zelkovaefolia* no 31.4.2.267. Scale bars 1 cm.

The family of Salicaceae is represented by the genera *Populus* L. (Fig. 3b) and *Salix* L. (Fig. 3d). The former comprises of tri-veined leaf forms with large teeth which are quite similar with the poplar foliage remains from Gabbro, in central Italy, described by Berger (1957) under the name *P. crenata* Berger. In the Greek Neogene, these leaves correspond better to the population from the Late Miocene flora of Vegora in Macedonia (northern Greece), assigned to the common poplar species *Populus populina* (Brongniart) Knobloch (Kvaček et al., 2002). Nevertheless, taking into account the great leaf variation that most of the modern poplar species demonstrate, it is not quite clear whether leaf forms like those recovered in Pitsidia represent a separate ancient species (i.e. *P. crenata)* or consist part of the leaf variation inside the common species *P. populina*.

An account of pollen grains from several sediment samples from the Kastellios hill sections, indicates that the family Juglandaceae in Messara basin was quite abundant and widely diversified (Benda et al., 1974; van der Weerd, 1983; Sen et al., 1986). These sections, located in the easternmost borders of the basin, are considered to be very close or even identical in age with the fossiliferous layers from Pitsidia. Surprisingly, in the Pitsidia assemblage, the family Juglandaceae by no means dominates, comprising until now merely of two leaflets that probably belong to the species *Carya minor* (Saporta et Marion) Saporta (Fig. 3c).

The family of Leguminosae is represented by the well known element *Podocarpium podocarpum* (A. Braun) Herendeen (Fig. 3e), and a few small leaves with entire margin and more or less asymmetrical basis (Fig. 3j). Especially *Podocarpium podocarpum* is only documented by a sole incomplete leaflet. Its venation, which is characterized by a pair of prominent basal secondary veins originating at acute angles and extending parallel to the lamina margin, allowed us to attribute this specimen with certainty to this species. After numerous taxonomic treatments by many authors, this taxon seems to represent an extinct genus of the Leguminosae family and does not correlate with any extant legume (Herendeen, 1992 a, b; Wang et. al, 2007).

In addition, a few interesting, though very poorly represented accessory elements, have been collected from Pitsidia deposits that correspond to the ancient morpho-species *Acer pseudomonspessulanum* Unger (a sole leaf specimen) (Fig. 3k), *Buxus pliocenica* Sapota et Marion (two leaf specimens) (Fig. 3g) and probably *Zelkova zelkovaefolia* (Unger) Kotlaba (one leaf specimen) (Fig. 3l).

Finally, we must point out that numerous findings consisting of leaf and fruit remains as well as excellent-preserved compressions of male inflorescences (mainly catkins), that have a questionable affinity are not presented in this study as their taxonomic determination was not considered plausible (Figs. 3f, 3h). In the future further investigations will be undertaken including leaf cuticular analysis and catkin pollen examination in order to decipher the affinities of this unidentified material and furthermore, to confirm or even improve the identifications of the plant remains described above.

5. Vegetation reconstruction and paleoclimate

In fossil plant assemblages, the taphonomic processes during sedimentation bring together plant remains originating from different habitats. In order to obtain reliable results about the regional vegetation structure and the plant associations, a number of geological and taphonomical disciplines (e.g. Ferguson, 1985; 2005; Gastaldo, 2001; Greenwood, 1991; Spicer, 1989) along with the study and evaluation of numerous palaeofloras throughout Neogene is also necessary to be taken into account. According to the stratigraphical architecture and deposit lithologies that occur in Pitsidia and the adjacent areas, a characteristic estuary landscape interfingering with backswamp, floodplain, riverbank and probably bog habitats is well documented (Kröger, 2004). These depositional settings are in complete agreement with the relative abundance of the floristic elements in the assemblage and the autoecology of the identified taxa.

Within the deltaic plain, at a certain distance from the sea shore, typical backswamp systems were occurring. The permanent waterlogged soils were inhabited by a more or less closed canopy forest, which had been probably dominated by the typical swampy conifer *Taxodium*. This could have been either the sole canopy component or in some elevated areas it could have been associated with broadleaved elements like *Liquidambar europaea* or even with pine trees. In the understorey of the swamp plant community, only a few taxa probably grew like *Myrica lignitum* and *Comptonia difformis*, where the former clearly predominated.

Taking into account the extreme abundance of *Myrica* macro-remains in the assemblage, and the fact that many living species of this genus are considered as early succession elements with nitrogen-fixing nodules at the roots, which enable the plants to colonize soils that are very poor in nitrogen content, we expect a widespread occurrence of acid, shrub covered bogs in the Pitsidia wetlands. In these habitats, with low nutrient supply and ground water level lying near or above the earth surface, a dense population of *Myrica lignitum* apparently prevailed.

The active river channels and the allied oxbow ponds have been lined by a probably oligotypic gallery forest predominated in particular by Salicaceae (*Populus crenata* and *Salix*) and *Liquidambar* *europaea*. Furthermore, the presentation of *Myrica lignitum* in the understory of this riparian formation is quite possible, while *Equisetum* seems to constitute a usual element associating among others with ferns in the herb layer.

Beyond the influence of flooding, on the slopes of the adjacent hills, zonal vegetation was quite diverse but not uniform, depending on the moisture and fertility of the soil as well as on the sun exposition. On moderately moist substrates a widespread mixed mesophytic forest probably occurred, composed mainly of broad-leaved deciduous trees and an extremely low proportion of evergreen elements. This temperate forest clearly is related phyto-sociologically with the Class *Querco-Fagetea*. Except from the *attenuata*-type beech trees, the deciduous oaks and especially *Quercus roburoides*, were predominating in the forest canopy creating an association that could be named *Fagetum attenuatae – Quercetum mixtum*. The evergreen *Daphnogene polymorpha* and presumably the deciduous *Podocarpium podocarpum, Zelkova zelkovaefolia and Carya minor* represent the only accessory elements that have been found in the Pitsidia assemblage so far. The shrub layer was poorly developed probably consisting of both deciduous (*Comptonia difformis*) and evergreen (*Buxus pliocenica*) elements. On drier substrates, this ancient association seems to have been replaced by a well-developed xerophytic woodland. The characteristic species in the canopy were the sclerophyllous oaks of the *Quercus mediterranea*/*Q. drymeja* group, while shrubs of similar physiognomy were occurring in the understorey including *Acer pseudomonspessulanum, Buxus pliocenica,* Cupressaceae and Leguminosae. This plant association can be referred as the *Quercetum mediterraneum* association (Class of *Quercetea*). On southern slopes and in areas with poor substrate, the pine trees were probably forming pure stands, although the huge amount of pine needles and diaspores in the assemblage allows us to suppose that this element was spreading also on sites with higher soil fertility and moisture, possibly close to wetland, forming a mixed oak - beech - pine forest.

As it is revealed by this preliminary study, the Pitsidia assemblage floristically is characterized by the apparent predominance of ‘arctotertiaty’ elements, whereas thermophilic elements are quite rare (i.e. *Daphnogene*, Taxodiaceae). Besides, the zonal vegetation in the area consists of both mixed mesophytic forests with a relatively high percentage of broad-leaved deciduous taxa and sclerophyllous woods. The simultaneous occurrence of these units and elements attests to a relatively humid, warm-temperate climate with only one weakly dry period during the year (Cfa-type climate sensu Köppen, 1931), which actually is not directly comparable to the present Mediterranean type.

6. Comparison with other Neogene flora of Crete

Two outcrops with Neogene terrestrial plant macro-remains have been known in Crete so far. The oldest, situated near Makrilia village in the eastern part of the island, is dated as Late Tortonian, approximately 7.7 to 8.6 million years ago, while the youngest found in the western part of the island near Vrysses village is estimated to be of latest Tortonian – Early Messinian age (ca 7.5 - 6.0million years). Generally speaking, the Pitsidia flora varies rather profoundly from the other two due to its pronounced swampy-riparian character. Floristically they only share a few common elements, like *Quercus mediterranea, Acer pseudomenspessulanum, Buxus pliocenica* and *Daphnogene polymorpha*. However, all assemblages from Crete include without any doubt a prominent proportion of sclerophyllous woody plants except from mesic ones, reflecting in this way the significant occurrence of warm sub-humid habitats on the island during the Late Neogene.

Furthermore, the Makrilia assemblage is obviously closer, floristically and also physiognomically, to that of Pitsidia as they share many elements like the hydrophilic *Myrica lignitum, Taxodium, Eq-*

uisetum, Populus, Salix, and some, more or less, mesic arboreal elements including *Fagus* type *attenuata, Quercus kubinyii, Podocarpium podocarpum*. Of course, there are a few significant dissimilarities between them as well. Contrary to Pitsidia, the Makrilia flora presents an apparently small-leaved character and illustrates a remarkable higher diversity extending to 70 different identified taxa. Especially, the mixed mesophytic forests comprise a great number of various deciduous accessory elements like *Zelkova zelkovaefolia, Ulmus, Carpinus, Fraxinus* and *Tilia*. Moreover, the families Lauraceae and Magnoliaceae are well diversified in Makrilia flora, accompanied by other thermophilic elements like Engelhardieae, *Tetraclinis salicornioides* and *Asterocalyx styriacus*. Likewise, the sclerophyllous elements are more frequent and more diverse.

On the other hand, the assemblage of Vrysses is dominated by the sclerophyllous *Quercus mediterrane*a and numerous fragments of pine needles. Both three-lobed leaves of *Acer pseudomonspessulanum* and segments of *Tetraclinis* are quite common while various elements like *Daphnogene polymorpha*, *Buxus pliocenica*, *Juglans*, *Populus tremula* and a few leaflets of Leguminosae are also present. In addition, typical swampy plants are completely absent. Thus, contrary to Pitsidia, the flora of Vrysses demonstrates a more sub-humid character with many xeromorphic elements that indicate the occurrence of well-developed sclerophyllous plant associations. Also, the mesophytic woodland palaeocoenoses are clearly less diverse and probably poorly developed. Tall deciduous trees like beech and oaks are apparently lacking. Instead only a few deciduous shrubs like *Parrotia pristina* and *Ziziphus ziziphoides* seldom occur.

Finally, it is important to notice the strong presence of some conspicuous floristic elements like sweetgum, roburoid oaks and Pine trees with needles in fascicles of three in Pitsidia that are entirely absent from Makrilia and Vrysses ancient macro-floras. In particular the genus *Liquidambar* is absent even from the pollen spectrum of Makrilia.

7. Conclusions

The Late Miocene plant material from the area of Pitsidia in the southern part of central Crete is quite abundant with elements of both autochthonous and allochthonous origin, deposited in an estuary environment. The assemblage comprises of at least 25 different plant taxa, a number which is expected to increase dramatically in the future as, at the moment, this study is in a preliminary stage. It consists mainly of broad-leaved deciduous or evergreen angiosperms and a few conifers and ferns. Leaf remains of *Myrica lignitum* and pine needles in fascicles of three predominate. Also, *Taxodium* with sterile shoots, *Quercus roburoides*, *Fagus* type *attenuata* and *Liquidambar europaea* are considered common elements of the flora. Among the identified taxa, fern macro-remains, 3-needled *Pinus*, *Comptonia difformis*, *Liquidambar europaea*, roburoid oaks, *Quercus drymeja* and *Populus crenata* are reported for the first time from the Neogene of Crete. The floristic composition of Pitsidia is in full accordance with the results of earlier pollen grain analyses from contemporary sediments at the eastern border of Messara basin which record the predominance of Myricaceae, Fagaceae and Taxodiaceae elements.

According to the current data, the palaeoflora of Pitsidia indicates the occurrence of extensive swampy and riparian woods throughout the wetlands, together with both deciduous mesophytic and evergreen xerophytic, mid altitude forests at the slopes of the surrounding hills, developed in a relatively warm temperate climate with a weakly developed dry period. So, we are convinced that these new plant findings will provide a unique opportunity to enrich our fragmentary knowledge of the past and emerge a more accurate picture of the vegetation succession and the palaeoenvironmental history of the southernmost European province.

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STUDYING IN THE PAXOS ZONE THE CARBONATE DEPOSITIONAL ENVIRONMENT CHANGES DURING UPPER CRETACEOUS, IN SAMI AREA OF KEFALLINIA ISLAND, GREECE

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Abstract

The shallow-marine carbonate sequence of Sami (Kefallinia isl. Fig. 1) is a part of the Upper Cretaceous carbonate platform of the Paxi zone. Detailed lithostratigraphic and microfacies analysis of that sequence revealed clear periodicities and cyclicity. The high-resolution stratigraphic analysis has shown a number of lithofacies organized in groups (lithofacies associations), suggesting, on the whole, sedimentary environments ranging from lagoonal to peritidal context. The vertical arrangement of these lithofacies allowed the identification of a cyclic recurrence of the depositional and early diagenetic features, including a meteoric overprint on top of the elementary cycles. The cycles exhibit a shallowing upward trend from shallow subtidal to inter-supratidal and hypersaline facies, in a warm shallow marine environment.

Key words: *peritidal carbonate, Upper Cretaceous, Paxi zone, Kefallinia.*

1. Introduction

Peritidal carbonates are shallow-subtidal, intertidal and supratidal sediments formed in marginal-marine and shoreline depositional environments. These carbonates settings include the deposits of tidal flats, sabkhas, and shallow subtidal areas such as lagoons (Flügel, 2004). They have an important economic significance, for not only do they act as hosts for metalliferous and non-metalliferous mineral deposits but may also form sources, seals, and reservoirs for hydrocarbons (Wright, 1984).

The peritidal deposits are easy to be recognized in outcrops and in thin sections. They are important paleo-bathymetric indicators, reflect sea-level fluctuations, and form the basis for evaluation of sedimentary cycles and stratigraphic sequences.

The recognition and interpretation of ancient marginal-marine carbonate is fundamentally depended on comparison with modern transitional-marine carbonate environments. This approach is very successful, but should be applied cautiously. Fine-laminated carbonates do not necessarily originate in tidal zones, and spar-filled voids in micritic rocks could have been formed in tidal zones as well as in various subtidal environments. The best way to overcome these difficulties is to use the whole set of facies criteria and take into consideration the changes in microfacies and the sedimentary structures within vertical sequences.

Ancient carbonate rocks are traditionally studied by dividing peritidal environments into subtidal,

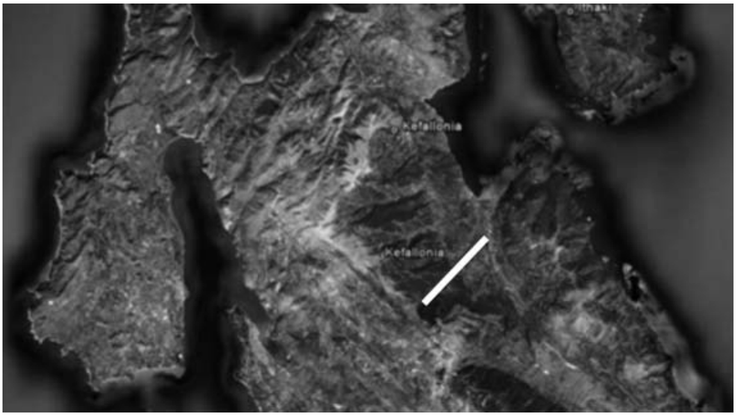

Fig. 1: Kefallinia Island. Simplified map showing the studied cross-sections.

intertidal and supratidal zones, despite the problems involved. Whether an area is subtidal, intertidal or supratidal depends on the tidal range, mean sea level.

According to Flügel (2004), subtidal sediments are seldom exposed to air. The term subtidal is restricted to those sediments seaward of a tidal flat system or within a system, such as in tidal channels. Intertidal sediments lie within normal high tide and normal low tide and they were exposed either once or twice daily normal, depending on the tidal regime and local wind conditions. Finally, supratidal sediments were deposited above normal or mean high tide and exposed to subaerial conditions most of the time because they were flooded only by spring and storm tides. Spring tides occur twice each month, and storm tides, the largest of all, occur sporadically during certain seasons and are less frequent.

Peritidal formations are commonly characterized by cyclicity. Cyclicity is a common feature of many limestone successions and occurs across different carbonate environments from platforms to reefs and down to basins. Understanding the origin of cyclicity in platform carbonates is crucial if cycles are to provide information on climate, eustacy and local tectonics, and if they are to be useful for high precision correlation. A cycle is a group of rock units that occur in a certain order, with one unit being frequently repeated through- out the succession. A stratifaction cycle is a group of beds which are regularly repeated. Regularity may be recorded by bed composition, repeated sequences of bed thicknesses, or constant number of beds composing the cycles. Many cycles are ascribed to corresponding, high- frequency and low amplitude sea-level changes (Flugel, 2004; Brescia et al., 1996; D'Argenio et al., 1997, 1999).

2. Geological setting

Kefallinia lies at the external (foreland) edge of the Hellenides fold-and-thrust system created in response to Cenozoic continental collision following closure of the Tethyan Ocean. The external Hellenides lie to the west of the Pindos thrust and are subdivided into three isopic zone: Gavrovo-Tripolitza, Ionian, and Paxi zones. The Gavrovo-Tripolitza and Ionian zones have been considered to represent the external large Hellenide thrust sheets emplaced onto the stable Paxi autochthon as a part of the latest Hellenide events (Abouin and Dercourt, 1962; Temple, 1968; Jenkins, 1968; Smith and Moores, 1974; Underhill, 1989).

During the Early Mesozoic times, an extensive rifting had been developed in the western Greek territory, which due to the platform, in Early–Middle Jurassic times, was subdivided into ridges, and corresponded to the Gavrovo and Paxi zones, and basins, the Ionian and Pindos zones. Post-rift sedimentation

Fig. 2: The peritidal carbonate unit of the studied section (c: cycle).

persisted throughout the Cretaceous leading to the deposition of shallow marine carbonates on the ridges and deep-water carbonates in the basin (Tucker et al., 1990; Getsos, 2005; Getsos et al., 2007).

From the Triassic to the Upper Cretaceous, Western Greece was part of the Apulian continental block on the southern passive margin of Tethys. The island of Kefallinia is characterized by widely exposed Cretaceous limestones of the Paxi and Ionian zones, which were deposited at the margin of the Apulian carbonate platform. Sedimentary rocks in the Paxi zone consist of Triassic to Miocene deposits, mainly neritic carbonates. The Ionian zone comprises sedimentary rocks ranging from Triassic evaporites to Jurassic- Upper Eocene carbonate and minor cherts and shales which are overlain by Oligocene flysh (Karakitsios and Rigakis, 2007).

The Paxi zone forms the major part of the island of Kefallinia. It has been regarded as being the autochthonous foreland to the Hellenide fold-thrust belt which is generally believed to have been unaffected by major shortening (Aubouin, 1965; Jones 1968; British Petroleum Co. Ltd., 1971; Smith and Moores, 1974; Underhill, 1989).

Sami lies immediately to the west of the Ionian thrust and is composed entirely of thick Upper Cretaceous limestones that have been folded into a broad, open, northwest-southeast – trending pericline. The studied sections belong to the Paxi zone and lie across the main road Sami-Argostoli where well exposed outcrops occur. The aim of this work is to recognize depositional environment of a 27m thick unit (part of the Cretaceous succession) which is composed of well-bedded limestone.

3. Data collection and methodology

Shallow-marine bedded carbonate sequences need a detailed sampling program, because they exhibit high microfacies variability due to changing subtidal and tidal depositional sites and common occurrence of cyclic sedimentation patterns. The study aims to understand of short- term changes in environmental of biota and sedimentation and for this reason an almost bed-to-bed sampling has been performed.

The studied area consists of 7 sections extending along 4-5 km and the thickness of the entire study area averages 150 m. In total, 300 samples have been collected. In the present paper the data which are presented, resulted from the study of the fifth section which is 27 m thick (Fig. 2). Microfacies analysis is accompanied by X-ray diffraction analysis.

In the studied succession, the high-resolution stratigraphic analysis has shown a number of lithofacies organized in groups (lithofacies associations), suggesting, on the whole, sedimentary environ-

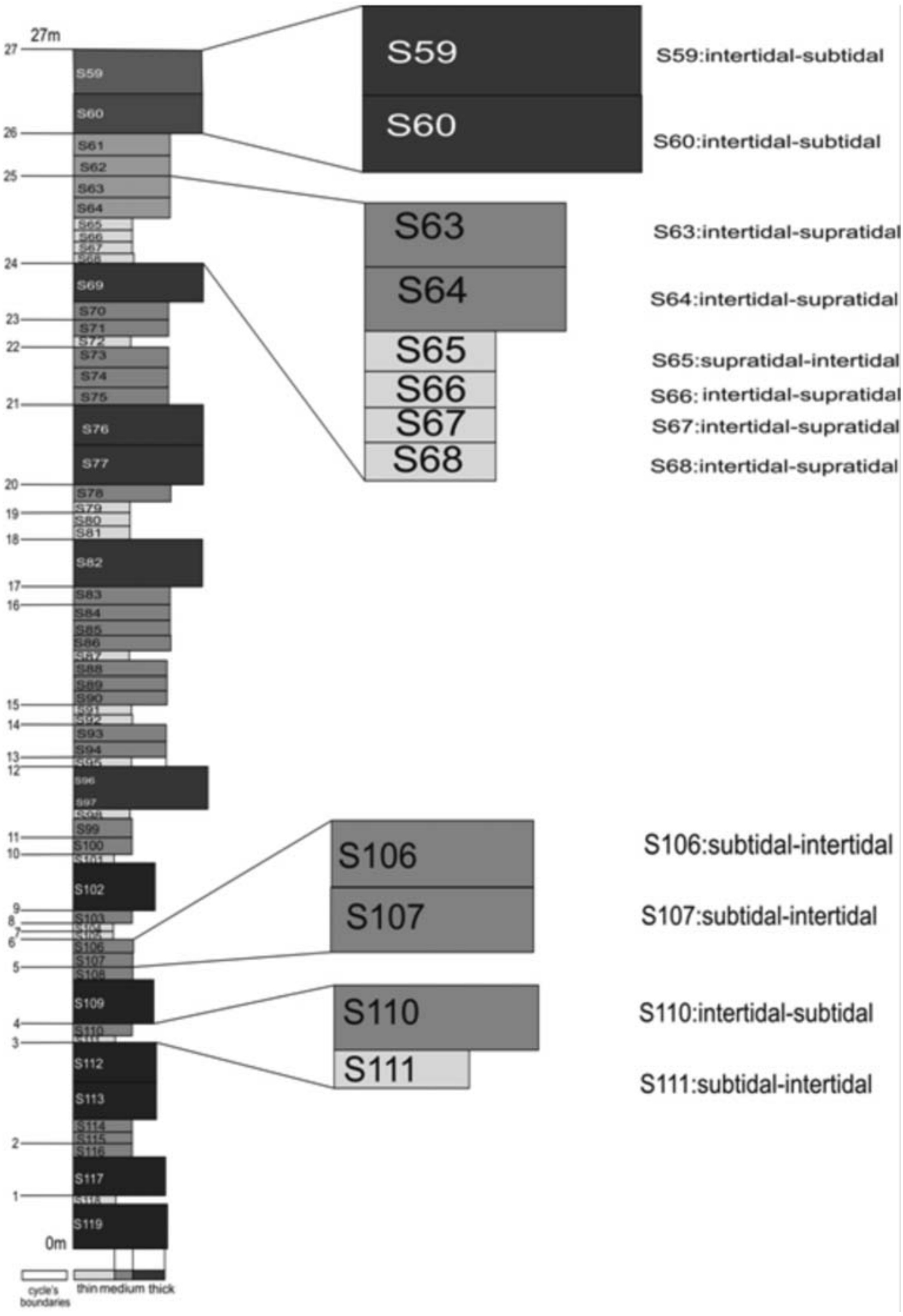

Fig. 3: The stratigrphic sequence of the studied section. Black color represents the thickly bedded limestones, grey color represents the medium bedded limestones and finally white represents the thinly bedded limestones.

Sample	Definition	Sample	Definition	Sample	Definition
S59	intertidal-subtidal	S81	intertidal-supratidal	S103	supratidal-intertidal
S60	intertidal-subtidal	S82	subtidal-intertidal	S104	subtidal
S61	supratidal-intertidal	S83	intertidal-supratidal	S105	supratidal-intertidal
S62	supratidal-intertidal	S84	intertidal-subtidal	S106	subtidal-intertidal
S63	intertidal-supratidal	S85	intertidal	S107	subtidal-intertidal
S64	intertidal-supratidal	S86	subtidal-intertidal	S108	supratidal-intertidal
S65	supratidal-intertidal	S87	intertidal-subtidal	S109	supratidal-intertidal
S66	intertidal-supratidal	S88	subtidal-intertidal	S110	intertidal-subtidal
S67	intertidal-supratidal	S89	subtidal-intertidal	S111	subtidal-intertidal
S68	intertidal-supratidal	S90	subtidal-intertidal	S112	supratidal
S69	shallow subtidal	S91	intertidal-supratidal	S113	intertidal-supratidal
S70	subtidal-intertidal	S92	intertidal-supratidal	S114	intertidal-supratidal
S71	intertidal-supratidal	S93	subtidal-intertidal	S115	intertidal-supratidal
S72	supratidal-intertidal	S94	intertidal	S116	subtidal
S73	subtidal	S95	supratidal-intertidal	S117	subtidal-intertidal
S74	intertidal-subtidal	S96	subtidal	S118	intertidal-supratidal
S75	intertidal-subtidal	S97	subtidal	S119	intertidal-supratidal
S76	shallow subtidal	S98	subtidal-intertidal		
S77	subtidal	S99	intertidal-subtidal		
S78	subtidal-intertidal	S100	intertidal-supratidal		
S79	subtidal-intertidal	S101	intertidal-subtidal		
S80	intertidal-supratidal	S102	intertidal-subtidal		

Fig. 4: The data of depositional environments in the studied area. They have been collected 60 samples, one sample for each bed. The thickness of the studied unit is 27m.

ments ranging from lagoonal to peritidal. The vertical arrangement of these lithofacies allows the identification of a cyclic recurrence of the depositional and early diagenetic features, including a meteoric overprint that may be observed on top of the elementary cycles.

4. Facies analysis

Peritidal carbonates have been observed in the Sami stratigraphic section. They are represented predominantly by micrites, often peloidal micrites. Common limestone types are mudstones, wackestones and bindstones. Intercalations of grainstones may be present in tidal channels, or as storm deposits. In the studied section subtidal, intertidal and supratidal zones are repeatedly observed overall the section forming shallowing-upward cycles (Figs. 3 and 4). High-frequency cyclicity, is ubiquitous in the studied Cretaceous shallow-water carbonates. The cycles seem to correspond to group of beds.

By studying the carbonate unit of the Sami stratigraphic section we attemted to understand their depositional settings and to distinguish between subtidal, intertidal and supratidal carbonates, by focusing on diagnostic criteria.

High-frequency sea-level fluctuations best explain this cyclic organization because shallow subtidal facies predominate, and emersion-related features are superimposed directly on subtidal (rarely on tidal) sediments (Buonocunto et al., 1994, 1999; D'Argenio et al., 1997, 1999; Raspini, 1998; Pomoni-Papaioannou, 2008; Pomoni-Papaioannou & Kostopoulou, 2008).

4.1 Subtidal

This zone below the intertidal zone is permanently submerged. Water depth is a few meters. The subtidal zone is conventionally subdivided into a shallow and a deeper subtidal zone. The shallow subti-

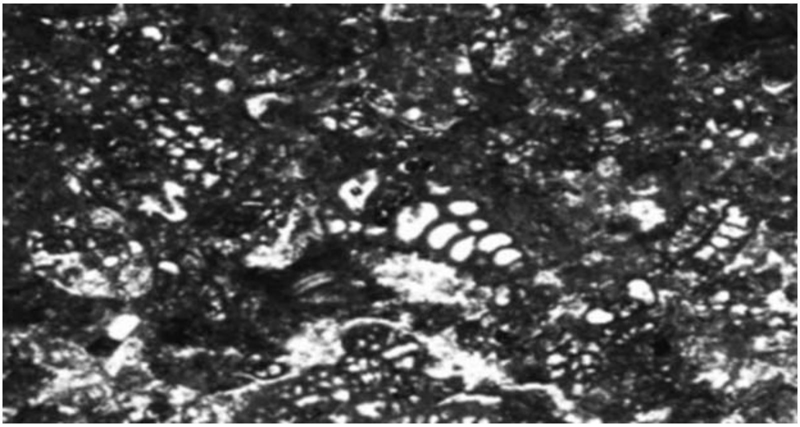

Fig. 5: Packstone with benthic foraminifera: subtidal.

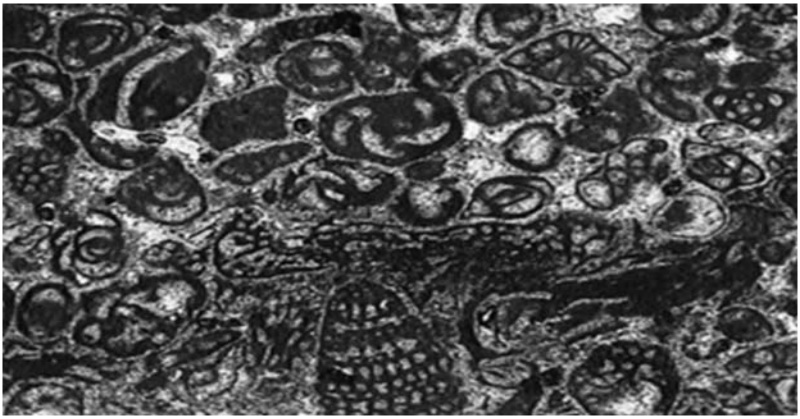

Fig. 6: Grainstone with benthic foraminifera (high energy environment) :subtidal.

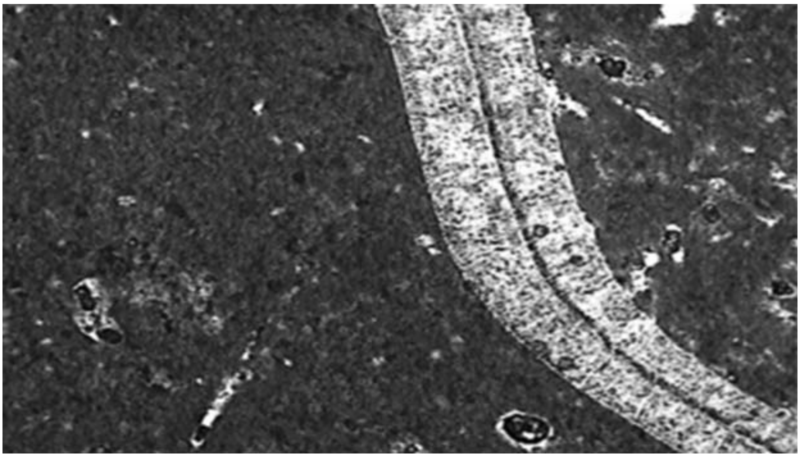

Fig. 7: Floatstone with rudist (low energy environment) :subtidal.

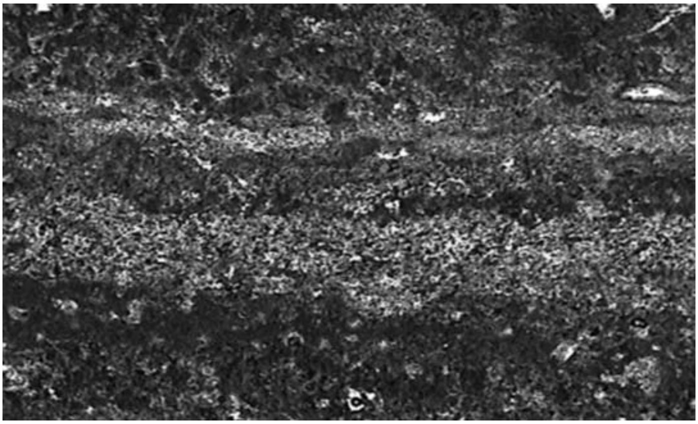

Fig. 8: Fine-laminated lime mudstone.

dal zone characterized by calcareous algae and invertebrates adapted to the phytal (e.g. foraminifera, bryozoans, worms). Epiphytes are common. Important indicators are the occurrence of dasyclad algae and encrusting organisms. The lower boundary, after comparison with recent zonations, can be drawn at approximately 30 m. The deeper subtidal zone is characterized by high-diversity benthic organisms. Calcareous algae still occur (red algae). Dasyclads, however, are absent. The *subtidal* is characterized by burrowed and variably argillaceous lowest member. It consists of mudstone, wackestone or packstone (Fig. 5), often with a basal bio- or intraclastic grainstone (Fig. 6), as a transgressive lag on top of the preexisting succession. In subtidal zone lamination and teppes are absent. Mesozoic bivalves' bioclasts (rudist) occur, in places, which were adapted to euryhaline conditions. Rudist (Fig. 7) attributes the Late Cretaceous age of the studied deposits.

4.2 Intertidal

This zone is alternately flooded and exposed. Intermittent exposure is indicated by desiccation features, muddy surfaces with animal tracks and trails, and pores filled with vadose cement. Characteristic features of the intertidal regime are alternating erosion and deposition and rapid changes in current and wave velocity. These processes result in discontinuous sedimentation associated with scour–and–fill and the formation of channels, accumulation of reworked sediment, and substantial changes in grain size from lamina and bed to bed. The lower intertidal member exhibits thin-bedded, variably bioturbated mudstones, and bioclastic. In the studied section we observed repeated microbially laminated argillaceous mudstone/bindstone with small vertical desiccation cracks indicating the shallowest supratidal parts of the cycle (Fig. 8).

4.3 Supratidal

This is the most diagnostic zone in humid and arid tidal flats and represents the splash zone above high tide. It is flooded only a few times each month by spring tides or storms. Most of the sedimentation occurs above normal high tide during storm flooding. Diagnostic criteria for supratidal environment are:

- Evidence of subaerial exposure and pedogenetic influence.
- Evidence of cementation in the vadose zone.

The supratidal member is characterized by mudstones-wackestones with fenestral fabrics (Fig. 9), desiccation structures and thin interbeds of intraclastic packstone and laminae consisting of peloidal or bioclastic grainstone. Also the diversity of biota is very low.

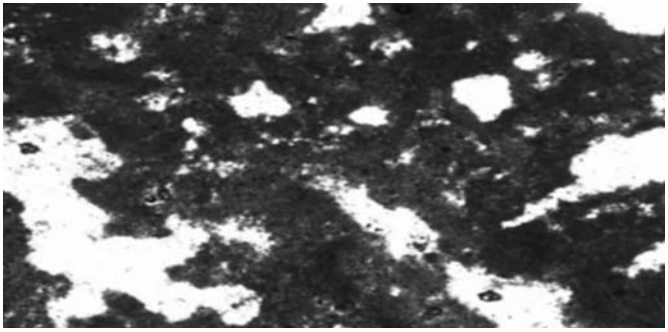

Fig. 9: Fenestral fabrics, mudstone, paucity of fossils.

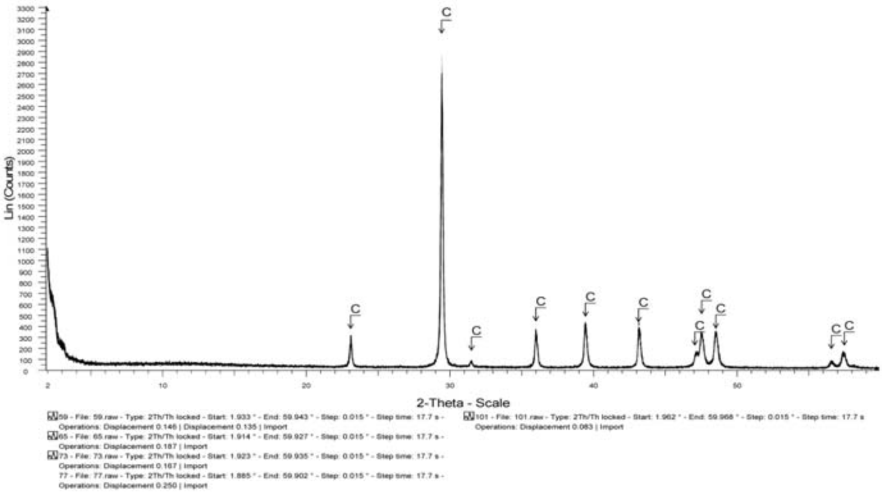

Fig. 10: X-Ray Diffraction pattern of bulk sample (samples S59, S65, S73, S77, S101). C: calcite.

5. X-Ray Diffraction data

Whole rock samples were analyzed by X-ray diffraction and consist of calcite (Fig. 10). The fraction soluble in 25% v/v acetic acid (CH_3COOH) was determined for all samples following the method of Hirst &Nichols (1958). This fraction consists mainly of carbonate minerals, whereas the fraction insoluble in acetic acid consists of clay minerals. The clay minerals present are chlorite, illite and the mixed-layer clay minerals illite-smectite and chlorite-smectite. The preparation of the samples was based on the method Tsolis- Katagas (1987). Due to the low quantity of the clay fraction it is not possible to talk about early diagenetic features.

6. Conclusion

In the Upper Cretaceous studied unit of the carbonate succession, up to 27m thick, a number of well-developed subaerial exposure surfaces and palaeosols have been recognized, that display strong evidence of vadose diagenesis and terrestrial conditions.

The high-resolution stratigraphic analysis has shown a number of lithofacies organized in groups (lithofacies associations), suggesting, on the whole, sedimentary environments ranging from lagoonal to peritidal context. The vertical arrangement of these lithofacies allowed the identification of a cyclic recurrence of the depositional and early diagenetic features, including a meteoric overprint on top of the elementary cycles.

Small-scale cycles, formed in a low-energy peritidal environment, are characterized by the repetitive stacking of the facies types. The cycles exhibit a shallowing upward trend from shallow subtidal to inter-supratidal and hypersaline facies, in a warm shallow marine environment. The presence of cyclic sedimentary record in the studied carbonate platform deposits display facies patterns changes that might have been caused in response to fluctuations in eustatic sea level.

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We would like to thank the Section of Earth Raw Materials, Department of Geology, University of Patras, for the X-Ray diffraction method. Eleni Koutsopoulou is thanked for the definition of clay minerals. We thank P. Tsolis-Katagas for her constructive comments.

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ΓΕΩΑΡΧΑΙΟΛΟΓΙΑ / GEOARCHAEOLOGY

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A MINERALOGICAL STUDY OF SOME MYCENAEAN SEALS EMPLOYING MOBILE RAMAN MICROSCOPY

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Abstract

The National Archaeological Museum in Athens is the largest archaeological museum in Greece, and one of the most important museums in the world, devoted to Ancient Greek art and history. Among other exhibits, it owns a large collection of gemstones some of which were used during prehistoric times (Mycenaean period) as seals. Their shape varies from round to oval, flattish or cylindrical, and they are delicately engraved as intaglios with a variety of depictions (lions, bulls, man, etc). They show a wide range of colours from reddish, brown, to purplish and blue. The six sealstones described here come from the Chamber Tombs of Mycenae (15^{th}-14^{th} cent. BC). Museum exhibit labels recognize them as varieties of quartz such as jasper (NAM 3138), sardonyx (NAM 2316 & 2865), agate (NAM 4928), amazonite (NAM 2863) and gold-mounted carnelian (NAM 6489). Raman Spectroscopic analysis has been carried out with a new MRM (Mobile Raman Microscope) using a Kaiser Holoprobe with a NIR 785nm laser. The Raman spectra acquired from 1s-60s measurements confirmed that, in all six sealstones, quartz was the major mineral species clearly identified by its characteristic peaks. The second most important phase was moganite, a little-known polymorph of quartz. The amber-coloured sealstone (NAM 6489) was confirmed as carnelian, whereas the blue-green amazonite-coloured sealstone (NAM 2863) was not detected as amazonite. Small amounts of haematite were detected in the NAM 2865 & NAM 3138.

Key words: *Mycenaean sealstones, gemstones, Raman spectroscopy, archaeometry.*

1. Introduction

Raman spectroscopy has become an important technique in Archaeometric studies, in Archaeology and Art History since about 1996, due principally to its microscopical, no sample treatment and non-destructive capacities, and the pseudo-acronym 'ARCHAEORAMAN' was coined by Smith (1999) to summarize this wide field of research activity. 'Mobile Raman Microscopy' (MRM) was also employed (Smith, 1999, 2002) to analyze art works in situ, directly in the museums by taking the laboratory to the object, rather than taking the object to the laboratory as in conventional 'Immobile Raman Microscopy' (IRM). Apart from non-destructiveness MRM has gained ground among other physicochemical methods due to the small amount of sample required and the high spatial resolution allowing the analysis of small heterogeneities in complex matrix.

Textbook explanations of Raman Spectroscopy for Geologists, Gemmologists and Archaeologists are provided in Smith and Carabatos (2001) and Nasdala et al. (2004) and reviews on MRM applications in Gemmology are available in Smith (2005, 2006). A gemmological database for the Raman spectra of gems was published by Pinet et al. (1992).

In the early 2000's several other researchers in the UK (H.G.M.Edwards), Belgium (P.Vandenabeele), France (P. Colomban), Switzerland (L. Kiefert), Spain (F. Rull-Perez) and Italy (G. Di Lonardo), have helped to pioneer MRM in Archaeometry, and in the late 2000's this topic lead to an exponential increase in publications and frequent international congresses.

The National Archaeological Museum in Athens, owns a large collection of gemstones including some prehistoric seals (15^{th}-14^{th} cent. BC), from the Mycenaean Chamber Tombs. They came in the limelight after the excavations of 1892. They are mostly round or oval, and flattish or cylindrical; altogether they show a very wide range of colours ranging from reddish and brown to purplish and blue. They are delicately engraved like intaglios and depict a large variety of themes from the everyday activity and the nature (Vasilikou, 1995). Whilst carrying out a new MRM (Mobile Raman Microscopy) analytical operation in the NAM on pigmented artworks using a Kaiser Holoprobe MRM from IGME (Athens) fitted with a NIR 785 nm laser and a specially-made strong tripod support, six sealstones were extracted from their glass display case to make some rapid non-destructive analyses of the material in an attempt to establish definitively the mineral species present in these carved stones, and, by consequence, also the rock type when possible.

2. Art History and Seal engraving in Prehistoric Greece

Seals were particularly important for the period in question (Late Bronze Age, 1500-1100 BC), as they were connected with trade and administration. The abundance of materials used and their iconography provides information for the everyday life and the religion of the Mycenaeans. Workshops for the manufacture of seals existed in the palace centers of Crete and the Peloponnese (Mycenae, Tiryns, Pylos), as they formed part of the administrative system. They were usually made of semi-precious stones (quartz, amethyst, agate, jasper, carnelian, haematite, rock-crystal), but also of artificial materials such as glass and faience or organic materials like bone and ivory; sometimes they were gold-mounted. The most popular shapes were the lentoid, the almond-shaped and the cylindrical. Apart from their use to protect the products to be transported from theft (by leaving their impression on wet clay placed on the mouth of storage objects), seals were also worn as jewellery, with protective or purely decorative character. To their owners, they constituted a symbol of prestige (Sakellariou, 1964; Vasilikou, 1995). Lions were a very popular theme for the seals as well as for other forms of Mycenaean art. They were a symbol of royal strength. The bull was another frequent theme as it was the dominant animal for sacrifice. The leaping bull used to be a kind of ceremony in social events. Well-trained male and female acrobats used to catch the bull from its horns and jump on to its back (Sakellariou, 1964; Vasilikou, 1995).

3. Mineralogical considerations

The very common mineral species quartz (α-SiO_2) may occur as monocrystals. If there is no other mineral phase present the colour would be colourless or white (rock crystal) or may be coloured due to impurities, usually of Fe^{3+}-rich minerals like rose quartz (pink colour), citrine (yellow), amethyst (purple), morion (black) etc. Yet other varieties may be coloured by intergrown extra mineral phases like green fuchsite (aventurine), blue dumortierite or zoisite, brown riebeckite (crocidolite), haematite, gold or cupreous rutile (rutilized quartz). Quartz of invisible microcrystalline size is called cryptocrystalline quartz. The main colour of those varieties can be defined by the combination of texture and features. Some varieties are chalcedony, agate, sard, onyx, sardonyx, jasper, carnelian, prase, chrysoprase, heliotrope. Usually the quartz is accompanied by the polymorph moganite (SiO_2) that was discovered only recently, having a crystal structure that resembles α-quartz twinned on a unit cell scale. It is still not known why this moganite exists; probably it is related to the kinetics and chemistry of percolating solutions during growth).

All varieties of cryptocrystalline quartz show the same essential physical and chemical properties as α-quartz, with additional moganite in variable proportions (Table 1).

Table 1. Physical properties of quartz and cryptocrystalline quartz varieties.

Mineral Class	Oxides	***Mineral Species***	Quartz (alpha)
Chemical Composition	SiO2	***Crystal system***	Trigonal
Hardness	7	***Specific Gravity***	2,66
Refractive Index	1,544-1,533	***Appearance***	Vitreous, opaque
Cleavage	Poor	***Fracture***	Conchoidal

4. Etymology and use in ancient Greece

Gemological notes on the colours, etymology and uses in antiquity (Cipriani and Borelli, 1986; Harding, 2007) for the mentioned chalcedonies are provided below:

Agate

Colour: No gemstone is more creatively striped by Nature than agate that forms in concentric layers in a wide variety of colours and textures. Each individual agate forms by filling a cavity/vesicle in the host rock. As a result, agate is often found as a rounded nodule, with very fine concentric bands like the rings of a tree trunk. The bands sometimes look like eyes, sometimes-fanciful scallops, or even a landscape with dendritic trees.

Etymology: The name originates from the word "*Achates*", the ancient Greek name of the Sicilian river Drillo in which the mineral was first found. Agate was highly valued as an amulet in ancient times. It was said to quench thirst and protect from fevers.

Sardonyx

Colour: Reddish-brown with prominent white strips and bands.

Etymology: The name sardonyx derives from the words "*sard*", and "*onyx*" related to the striped or banded appearance of layers of white, grey or black interspersed with reddish-brown. According to Pliny, sard is named after "*Sardis"* where the mentioned mineral is found. The ancient Greeks and the Romans were very fond of sardonyx and believed it could bring courage and victory.

Carnelian

Colour: Reddish-orange or brownish-orange due to the traces of the ferric iron oxide haematite (Fe_2O_3).

Etymology: The name carnelian is said to be derived from the Latin word "*carnis*", meaning "flesh", due to its colour. Others believe that the name comes from a variety of cherry having the same colour. This gemstone is believed to cleanse the blood and improve one's outlook too. It had been believed for a long time that the carnelian gemstone stops bleeding and helps heal wounds.

Jasper

Colour: Commonly red, it also comes in pink, yellow, green, brown, black, and greyish blues and frequently in combinations of these colours. The association with other minerals gives jasper nice bands and patterns.

Etymology: The Greek origin of the word jasper, "*iaspis*", means "spotted stone". The black variety known as "*Lydia lithos*" (=stone of Lydia) was used for thousands of years for the quantification of gold in various alloys. The test is done by friction of the sample on the jasper. The colour of the dust line produced is used to calculate the quantity of pure gold in the alloy. The gem was a favourite in the ancient world, and the name jasper can be traced back in Hebrew, Assyrian, Persian, Greek and Latin. People of the 4th century (BC) used to call it the great "rain-bringer",» and it has been considered to strengthen the stomach and cure gynaecological troubles. Some people also used it to drive away evil spirits and protect against snake and spider bites. It supposedly gives you the courage to speak out and the bravery to achieve personal independence.

5. Materials and Methods

Six sealstones from the large gemstone collection of the National Archaeological Museum in Athens, were studied by means of portable Raman microscopy. The sealstones studied here are depicted in Fig. 1 and detailed described in Table 2. They come from the Chamber Tombs of Mycenae (mainly 14^{th} - 13^{th} century BC), family tombs of both high-ranking officials and simple civilians, around the Mycenaean citadel (Vasilikou, 1995). They are mostly round or oval, and flattish or cylindrical, and are delicately engraved like intaglios; altogether they show a very wide range of colours ranging from reddish and brown to purplish and blue. Color inhomogeneities occur in the sealstone No 2316.

A Kaiser "Holoprobe" Mobile Raman Microscope (MRM) from the Institute of Geological and Mineral Exploration (IGME) of Athens, Greece, was tested for the first time directly in the National Archaeological Museum (NAM) of Athens, Greece. The analysis was carried out using a 785nm laser. A calibration of the instrument was obtained with a standard of Si, giving a characteristic peak at the 520.5 cm^{-1}. Preparation of the samples was not necessary and the samples were placed in front of the focused 785nm laser in their normal form. The video camera of the Raman system was employed in order to be able to observe different areas of the sealstones. The power of the laser was 200-500mW. The Raman spectra were acquired from 1-6 s and 1-10 accumulations and they were treated with HoloGRAMS 4.0 software (baseline correction, peak fit).

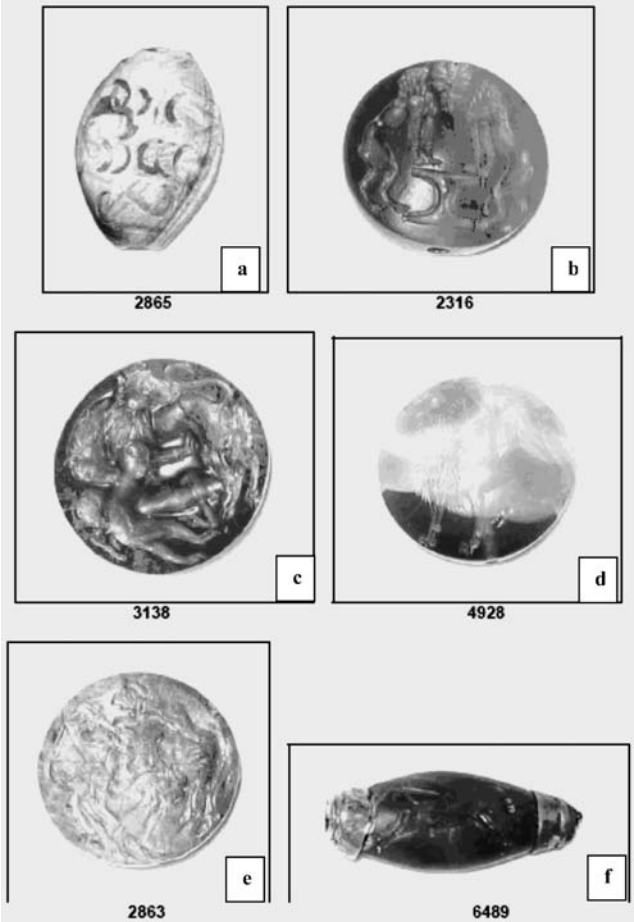

Fig. 1: Photographs displaying the shape, colour and engraved patterns of the six sealstones examined, a: a sea plant engraved on sardonyx, b: two heraldic lions engraved on sardonyx, c: two lions attacking a bull engraved on jasper, d: a man fighting a lion engraved on agate, e: a man capturing two bulls engraved on amazonite, f: a bull leaping engraved on carnelian.

6. Results and Discussion

The spectra acquired during the analysis of the Mycenean seals, confirmed the exhibit labels for the majority of the cases considered herein. Representative Raman spectra of the sealstones analyzed here are given in Fig. 2.

The comparison of each spectrum with published fingerprint spectra (e.g. Kingma & Hemley, 1994; Götze et al., 1998, Burgio & Clark, 2001) revealed the presence of the mineral species summarised below:

Specimen 4928: α-quartz and moganite were detected by their characteristic bands respectively at 464 and 502 cm^{-1} Moganite is known to coexist with a-quartz in many types of chalcedony such that most of these sealstones were confirmed, -, as chalcedony, but of different varieties according to their colours and textures (e.g. agate, jasper, sardonyx). However the proportion of moganite varied from very poor to very rich with $I_{502}/I_{465} = \sim 35\%$ in NAM 4928. The proportion of moganite is a key crystallographical/petrographical feature that may help to locate the geological provenances of these stones (Kingma & Hemley, 1994; Götze et al., 1998).

Specimen 2316: Only the yellow part of the sealstone was analysed in the time available. Quartz

Table 2. Description of the sealstones.

Specimen Code	*Museum label*	*Color*	*Shape*	*Diameter (cm)*	*Shematic*	*Chamber tomb*
2865 (Sakellariou-Xenaki, 1985)	Sardonyx	Pink-white	Almond-shaped	1.6-2.2	Sea plant	
2316 (Sakellariou, 1964; Sakellariou-Xenaki, 1985)	Sardonyx	Red-yellow	Lentoid	2.1	Two heraldic lions have their front legs up and step onto an altar. Bodies are rendered in katatomi, while their common head in frontal view.The representation recalls the large of the Lions Gate at Mycenae.	8
3138 (Sakellariou, 1964; Sakellariou-Xenaki, 1985)	Jasper	Red-brown	Lentoid	2.5-2.6	Two lions attacking a bull. The two lions are fighting over the bull and bite each other on the back.	83
4928 (Sakellariou, 1964; Sakellariou-Xenaki, 1985)	Agate	Purplish gray-brown	Lentoid	2.75	A man fighting a lion	103
2863 (Sakellariou, 1964; Sakellariou-Xenaki, 1985)	Amazonite	Blue-gray	Lendoid	2.2	A man captures a bull from the head and one of the legs.	58
6489 (Wace, 1932; Sakellariou, 1964)	Carnelian	Amber-gold	Almond-shaped	1-2.7	Bull leaping	518

(206, 354, 464 cm^{-1}) was found and a weak band at 397 cm^{-1} could indicate the presence of goethite, which is a typical yellow Fe^{+3} colorant (Burgio & Clark, 2001).

Specimen 6489: Quartz and moganite are present, as indicated by the dominant bands at 464 and 502 cm^{-1}.

Specimen 3138: Quartz and possibly moganite occur with their characteristic bands at 465 and 501(very weak) cm^{-1}, respectively. Also the presence of haematite (224, 411, 612 cm^{-1}) and indications of goethite (293, 387, 393 cm^{-1}) were observed.

Specimen 2863: Quartz, possibly moganite and a copper mineral in question, judging and from the

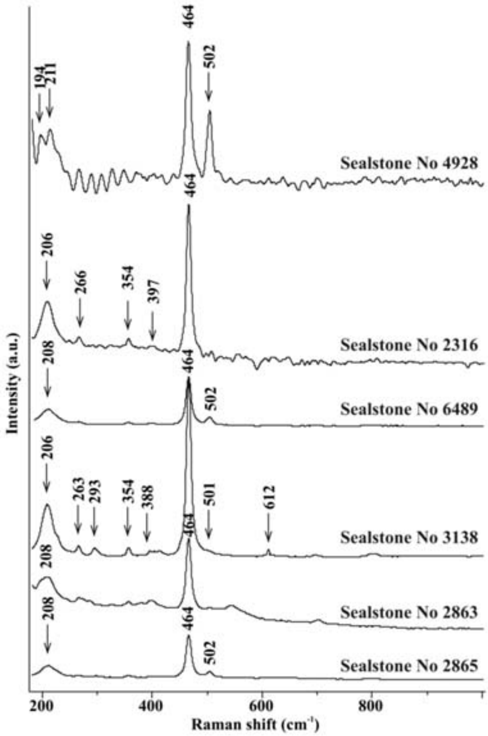

Fig. 2: Raman spectra of the six sealstones analysed; 4928: admixture of a-quartz and moganite, 2316: quartz and goethite, 6489: admixture of a-quartz and moganite, 3138: admixtrure of a-quartz and moganite with presence of haematite and goethite, 2863: a-quartz, 2865: admixture of a-quartz and moganite with presence of haematite.

colour of the stone. More analytical time is necessary to search for the additional bands.

Specimen 2865: Quartz (464 cm^{-1}) and moganite (502 cm^{-1}) exist. Haematite is indicated by a weak band at 411 cm^{-1}. More analytical time is necessary to clarify the nature of the extra bands.

7. Conclusions

The Raman spectra acquired rapidly from a few 1s - 60s measurements confirmed that, in all six sealstones, quartz was the major mineral species clearly identified by its characteristic peaks; (major Raman peak at 465 cm^{-1}); nevertheless it was never found alone. The second most important phase found was moganite, the little-known polymorph of quartz with its strongest peak at 502 cm^{-1}. The amber-coloured sealstone NAM 6489 is compatible with carnelian, but no proof of the presence of an iron oxide colouring agent was detected. The blue-green coloured sealstone NAM 2863, previously recognized as amazonite by the archaologists, did not reveal any trace of microcline feldspar - through its Raman analysis; on the contrary, it revealed quartz and moganite; it might be an agate coloured blue by precipitated copper minerals. Thus one of the assignments claimed by the Museum labels is vitiated.

Small amounts of haematite {Fe_2O_3} were also detected in two samples (NAM 2865 & NAM 3138) and the presence of goethite {FeOOH} is indicated in two samples (NAM 2316 & NAM 3138). These are to be expected in minerals coloured respectively red or yellow by iron.

Four of these six sealstones revealed some extra Raman bands that have not yet been attributed and merit further Raman analyses to help elucidate non-destructively the nature of the extra mineral species present. The species of these extra mineral phases should help to better determine the petrogenesis of these rocks and also be a valuable aid to studying their provenance.

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EARTH SCIENCE APPLICATIONS IN THE FIELD OF ARCHAEOLOGY: THE HELIKE EXAMPLE

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Abstract

Earth science applications are widely used in the field of archaeology today. The Helike Project made use of such applications at a time when archaeology in Greece was mostly limited to traditional methodology only. Thus Helike constitutes a pioneer study case of such investigations and of their usefulness in the field of archaeology. In searching for Ancient Helike, our team since 1988 combined extensively traditional archaeological research methods and geophysical and geological exploration. The results of this multidisciplinary approach were in most cases successful beyond expectations. In this paper, I present and discuss the most significant archaeological discoveries in the area of Helike based primarily on data from our geological and geophysical investigations the last 20 years.

Key words: *Helike, poros, Early Helladic Rizomylos, Dye-Works Valimitika, Mycenaean Geometric Nikolaiika, Roman road.*

1. Introduction

The exact location of Helike on the southwestern shore of the Corinthian Gulf remained for decades an unsolved riddle for archaeology. The Helike Project began a search for the city in 1988 using surface surveys, geophysical exploration and extensive bore hole drilling to solve an archaeological question at a time when archaeology in Greece was mostly limited to traditional methodology only. The significant results of the multidisciplinary research in Helike show in a prominent way the usefulness and effectiveness of such investigations in the field of archaeology.

According to ancient sources, Helike was founded in Mycenaean times and was destroyed by a catastrophic earthquake in 373 BC, after over a thousand years of prosperity. The earthquake happened on a winter night and was preceded with a variety of unusual phenomena including the appearance of comets and animals deserting Helike five days prior to the earthquake (Katsonopoulou 2005a). The destruction was the result of two combined natural forces: earthquake and tsunami. The earthquake caused the sea to rise to an immense height and completely flood the city, along with the sanctuary of Helikonian Poseidon worshipped in Helike as the god of waters and earthquakes (Katsonopoulou 2009).

2. The research

The erroneous interpretation of the reported submergence of Helike under seawaters led scholars in the past to seek the lost city beneath the Corinthian Gulf, with inconclusive results (Katsonopoulou 1991).

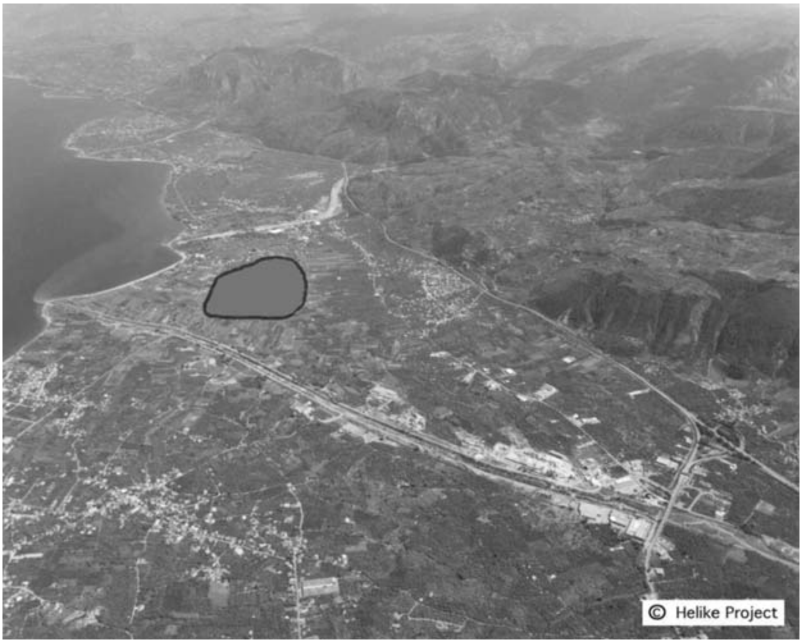

Fig. 1: Aerial view of the Helike Delta, looking southeast, between the Gulf of Corinth (left) and the mountains of the Peloponnesos (right). Three rivers cross the delta: the Selinous (foreground), Kerynites (midground) and Vouraikos (background). The black circle indicates the approximate location of the ancient lagoon.

Surprisingly, the scholars overlooked a critical source on Helike's location. The 3rd century BC philosopher and mathematician Eratosthenes visited the area of Helike about 150 years after the catastrophe. He was told by the ferrymen that the bronze statue of Poseidon, holding a hippocamp (a sea horse) in one hand, stood in the *poros* and was dangerous for those fishing with nets. The word *poros* used by Eratosthenes must be interpreted as indicating the existence of a narrow passage of water in the place where the city of Helike stood before the earthquake (Katsonopoulou 1995 and 2005a). This would imply that a lagoon was formed as a result of the 373 BC earthquake and the subsequent tsunami. A similar lagoon probably existed in the vicinity of Helike before the earthquake, and was presumably enlarged by the earthquake.

Consistent with this interpretation, in 1991 The Helike Project launched a search for Helike on dry land, and soon found substantial evidence of the existence of an ancient lagoon under today's coastal plain, covering an area of about 1.5 km^2 in a NW-SE direction between the Selinous and Kerynites rivers (Fig. 1). In the center of this area, at a depth of about 3 m, buried under lagoonal strata, were discovered remains of Classical walls showing evidence of destruction by earthquake and accompanying tsunami. The location of these ruins (Fig. 2, B) is in complete agreement with the reported location of Helike forty stadia (about 7 km) east of Aigion, according to Pausanias (7.24.5).

Systematic excavations carried out in the region by The Helike Project since 2000 justified in an impressive way the results of borehole drilling and geophysical exploration in the area in previous years. A magnetometry survey carried out in 1994 at the Klonis field in contemporary Eliki (Fig. 2, Kl), near the center of the area in which our borehole drilling showed evidence of ancient occupation, revealed promising targets buried about 2 m below the surface (Papamarinopoulos et al. 1998).

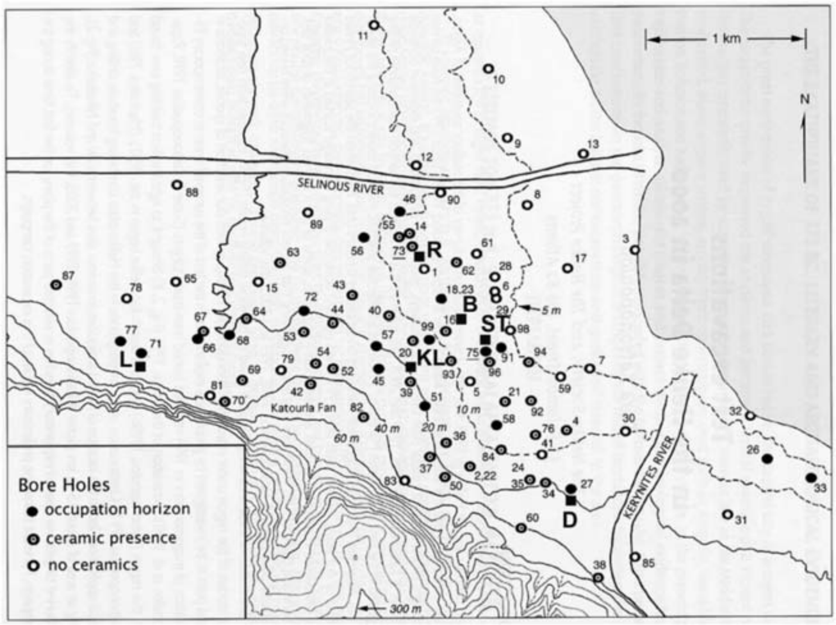

Fig. 2: Topographic map of the central Helike area, showing locations of boreholes (numbered circles) and locations of archaeological sites (written in capital letters) from the Greek Army 1:5000 map (adapted from Katsonopoulou 2005, Fig. 1, p. 34).

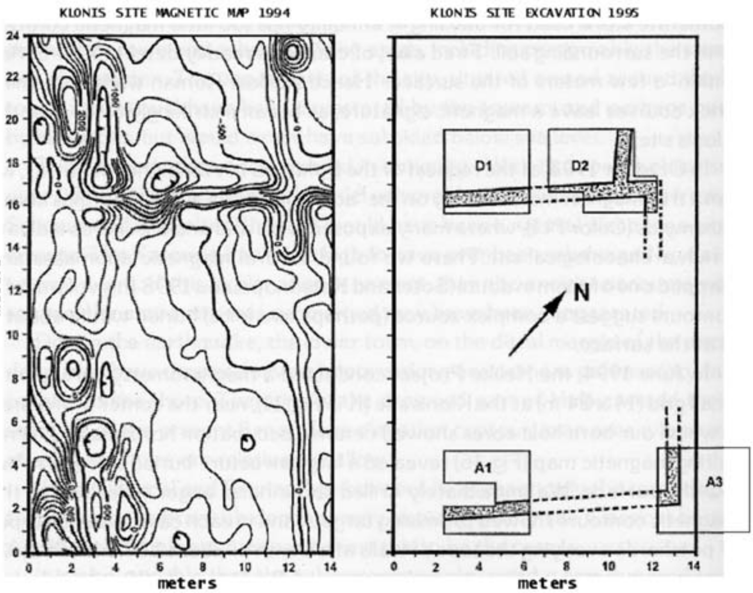

Fig. 3: Contours of magnetic intensity conducted at the Klonis site in 1994 (left). Plan of the excavated squares in 1995 (right), showing locations of walls corresponding to the magnetic contours (from Soter & Katsonopoulou 1998, Fig. 16, p. 106).

Excavations conducted at this location in 1995 following the geophysical survey, brought to light part of a large rectangular Roman building with walls standing about 2 m high. The typical Roman construction of the walls, with alternating courses of unworked stone and baked brick, apparently account for the excellent correlation between the magnetic data and the recovered walls (Fig. 3). An extensive destruction layer of fallen stones, bricks, plaster and roof tiles, found both within and outside the building, shows that it was destroyed by an earthquake, most probably in the 5th c. AD (Katsonopoulou 1998).

It is worthy to note that major discoveries in Helike's area, successfully located on dry land by our team, are primarily the results of the multidisciplinary methodology we applied in our search. I will describe below the most prominent of these discoveries.

3. The Early Helladic settlement in Rizomylos

Borehole B75 was drilled to a depth of 11 m in the field of Panagiotis Saitis in Rizomylos in 1998 (Fig. 2, ST). It is perhaps the most impressive of the boreholes drilled in the Helike plain between 1991 and 2002. Many core samples from alternating layers of greenish/gray silt and clay contained a variety of anthropogenic indicators: potsherds, burned bone and charcoal in a continuous depth from about 3 to 6.6 m, strongly suggesting the existence of a buried ancient site in this area. Thus, the location was selected among the first to be tested by means of excavation in 2000, when our first excavations campaign began in the Helike plain.

Trench H7, was opened near the location of borehole B75 and its results were indeed rewarding. At a depth of 3.3-3.6 m, we brought to light remains of Early Bronze Age walls, 0.6-1 m wide, built with different types of unworked stone in an impressive variety of color: gray limestone, red, green and orange color psamite stones, and conglomerate gray psamites. In few instances red chert and black dolomite stone were also used (Katsonopoulou 2005b). Continuation of excavations in the following years revealed that in Rizomylos are preserved the extensive remains of an EH II-III settlement (2500-2200 BC) buried between 3-5 m under the coastal plain sealed under lagoonal sediments. The EH architectural remains brought to light so far in the Helike plain belong to large rectilinear buildings made of stone foundations and upper walls built with sun-dried bricks and coated with clay. The floors inside the buildings consist of packed earth but also quite often are made of pebbles. The buildings are constructed according to organized town planning flanking the sides of cobbled streets and open areas (Fig. 4). They are furnished with architectural features showing advanced technological level such as inside benches, stone platforms and clay architectural plinths (Katsonopoulou 2007 & 2010).

The pottery found in the rooms of the excavated buildings is amazingly rich in number, shapes, and decoration, including an impressively large number of complete pots (Katsarou-Tzeveleki 2010). Other finds from the excavated rooms and exterior areas include pointed bone tools, spherical stone tools, terracotta objects, such as spindle whorls and spools, obsidian blades and flint objects for cutting and scraping activities. Food remains include sea shells and animal bones. Remains of seeds were found inside some of the recovered vases.

Excavation data from the Early Helladic settlement suggest that it was destroyed by an earthquake and accompanying fire, and that it was immediately abandoned, thereby leaving its contents intact, sealed under thick clay deposits. Analysis of sediments covering these early ruins showed remnants of a mixture of freshwater, brackish, and marine microfauna, indicating that the site was buried under the sediments of a lagoon, which actually protected it from any later human intervention (Alvarez-Zarikian et al. 2005 & 2008).

Fig. 4: Architectural remains of an Early Helladic building, probably a "corridor house", revealed in trench H38 in Rizomylos in 2003.

4. The Mycenaean-Geometric site in Nikolaiika

An unexpected discovery was made by our team during the 2006 excavation season in the area of Nikolaiika about 1.2 km east of the Early Helladic settlement in Rizomylos. The location was first explored in 1993 when we drilled borehole B27 to a depth of 20 m (Fig. 2). We discovered fragments and chips of ceramics in several core samples recovered from near the surface to about 4 m depth suggesting the presence of occupation horizons at this location (Soter and Katsonopoulou 1999). Excavation of trench H58 in 2006 brought to light a group of well constructed tile-covered Roman tombs (3rd-4th c. AD) at about 1.3 m below the surface and in the underlying strata, from 2-4 m, fine quality pottery layers dated to the Geometric and Mycenaean times (Fig. 2, D). These are two important chronological phases for Helike's history. The city, according to the sources, was founded in Mycenaean times by Ion (14th/13th c. BC) (Katsonopoulou 1999) and sent her most important colony to the West, the famous Sybaris, in the Geometric period (8th c. BC). Continuing excavations following the 2006 season, revealed new Geometric pottery layers including a circular hearth and a well built long wall of Late Classical-Early Hellenistic times, most probably an enclosure wall.

5. The Hellenistic Dye-Works in Valimitika

In the western area of the Helike region near the Selinous river, combined application of georadar (Fig. 5) and borehole drilling detected targets of interest at depths between 2 and 3 m (Kutrubes et al. 2003).

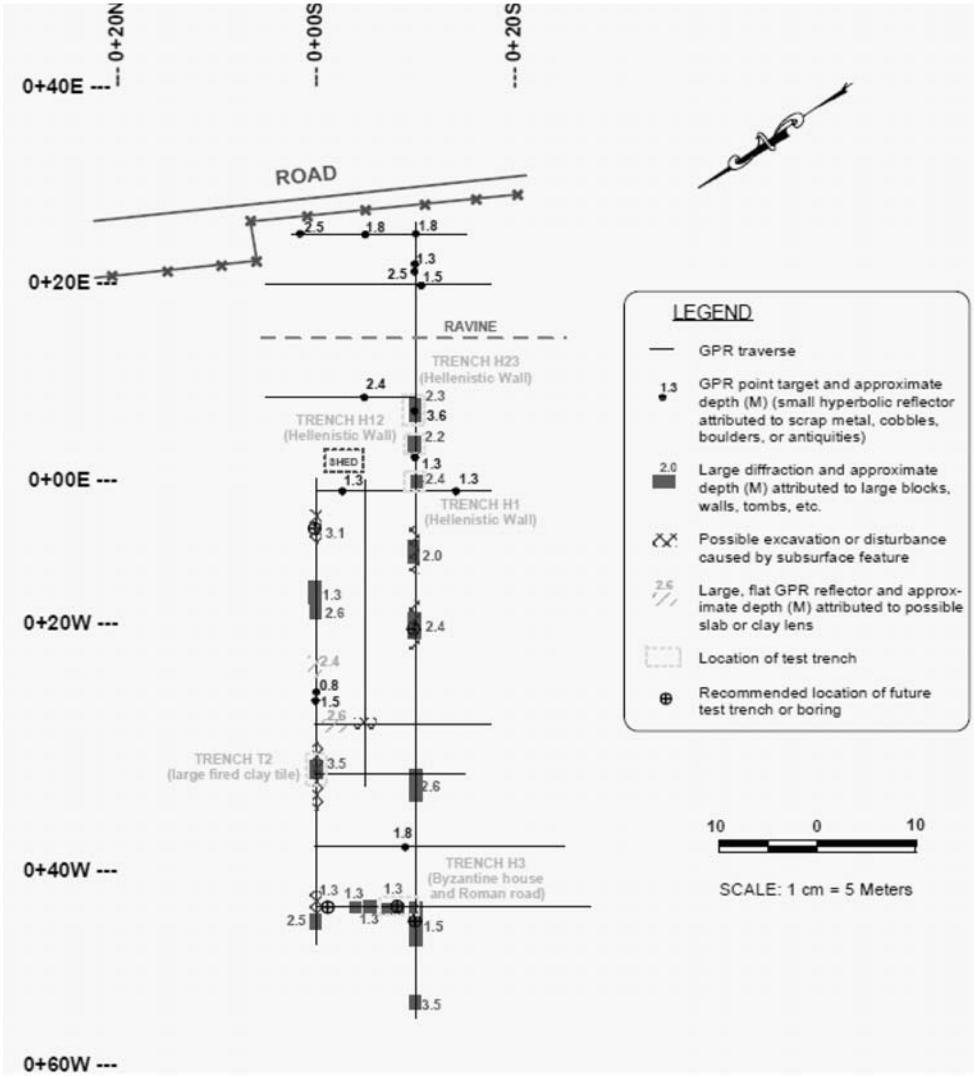

Fig. 5: Results of the 1996 GPR survey at the Romanos site in Eliki/Valimitika and locations of excavated trenches H1, H12 and H23, where Hellenistic walls were revealed (from Kutrubes et al. 2003).

Excavation of a number of trenches from 2000 onwards at this location (Fig. 2, R) revealed important archaeological finds. At a depth of about 2.3 m from the surface, came to light architectural remains of Hellenistic structures including a rare building of Dye-Works, preserving a complex of four pebbled floor basins and other installations for washing and dyeing fabrics in an excellent state of preservation (Fig. 6). Associated finds from the excavated areas of the building are abundant. The large array of pottery includes black glazed, red glazed, West Slope and relief decorated vases. Other finds include clay lamps, clay loom weights, metal objects in bronze, iron and lead, and a rich collection of bronze coins, mainly Sicyonian and of the Achaean League. Among the finds, we note the discovery of a terracotta statuette of a Tanagra lady.

Fig. 6: The well preserved Hellenistic four pebbled floor basins complex in Valimitika and plastered channels.

6. The Roman road through the Helike Plain

In the same area, in a horizon overlying the Hellenistic structures was discovered another unique find. Segments of a Roman cobbled road (Fig. 7), 5-6 m wide, extending in a straight line through the Helike plain. The road was excavated in a total of 9 trenches between the Hellenistic (Fig. 2, R) and the Early Bronze Age Helike sites (Fig. 2, ST). Consequently, its course was detected by resistivity tomography between the Selinous and Kerynites rivers 1.3 km long (Tsokas et al. 2009). The location of the Roman road at this position about 200-300 m southwest of the modern railroad line (Fig. 8), where the northern edge of the ancient lagoon lies, suggests that by Pausanias' time the lagoon was mostly silted over, making the construction of a major coastal road possible.

Fig. 7: Trench H12 showing part of the 5 m wide Roman road. In an older horizon in the southern section of the trench are revealed Hellenistic walls.

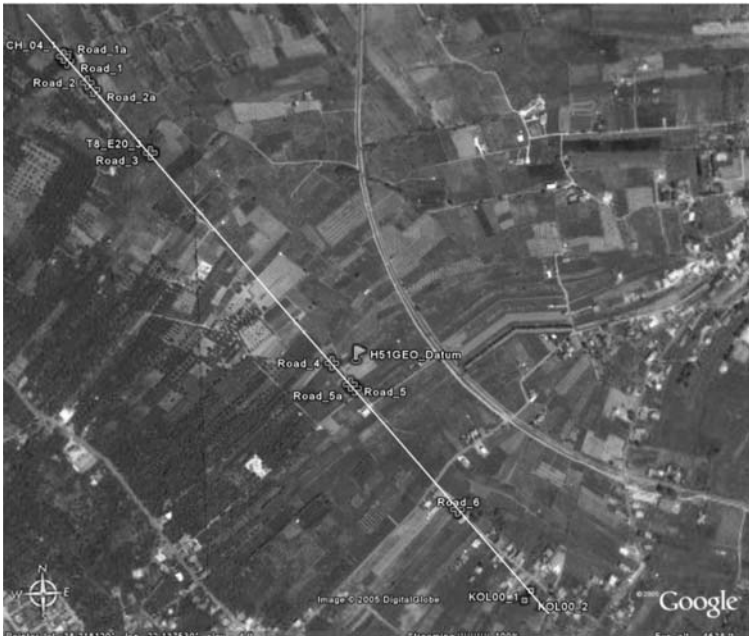

Fig. 8: The 2 km investigated course of the Roman road through the Helike plain. Excavation and resistivity tomography located the road at a length of 1.3 km between the locations Road 1 (west) and Road 6 (east).

During a description of his journey through the region, Pausanias (2nd c. AD) narrates that after visiting the town of Aigion, he proceeded east and at a distance of about 7 km arrived at a place by the sea named Helike. This place was at the same location where the city of Helike and the holiest sanctuary of Helikonian Poseidon existed before (Paus. 7.24.5). The traveller further noted that ruins of Helike, although corroded by seawater, could be seen beneath the water (Paus. 7.24.13). Indeed, in the area of Rizomylos, we discovered the Roman road and, in deeper horizons underneath, at three different locations, remains of Classical, Hellenistic and Early Bronze Age walls.

7. The new Hellenistic site in Eliki

Another impressive example of unexpected archaeological discoveries based on geoarchaeological data from borehole B71 drilled in 1998 (Fig. 2), is the most recent discovery of notable ancient walls in another location about 1 km west of the contemporary village of Eliki, near the foothills. Excavation of trench H64 (Fig. 2, L) in 2009, brought to light architectural remains of ancient buildings with well built walls, 0.55-0.65 m wide, preserved up to 0.5 m high, dated on the basis of associated pottery and other finds to the Hellenistic times. The discovery of Hellenistic structures at this location, more than 1.5 km southwest of the Hellenistic site and the Dye-Works establishment discovered in the northern area of contemporary Eliki/Valimitika in previous years, suggests extensive habitation of the western part of the Helike region in the period following shortly after the destructive event of 373 BC. The 2009 excavation data shed new light on the ancient habitation pattern in the area, reportedly completely abandoned and deserted as a result of the seismic phenomenon, thus leading to reconsideration of the reported disastrous earthquake effects in the region of Helike, in the period following the destruction of 373 BC.

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GEOMYTHOLOGICAL APPROACH OF ASOPOS RIVER (AEGINA, GREECE)

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Abstract

In Greek Mythology rivers are, with some exceptions, Gods and they were "born" by the Titans, Oceanus and Tethys. The River Gods are also considered to have given birth to some Islands. Amongst them Asopos River has the most important position as he is considered to have given birth to Aegina, Salamis, Euboea and some other islands as well.

The myth of Asopos River is remarkable because it is a typical case where the physical-geological evolution allows us to explain the myth, and at the same time, the myth lets us to give an explanation about the diachronic route of Asopos riverbed, especially during the crucial period between 18,000 to 6,000 BP.

The area, known as Saronic Gulf today, used to partly be land, including a great lake, the Epidaurus Paleolake, until 13,000 BP. Asopos River, nowadays known as "Rema tis Skotinis", is located on Aegina island.

In this paper we are trying to investigate whether Asopos River was flowing either into the Epidaurus Paleolake or into the Saronic Paleogulf.

Key words: *geomythology, Asopos, Saronic Gulf, Aegina, paleogeography.*

1. Introduction

According to Theogony, which was composed by the great poet Hesiod, rivers were "born" by the couple of Titans known as Oceanus and Tethys. These Titans gave birth to over three thousands Rivers and to an equal number of Oceanides (Fig. 1). After all, according to the same poet in the genealogy of the Greek Theogony, rivers belong to the 4th generation of Gods. The fact that they belong to the same generation of Poseidon and Zeus, who are sons of two others Titans Cronus and Rhea, it is also remarkable.

Rivers are the only physical geographical systems that have been deified. It is also remarkable the fact that neither the Mountains nor Pontus, the other big physical geographical system, which belong to the 2nd generation, had been deified.

Rivers have defined the cultural process of human societies, especially those who lived in the Aegean and Peri-Aegean regions, but also those who lived in European and African regions as well. This is the reason why the Greek Mythology also refers to rivers, which are located beyond the Greek territory like the Nile, Istrus (Danube), Eridanus (Po), Vorysthenis (Dnieper), etc.

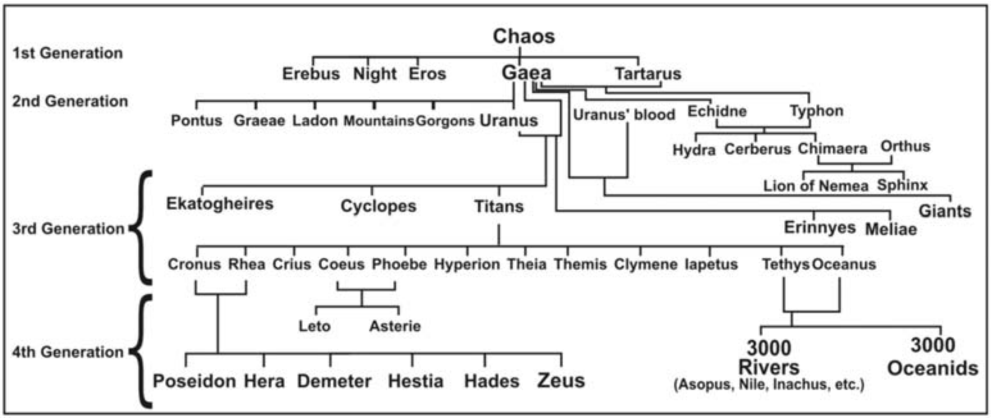

Fig. 1: Genealogical chart of Gods and Heroes.

The River-Gods are usually considered to be the progenitors of many islands. Asopos is considered to have been the progenitor of Aegina, Salamis, Euboea and some other islands, whereas Acheloos is considered to have been the progenitor of the Echinades islands, Nile of Egypt, etc. In other occasions, the genealogy of a river, which is located in a specific area, is connected with kings, who gave their name to some islands. For example, Meander is considered to be the progenitor of Samos Island.

We think that the reasons of that interrelationship must be connected with the vertical displacement of the sea level, probably because they had accepted that rivers water should be responsible for this.

Nowadays, of course, we know that the global sea level rising is attributed to the melt of the glaciers. In other words with movements which are well known as climatic-eustatic. In the prehistoric era, the inhabitants of the Aegean and Peri-Aegean regions were certainly unaware of the relationship between the increase of the global mean annual atmospheric temperature, the melt of the glaciers and the sea level rising.

2. The Rivers as physical geographical system

Almost all rivers are distinguished in two parts, upstream and downstream. The beginning of the upstream creation, in many cases, is usually very old and it is preceded the appearance of Homo.

Therefore all physical geological processes that are connected with the upstream of various rivers cannot influence the diachronic cultural development of Homo sapiens and as a result the inhabitants of the Aegean and Peri-Aegean region, as the Homo sapiens had not yet existed. So all the physical geological processes, related to the upstream of rivers are not expected to appear in Greek Mythology. Of course, we cannot exclude the possibility that somewhere, a myth could have been related with the upstream since in certain areas alterations have influenced the cultural development of inhabitants, who have settled along a river terrace or generally in an area around it. This is expected since the upstream of the rivers doesn't remain completely unchangeable. This mainly concerns to the rivers of the Greek territory because in major drainage networks, outside Greece, the environment is significantly different and much more complicated.

Therefore most references in Greek Mythology, but also in the mythology of other nations, must be associated with those parts of the rivers which have evolved from the appearance of humans and onwards. In the case of rivers downstream, when flew across the alluvial fans and deltas areas, the physical geological evolution is complicated and it becomes even more complicated because of the sea level fluctuations due to climate changes. It is known that many references in Greek Mythology concerning the above facts have been unfortunately ignored, obviously because they have been considered as imagination of the Greeks.

The delta areas have determined the cultural development of humans. This concerns all deltas all over the world and especially the large ones. In the Aegean and Peri-Aegean area, although the rivers are comparative smaller, they have effected the development of the ancient Greek civilization. This is the basic reason why rivers are often reported in Greek Mythology. As a result, anyone could hardly claim that there is a river, which is not reported in Greek Mythology. Therefore the detailed study of the rivers' delta presents not only geomythological interest but also scientific and "historic" interest, because under certain circumstances they allow us to "date" some physical geological processes, and in addition we can raise two issues:

(i) Greek Mythology is not an imaginary fiction, it is not a fairy-tail, but it is a story that describes physical geological events of a past period, which is so old that it is very difficult for us to understand it. The last is absolutely excused because today's physical geological status is completely different from that of the period before 6,000 BP, and
(ii) how old the Greek Mythology is.

How can someone, who is not familiar with all these impressive changes of the land surface relief in the wider Aegean and Peri-Aegean region, for example, realize that Aegina didn't exist as an island approximately 14,000 years BP or that Salamis became an island just 4,000 years BP (Mariolakos & Theocharis, 2003).

3. The Asopos River and the myth

Asopos is a very small stream, which is located on Aegina Island and discharges south of the city of Aegina. Its ancient name is almost unknown to the inhabitants of Aegina as it is called today "Rema tis Skotinis".

The name Asopos has been given to other rivers as well. One of them is located in Attica and discharges into the southern Evoikos Gulf, another one crosses part of Fthiotis prefecture, near to Thermopyles, and discharges into the northern Evoikos Gulf. So both rivers have been considered as the progenitors of Euboea Island. Another river with the same name is located in Korinthia prefecture and discharges into the Korinthian Gulf.

It is remarkable though how such a currently insignificant stream has been considered as the progenitor of two of the biggest islands of the Saronic Gulf, namely Aegina and Salamis, including also some other islands such as Euboea and others. Could it simply be imagination or it could include fragments of truth regarding the paleogeographical evolution of Aegina and Salamis and consequently the paleogeographical evolution of the Saronic Gulf in general?

From a geomythological point of view, the myth that considers Asopos as the father of Aegina and Salamis is noteworthy, because it's a typical case where the physical geological evolution of the wider area helps the myth to be explained and at the same time the myth helps a correct explanation to be given about the diachronic route of the Asopos river.

A land with a relative great lake, the Epidaurus Paleolake, was developed until around 14,000 years BP in the area that today is partly occupied by the western Saronic Gulf (Mariolakos & Theocharis,

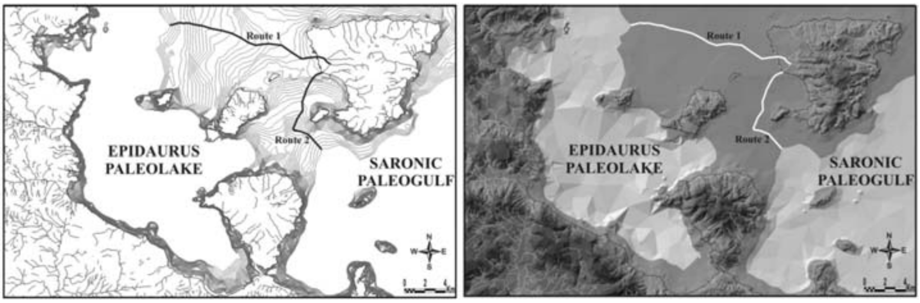

Fig. 2: The possible routes of Asopos river to Epidaurus Paleolake (Route 1) and Saronic Paleogulf (Route 2) is represented: a) on isobaths map of the present day Saronic Gulf, contour interval 5 m, from 0 to –125 meters, b) digital terrain model of the paleorelief which corresponds to 18000 BP.

2003). That means that the bigger and smaller islands, which are seen today, hadn't been shaped by that time. The main branch of Asopos, which is known today as "Rema tis Skotinis", begins from the interior of Aegina Island draining the slopes of the mountains Platyvouni, Trikorfi and Vouno Dendrou.

In the case of Asopos, a big question is raised, concerning especially the period that the Saronic Gulf hadn't yet been shaped. Was the water of Asopos River discharged into the Epidaurus Paleolake (Route 1, Fig. 2) or into the Saronic Paleogulf (Route 2, Fig. 2)? The answer in this question is very important because, if the physical geological – paleogeomorphological analysis proves that paleo-Asopos discharged into the sea and not into the Epidaurus Paleolake then the view that Asopos is considered to be the father of Aegina is enhanced because humans, who were living in the Upper Palaeolithic era probably connected the rising of the sea level with the rivers' overflow.

In order to provide an answer to this question a comparative analysis should be carried out including i) the alluvial fans of the river and ii) the coastline displacement due to the climatic-eustatic movements after 18,000 BP. So let's follow step by step the paleogeographical evolution of Asopos route and its alluvial fans (Fig 3, 5) based mainly: i) on the alluvial fans that have been deposited

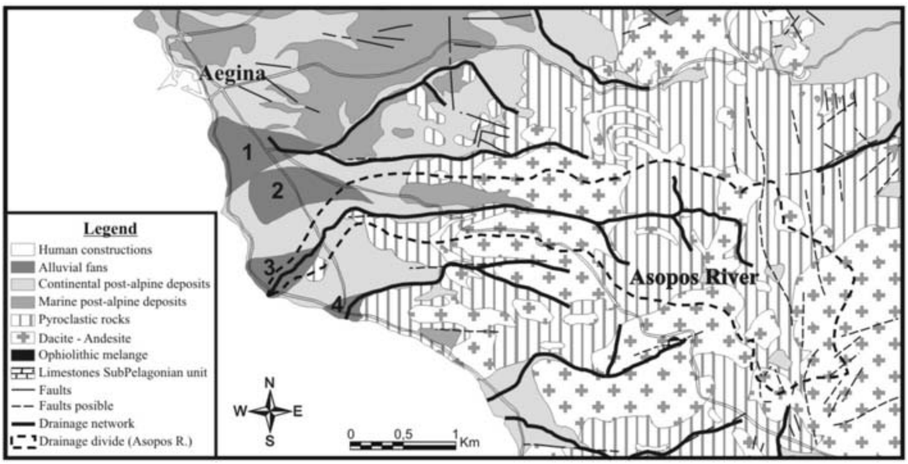

Fig. 3: Geological map modified from Dietrich et al 1991. It is shown, also, the catchments area of the Asopos River and the four alluvial fans of the wider area.

Fig. 4: Boulders in the riverbed Asopos indication of the transport capacity of the river in an earlier period.

after the stabilization of the sea level, that happened after the climate optimum of the Holocene (6,000-4,000 years BP), ii) on the shape of isobaths and iii) on the qualitative morphological correlation with the present shape of the alluvial fans.

Currently, Asopos River, who's its drainage basin extends to the western part of the island, flows initially to the west and then turns around abruptly to the southwest, developing along its banks an alluvial fun, which today is eroded by the river.

In the area around the modern banks of Asopos River, appear four alluvial fans (fig. 3). From the north to the south an alluvial fun appears, which is partly crossed by the anonymous stream (fan 1, Fig. 3). In modern times, the anonymous stream cannot reach the sea. This shows that the specific alluvial fan is not active now and furthermore the stream, which has washed away the material, must be inactive under today's climatic conditions.

Another alluvial fan (fan 2, Fig. 3) is developed southern than the previous one, which seems to be an abandoned fan of Asopos. Exactly on the top of the second fan, Asopos turns abruptly to the southwest, abandoning the specific fan and creating another younger one (fan 3, Fig. 3), which its top is located further west, of the present street, which runs across all these three alluvial fans.

Further south, another alluvial fun exists (fan 4, Fig. 3), which is drained by another stream that is much smaller than Asopos and the anonymous one, and flows northern. It also creates an abrupt angular bending in two sites.

The general overview shows that Asopos flowed northwestern of its today's flow until a certain time. We have a sudden shifting of the riverbed. Consequently this alluvial fun (fan 2) must be older and must have been abandoned for some reason. The most probable reason is the active tectonism of the area. In addition this area is volcanically active consequently a volcanic eruption could have created a change like this in the past.

Based on the above mentioned it is possible that Asopos River could have been formerly joined with the anonymous one, which flows further north, if we take into account the fact that the anonymous river does not reach the sea today. The question is whether a stream of that size can create such an extended alluvial fan.

These four alluvial fans have been definitely created after the climate optimum of the Holocene, and thus after the final formation of the Saronic Gulf. Consequently any shape and flow direction of Asopos can not characterize Asopos River as the progenitor of Aegina and Salamis, since the

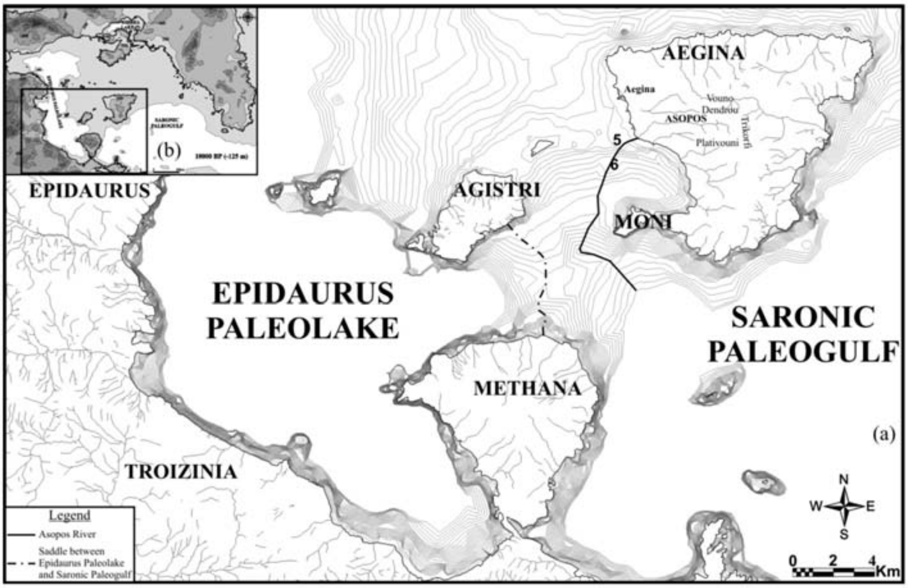

Fig. 5: (a) Offshore alluvial fans distinguished by the shape of isobaths. The alluvial fan 5 bounded by the contour of minus 10 meters and the alluvial fan 6 of the contours between minus 35 and 45 meters. (b) Paleo-geographical map of Saronic Gulf 18,000 BP (after Mariolakos & Theocharis 2003).

older islands inhabitants, that is before the period of the climatic optimum of Holocene, couldn't have witnessed the final formation of their coastlines.

It would be therefore interesting to observe up to the point where we can, what might have been the possible route of Asopos River in the period of time between 18,000 BP and 6,000 BP that is the period within which drastic climatic-eustatic movements occurred. For this purpose the topographic map of the bottom of the Saronic Gulf was drawn down (Fig. 5), using G.I.S. since earlier a digitization of all the bathymetric points was done from the maps of the Hellenic Military Geographical Service (HMGS).

In Fig. 5 a part of the map that includes Aegina, Methana, Troizinia and the Epidaurus Paleolake is depicted. Our aim is to define, up to the point that it is possible, a route of Asopos River during the last 18,000 years. For this reason we have chosen the contour line of minus 125 meters, as it is considered that the sea level that period must have been 120-130 meters below the present due to the climatic-eustatic movements (Lambeck 1996).

From the shape of the isobaths on the map of Fig. 5 it comes out that the contour of minus 10 meters creates a morphological lobe, which we consider that corresponds to a submarine alluvial fan (fan 5), created by the sediments of Asopos in a past era. From the depth that the alluvial fan is developed we consider that it corresponds to the time space between 7,000-8,000 BP. This conclusion is enforced by the fact that the morphological lobe is geographically located on the extension of the onshore fans and especially in front of the fans 2 and 3 (Fig. 3). As we mentioned above the alluvial fan 2 is older then the modern fan 3.

The former riverbed of the paleo-Asopos river, the period before the 7,000 BP, must have been directed to the submarine fan 6, which is developed between the isobaths of minus 35 and 45 meters. These depths must correspond to the former coastline during the period between 9,000 and 11,000 years BP approximately, taking into consideration the various curves of the shoreline displacement as those given by Kraft et al (1985).

Furthermore, paleo-Asopos follows the paleo-valley that had once been formed between the islet Moni and Agistri Island. So paleo-Asopos was probably discharging into the paleo-gulf, which is formed between Aegina, the islet Moni and the southeast part of Methana peninsula, which we consider to be the Proto-Saronic. This is the area were the sea entered through in a period of time when the sea level had risen over the saddle between Agistri and Methana, causing the flooding of the Epidaurus Paleolake.

4. Discussion – Conclusions

From the former analysis, it seems that due to the morphotectonic evolution and the volcanic activity of the area between Troizinia, Agistri island and the Methana volcanic peninsula it has been shaped a submarine saddle at depths 70-75 meters approximately which forms a kind of natural barrier that isolates the morphological depression which has been formed in the area occupied by Epidaurus Paleolake.

Taking into consideration the paleogeographical evolution of the coastal areas and generally the area that today is occupied by the Saronic Gulf we believe that the characterization of Asopos as the progenitor of the islands Aegina and Salamis is directly connected with the route of the river during the period between 18,000 and 6,000 years BP. The reason must be connected with the fact that the prehistorical inhabitants of these period, from the period of time they had realized that the sea level begins rising gradually, shortly after 18,000 BP and mainly after 16,000 BP, obviously wanted to give an explanation about the phenomenon which disturbed their whole life. It is sure that they didn't have knowledge of the climatic eustatic movements. The inhabitants were observing that the river carried away, day by day, its waters into the sea. Therefore they believed that Asopos was responsible for the gradual sea level rise and the flooding of the area, which early humans exploited available resources such as preys, water springs, etc.

With the gradual rising of the sea level various islands were formed. That's why a river, in this case Asopos, could become a God and in the same time the progenitor of many islands and in this case Aegina and Salamis.

It's certain that many won't accept the suggested interpretation. Anyway for us, who have studied the paleogeographic evolution of the wider area, we think it is a logical or reasonable geomythological explanation.

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ORACLES ON FAULTS: A PROBABLE LOCATION OF A "LOST" ORACLE OF APOLLO NEAR OROVIAI (NORTHERN EUBOEA ISLAND, GREECE) VIEWED IN ITS GEOLOGICAL AND GEOMORPHOLOGICAL CONTEXT

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Abstract

At a newly discovered archaeological site at Aghios Taxiarches in Northern Euboea, two votive inscribed stelae were found in 2001 together with hellenistic pottery next to ancient wall ruins on a steep and high rocky slope. Based on the inscriptions and the geographical location of the site we propose the hypothesis that this is quite probably the spot where the oracle of "Apollo Selinountios" (mentioned by Strabo) would stand in antiquity. The wall ruins of the site are found on a very steep bedrock escarpment of an active fault zone, next to a hanging valley, a high waterfall and a cave. The geomorphological and geological environment of the site is linked directly to the regional geodynamical context of Central Greece, a region of tectonic turmoil throughout the Pleistocene and Holocene, characterised by distinct landscapes produced by the activity of active fault zones, intense seismicity, and in part, volcanism and hydrothermal activity. The geomorphological and geological similarities of the Ag. Taxiarches site with those of the oracle at Delphi, seem to provide further support to the hypothesis that the former site can well be that of an ancient oracle, given the recently established connections between the geological environment at Delphi and Apollo's oracle there. Definitive verification of our hypothesis can only be obtained by further, detailed archaeological study, whereas geological/geomorphological, geochemical, and geochronological studies would be necessary to clarify the connection that the cave lying next to the wall remains may had with the site's function.

Key words: *Apollo Selinaios, oracle, geodynamics, geomorphology, Euboea (Evia).*

1. Introduction

The purpose of this paper is to present a resume of the available archaeological data and the results of a geological and geomorphological reconnaissance of a recently discovered archaeological site near Rovies, North Euboea (or Evia) (Figure 1). We will propose that the available literary, archaeological and geographical data, support the hypothesis that this site could well be the oracle of *Apollo Selinountios*, mentioned by Strabo (10, 1, 3) in his description of the northern part of the island. The

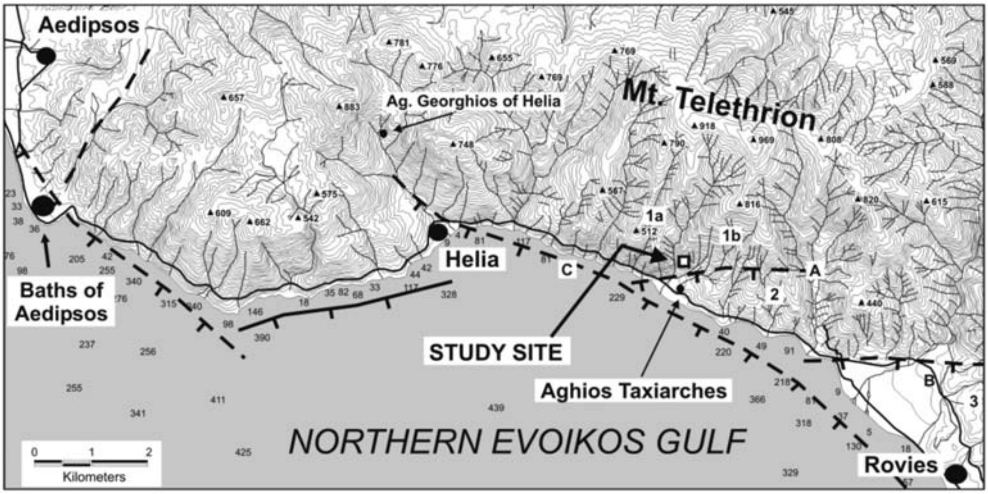

Fig. 1: Topographic map of the broader area of the study site (Telethrion mountain). 20 m contours from 1:50,000 HAGS topographic maps. On shore faults modified from the IGME geological map (Katsikatsos et al., 1984), and from this study. Major offshore fault traces are based on Van Andel & Perissoratis (2006), with modifications (see also Sakellariou et al., 2007 for smaller scale map). A great number of thermal springs are found in the Baths of Aedipsos (Loutra Aedipsou) and in Helia, which are accompanied by the emission of gasses. 1a: Triassic metavolcanics and crystalline limestones, 1b: Triassic metaclastics, 2: Permian metaclastics, 3: Neogene fluvio-lacustrine deposits of the Limni-Istiaia basin (Katsikatsos et al., 1984)

geomorphic and geological characteristics of the site will be presented and compared to those of the oracle of Apollo at Delphi, in order to bring forward the similarities existing between the two. Since recent studies have established the strong connection between the geological characteristics and phenomena at the famous oracle of Apollo at Delphi, and the particular use of the site in ancient times (Piccardi, 2000; de Boer and Hale, 2000; de Boer et al, 2001), this comparison provides further, indirect support to the hypothesis that the site discussed herein can well be the site of an oracle.

2. A cult place dedicated to Apollo Selinaios at Aghios Taxiarches and the oracle of Apollo Selinountios mentioned by Strabo

In 2001, at the steep western slope of Mt. Telethrion, in the vicinity of the chapel of Aghios Taxiarches, near the western euboean coast and 6.2 km NW of the village of Rovies (Figure 1), a votive inscribed stele and a fragment of a second one were discovered by a citizen and handed over to the Greek Archaeological Service where they were given the inventory numbers 216 and 217 of the Aedipsos Archaeological Collection. They were found, in a crack on bedrock and on the ground surface, together with surface pottery, identified as Hellenistic (see Nikolopoulos, 2005), right next to the ruins of a wall made of large, roughly worked blocks (Figure 2a/b). The wall, possibly part of an enclosure or of a retaining wall is preserved for a length of 13 m and ends abruptly to the North, apparently due to landsliding. The steepness of the terrain at the site, the high rock-fall hazard and potential increased slope instability do not allow a safe archaeological trial excavation at the moment. In any case, the slope and the wall sustains only a limited amount of soil covering the bedrock on which the wall remains rest, i.e., valuable archaeological evidence has been obviously washed away from the site.

The inscription no 216 (Figure 2c), mentions the dedication of a female slave to *Apollo Selinaios* so that after a certain time she could obtain her liberty. There are also mentioned the names of the dedicator and the authorities who were present. According to the type of the letters, it is dated in the 1st half of the 1st century BCE. The fragment No 217 (Figure 2d), mentions in its 1st verse the township (δήμος) of the area, Histiaia, and, in the 7th, a priestess (ιέρεια). This one is dated in the mid 4 th century BCE (Nikolopoulos, 2005).

Aed. Coll. inv. No 216

[- - - - - - - -] Α[...]
[..]ως Αἰολὲω[ς] ̣του Ἡρα̣
[κ]λείτου [Α]ἰολεύς Ἡρα
[κ]λείτου ἀνέθηκεν Ἀφρ[ο]
δ̣ισίαν ἐλευθέραν τῷ Ἀ̣
π̣όλλωνι τ<ῷ> Σελιναίωι
ἱεράν λειτουργοῦσαν
τῷ θεῶι· ἀρχόντων πα
[ρ]ῆ̣ν Ξένων Ἀριστοκλέ[ο]
υς· ἀστυνόμων παρ[ῆν]
Ἀ̣ντικράτης Χάρητ[ος]·
μ̣άρτυρες θεοὶ καὶ θῦ̣[ται]
vacat

Aed. Coll. inv. No 217

[- - -]ς Ἱστια[ι - - - -]
[- - -αίωι: Ει[- - - -]
[- - - -]μου Λυσα[- - -]
[- - - -δ]ήμου: Δ[- - -]
[- - -]υ Τιμοκλέ[ους - -]
[- - - - -]νου: Ξεν[- -]
[- - - - -]ἱέρεια [- - -]
[- - - - - - -]Π [- - - -]

We have seen that, according to the epigraphical material, a citizen of unknown provenance dedicated, at the study site, a slave to a sanctuary of Apollo, bearing an epithet unknown from any literary or epigraphical source. Liberation via dedication to the services of a god was a common practice in hellenistic and roman times, especially in east/central Greece, mainly in Boeotia, Phokis and Lokris, westwards of Northern Euboea. Over two hundred hellenistic and roman inscriptions refer to the dedication of slaves at sanctuaries, mainly of Asklepios, Sarapis, Zeus, Herakles, Artemis Eileitheia and Apollo (Darmezin, 1999), all deities and heroes with healing properties or related with medicine.

In Northern Euboea the cult of Apollo is mentioned only in one ancient source, in a passage of Strabo (10. 1. 3), where he mentions an oracle of *Apollo Selinountios* located in the area of Oroviai.

10,1,3 «...καὶ Ὀροβίας, ἐν ᾧ μαντεῖον ἦν αψευδέστατον· ἦν δὲ μαντείον τοῦ Σελινουντίου Ἀπόλλωνος».[1]

Various authors and scholars dedicated to the topography of ancient Euboea refer to this information, but have failed to spot the location of the oracle. Following a modern legend it was widely accepted - by historians and among monastic circles- that the oracle should not be next to ancient Oroviai (mdn. Rovies - Figure 1)[2], where Strabo located it, but farther North, under the XVI century monastery of Aghios Georghios of Helia (Figure 1, Bursian, 1872, 411, n. 2; Sackett et al., 1966, 39 n. 25).

[1] "... and Orovia; in this last place was an oracle most averse to falsehood (it was an oracle of Apollo Selinountios)..." Trans. H. L. Jones, The Geography of Strabo, Vol. V, The Loeb Classical Library, CA Massachusetts, Harvard University Press, London, 1988. (In this edition instead of the right transliteration *Oroviai*/*Oroviae* the toponym appears as *Orovia*).

[2] The ancient Oroviai stood where the modern village of Rovies is, 6.2 km SE of the chapel of Aghios Taxiarches. Today classical or later ruins and pottery are visible on the sides and on the top of a hill within the limits of the village where, according to Sackett et al. (1966, 47), the town must have moved from the nearby coast after the destruction it suffered by the earthquake of 426 BCE mentioned by Thucidides (3, 89).

Fig. 2: (a) / (b): Walling remains of the site of Apollo Selinaios. c, d: The inscribed stelae found at the same site (Nikolopoulos, 2005). The stele at (c) is dated at the 1st half of the 1st century BCE and mentions the dedication of a slave to Apollo Selinaios (ΣΕΛΙΝΑΙΩΙ) so that after a certain time she could obtain her liberty. The stele at (d) mentions the major township (demos) of the area, Histiaia, and a priestess (ΙΕΡΕΙΑ), and is dated at mid 4th century BCE.

A sanctuary of Apollo with oracular function is not unexpected in the area. In the Homeric *Hymn to Apollo*, a detailed description is given of the route taken by Apollo, in his quest for an appropriate site to found his oracle (Figure 3). Starting from Mt. Olympus, he headed south and, through Iolkos (in Thessaly), he arrived at cape Kenaeon (cape Lichas) of Northern Euboea. From there, following a route along the west coast of the island he reached the Lelantion field and he subsequently wandered westwards towards the area of Boeotia, before ending up in Phokis, where he founded the oracle of Delphi. The hymn describes how local deities were put under Apollo's domination and how at least one sacred place with a spring (*Telphoussa,* 9 in Figure 3*)* was destroyed upon resisting the domination of the god. It is remarkable that the site at Aghios Taxiarches, (AS in Figure 3), is located on the mythological route described in the Homeric Hymn. (Figure 3).

Considering the above, the epithet *Selinaios* used for Apollo in one of the inscriptions at the study site and the site's proximity to ancient Oroviai, the hypothesis that the ruins at the study site can be identified with the oracle of Apollo *Selinountios* mentioned by Strabo, in our view is a very plausible one. In Strabo's text of course, the epithet used for Apollo is "*Selinountios*", whereas inscription No 216 is dedicated to Apollo "*Selinaios*". The two epithets are not interchangeable, raising the question whether the text of Strabo may refer to a different site than one where the inscription referring to *Selinaios* Apollo was found. The name "Selinountios" could suggest a connection with the towns of Selinous in Sicily or a minor town with the same name on the island of Peparethos, NE of Euboea (today's Skopelos Island – Figure 3). Etymologically, both words (*Selinountios* and *Selinaios*) have the same root: "*σέλινον* / *selinon*" (= celery, bot. *Apium graveolens*), a plant that in antiquity had given indeed its name to rivers, lakes, towns, local deities or heroes in mainland Greece, the Aegean, Asia Minor and Sicily (RE[3], Σέλινος, Σελινούς). Considering that: (1) Strabo was based often on earlier written sources, (2) a literary text the original of which is not known may have suffered changes through the centuries by successive copiers, (3) the connections implied by the epithet *Selinountios* cannot be testified by any historical or archaeological source, (4) that the epithet

[3] Paulys Real Encyclopädie der Classischen Altertumswissenschaft.

Selinaios is unknown from any literary or epigraphical source and that (4) the hypothesis that next to Oroviai there were two different cult places dedicated to Apollo, bearing as epithets variations of the same root "*selinon*" is perhaps much weaker than the hypothesis that the epithet mentioned in Strabo is a result of error of transcription, based on the data available at the moment, we tend to favour the latter hypothesis. Furthermore, there is no reason to believe that a heavy dedicatory stele and a fragmentary one, both referring to the sacred nature of a place, are not related to the site or have been carried to such a steep place.

In an attempt to understand why especially the epithet *Selinaios* was given to Apollo, after a survey in ancient and early medieval greek literary sources, over 1220 occurrences of the word "*selinon*" and its derivatives were found, attributing to celery various properties and symbolisms. The great majority of texts either stress the medical properties of the plant (eg. For Galen and Hippocrates: Kuhn, 1821-1833, VI, 637 and Index; Kühn and Fleischer, 1989 398, 730) or relate it, directly or indirectly, with death and *chthonian* (earthly) powers personified in various local heroes. Such a connection insinuate the fact that celery leaves were used to adorn tombs (Plut., *Tim*.26.1.2) while crowns made of celery leaves were offered to the winners of the Pan-Hellenic games at Nemea and Isthmia, in NE Peloponnese (Broneer, 1962), commemorating, in the first case, the death of the child-hero Ofeltes (Paus., 8. 48. 2) killed by a dragon that was protecting a spring, and at Isthmia, the child-hero Melikertes-Palaimon (Gebhard, 1993) who was worshipped in a temple with an underground passage leading to an *adyton*, as Pausanias (2.2.1) describes it.

According to the dating of the two inscriptions and the surface pottery, the site could have been in use for at least two and a half centuries**,** between the 4th and 1st centuries BCE. It is not yet known whether its use was uninterrupted during this period, since our knowledge up to now is based on surface finds and a single literary source. Unless further field investigation is undertaken at the site – if this is technically possible – an answer to this question cannot be provided, since the archaeological data available so far are not enough. The same holds true for determining the period it was founded, when it was abandoned and why. What is sure, is that the site has suffered severe damages, so that only sparse architectural and epigraphical relics are remaining today. One –natural- process of degradation is rockfalls, the present-day morphology suggesting that at least part of the site may have slid away into debris now at the base of the cliff.

3. Regional geodynamic setting

The geodynamic province of "Central Greece" has been witnessing active crustal extension at a rate of about 10 mm/yr during most of the Quaternary (e.g. Jackson, 1994). The latest (Pleistocene) phase of the extension is responsible for the formation of the Northern Evoikos Gulf (e.g. Philip,1974; Lemeille, 1977; Rondogianni, 1984), a graben bound by a series of WNW-ESE to NW-SE fault zones which are active as of today (Figure 4). On the mainland side, the graben is bound by the NNE to NE-dipping fault zones of Atalanti and Arkitsa-Kammena Vourla (Afz and AKfz in Figure 4, respectively, e.g. Philip, 1974; Rondogianni, 1984; Kranis, 1999), whereas the Euboea side is defined by the SW-dipping Kandili fault zone (Kfz) as well as other zones on the side of Euboea (Rondogianni, 1984; Roberts and Jackson, 1991; Ganas, 1997 and many others). The activity of these fault zones has strongly influenced the landscape evolution of the region, and is related with significant historical (e.g. Bousquet and Pechoux, 1977; Rondogianni, 1984; Papaioannou et al., 1994 and several others) and instrumentally recorded seismicity (e.g. Papanastassiou et al., 2001).

A further important element of the regional geodynamics is volcanism, focused in the broader area around the Lichades islands (star n. 1 in Figure 4), which consist of Pleistocene volcanics (Fytikas

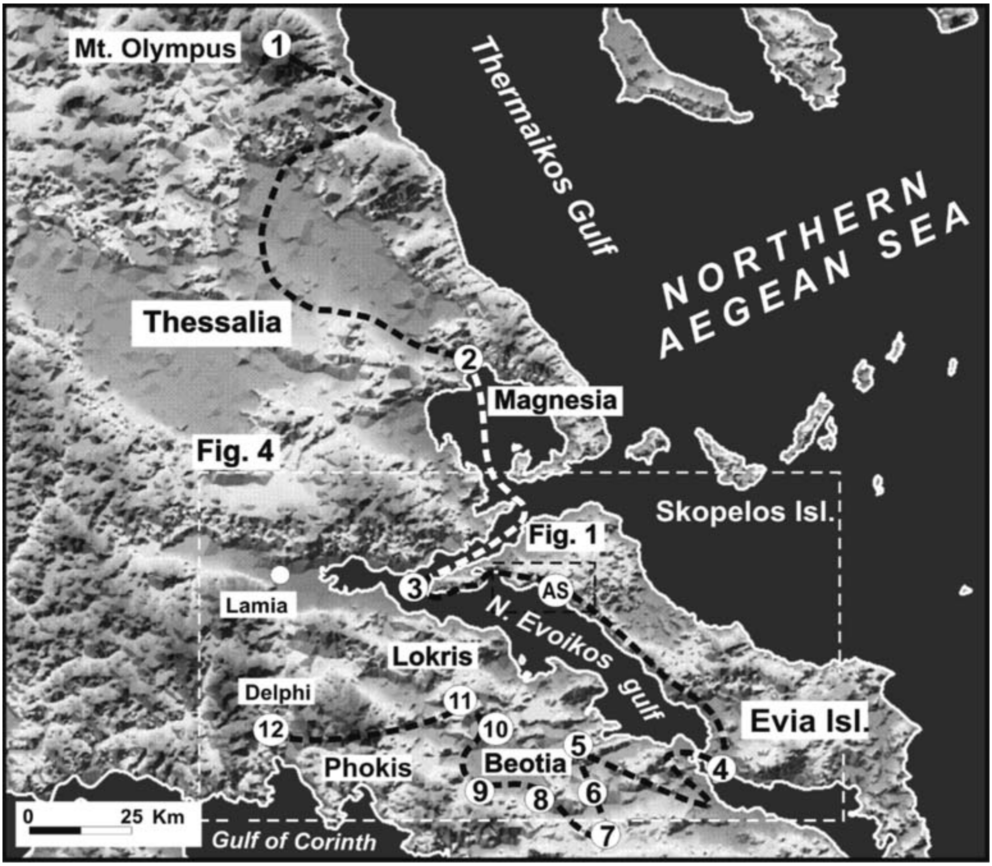

Fig. 3: The route Apollo followed from Mt. Olympus to Delphi on his quest for an appropriate place to found an oracle, according to the Homeric "Hymn to Apollo". Numbers indicate places mentioned in the Homeric 'Hymn to Apollo' including those where Apollo founded oracles before ending up in Delphi (the oldest and the most important oracles of Apollo, more recent ones being located in Asia Minor, on the islands of Lesvos, Lemnos and Delos, and one in Peloponnesos). It is remarkable that the oracles in their majority have been founded within the greater area between the Northern Evoikos Gulf and the gulf of Corinth, two major neotectonic graben trending WNW-ESE to NW-SE, which are associated with the most intense seismicity of mainland Greece.
1: Mt. Olympus, 2: Iolkos, 3: Cape Kenaeon, 4: Lelantion Field, 5: Ptoon Mt., oracle of 'Ptoos Apollo', 6: Ismenion, oracle of 'Ismenios Apollo', 7: oracle of Apollo in Isiae, 8: oracle of Apollo in Eutresis, 9: Telphoussa, 10: oracle of Apollo in Tegyra, 11: oracle of Apollo in Avai, 12: Delphi, where the most famous of Apollo's oracles are located, AS: The site at Ag. Taxiarches near Oroviai discussed herein. Oracle names from Ragavis (1888).

et al., 1984). Older, Miocene-age volcanic rocks are found at Chronia, SE of Rovies (star n. 2 in Figure 4, Lemeille, 1977; Katsikatsos et al., 1980). Volcanic activity has formed a significant number of thermal springs around Northern Evoikos, as in Hypate, Thermopylae (=hot gates or gates of thermal springs), Aedipsos (e.g. Kelepertsis et al., 2009) and Yialtra in N. Euboea, and at Limni (9 km SE of Rovies) and Helia (Figure 4; Sfetsos, 1988). The thermal springs are often found along fault zone traces and especially at their intersections. In the case of Aedipsos, the hydrothermal springs are related to extensive travertine deposits (e.g. Hancock et al., 1999).

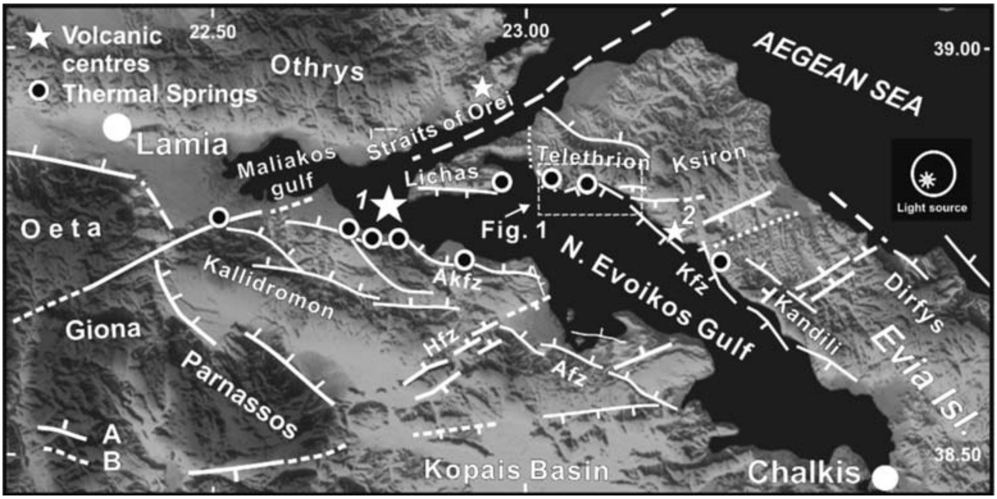

Fig. 4: The Northern Evoikos Gulf graben and surrounding area. Faults from Philip (1974), Katsikatsos et al. (1984), Rondogianni (1984), Kranis (1999), Palyvos et al. (2006), Van Andel & Perissoratis (2006) and references therein. Major thermal spring locations reproduced from Sfetsos (1988), volcanic centres from IGME maps. The existence of the thermal springs is attributed to the Lichades Quaternary volcanic centre (large star) and the presence of many active faults, along which –and especially at their intersections- the occurrence of these springs is favoured. Older volcanic centres are those of Chronia and Achillion (marked with a smaller star). A: normal fault (ticks on downthrown side), B: probable fault or fault extension.

4. Geological and geomorphological environment of the site

The ruins of the site discussed herein are located about 420 m North of the chapel of Aghios Taxiarches, on a south-facing slope of Mt. Telethrion overlooking the N. Evoikos gulf (Figures 1 and 5). Mt. Telethrion is part of the highest mountain range (700-990 m) of the northernmost part of Euboea (Figure 5).

The northernmost part of Euboea is dominated by Lower Miocene to Lower Pleistocene fluvio-lacustrine deposits of the Limni-Istiaia basin (Mettos et al., 1992). Uplift of the Telethrion range during the Quaternary has resulted in the removal of the original cover of Neogene deposits and the extensive exposure of alpine bedrock. In specific, the Mt. Telethrion consists of Upper Paleozoic to Middle Jurassic metamorphic rocks belonging to the Pelagonian geotectonic unit of the Hellenides. In the broader area around the oracle of Apollo, greenstones (meta-volcanics) with intercalations of schists and phyllites occur (Katsikatsos et al., 1984). These are interpreted to be the product of submarine extrusions of basic igneous rocks, mainly diabasic and basaltic, that were epizonally metamorphosed during the Alpine orogenetic cycle (Katsikatsos et al., 1984). Within the above formation, intercalations of Middle Triassic white-grey crystalline limestones can be found (Katsikatsos et al., 1984).

The morphology of the S-SSW face of Mt. Telethrion is characteristically straight and steep (Figures 1 and 5), its slopes descend to the sea with the deepest waters of the Northern Evoikos Gulf in front of them (>400 m – Figure 1). This morphology is the geomorphic expression of a presumably active fault zone directed roughly WNW-ESE, which bounds this part of the Northern Evoikos gulf graben to the N-NNE (Figure 4) – e.g. Van Andel & Perrissoratis (2006). Triangular facets, features typical of fault-bounded range-fronts (e.g. Burbank and Anderson, 2001) are present on the slopes of Mt. Telethrion (Figure 5). The ruins are located near the base of one of these facets (~800 m high - Figures 1 and 5), under the highest peak of Mt. Telethrion (970 m).

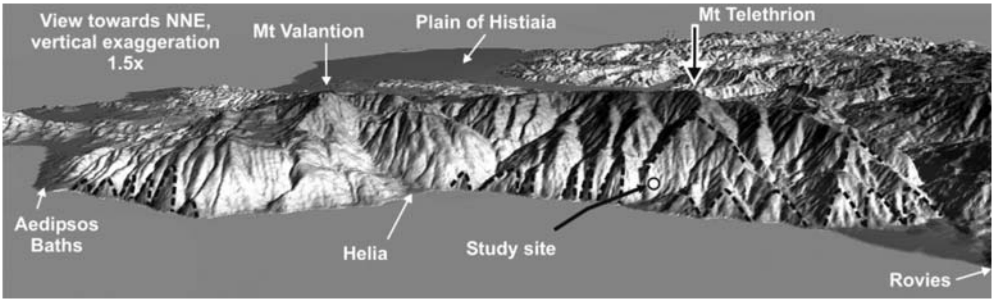

Fig. 5: Digital Terrain Model of Mt. Telethrion, where the study site is located. 3-D view from SSE towards NNW, vertical exaggeration 1.5x. DTM resolution is 20 m, interpolated from 20 m contours of HAGS 1:50.000 maps. The straight and steep morphology is due to the presence of a NW-SE active fault zone bounding Telethrion to the SW. Dashed lines mark triangular facets on the mountain front, in between deep wine-glass and V- valleys that dissect it. The large facet on which the study site is located, is drawn simplified (it can be subdivided in one upper facet and two lower ones).

In the 1:50,000 geological map of the Institute of Geological and Mineral Exploration (IGME - Katsikatsos et al., 1984) the respective fault zone along is traced at the base of the facet where the ruins are located, as a discontinuity that brings into contact the middle Triassic metavolcanics / crystalline limestones formation with Permian metaclastics (modified fault trace ‘A’ in Figure 1). The orientation of the fault zone at the base of the facet (and the facet itself) is oblique relative to the general direction of the offshore fault zone that bounds Mt. Telethrion to the SW (‘C’ in Figure 1). We consider fault zone A to be part of a different group of neotectonic structures (rather than a splay of the offshore fault zone C), because of (a) the existence of a second fault zone with this same direction farther SE (fault zone ‘B’ in Figure 1, which juxtaposes Neogene deposits against rocks of the Pelagonian unit), and (b) the existence of probable neotectonic faults with the same general direction crossing this part of Northern Euboea farther ESE (Palyvos et al., 2006 and references therein).

In most of its extent, the facet with the ruins is more or less concave in cross profile, consisting of easily erodible metamorphosed clastics (1b in Figure 1). Its SW tip though (where the ruins are located), consists of the metavolcanics of the Telethrion escarpment and the largest occurrence of crystalline limestones inside them (1a in Figure 1), both very hard lithologies, resulting in the specific part of the facet being steep and convex in profile. The morphological surroundings are particularly imposing: apart from the steepness of the bedrock escarpment, the site is located next to a very scenic waterfall more than 70 m high, at the exit of a small hanging valley (Figures 6 and 7).

The crystalline limestones / metavolcanics contact at the area of the ruins is dipping to the NE and it is well defined and readily observable on the western side of the hanging valley, all the way to the valley bottom (Figure 6). At the eastern side of the valley the metavolcanics disappear abruptly, and the escarpment facet in this specific part consists of limestones only. This is so because the contact is interrupted by a NE-SW trending, SE-dipping normal fault down throwing to the SE, which will be called ‘F1’ in the discussion that follows. We consider fault F1 to be a secondary splay of the facet-bounding fault zone A shown in Figure 1. Fault F1 was observed a few tens of meters W of the walling remains, and together with other discontinuities, relates to the presence of a cave that was discovered between the walling remains and the waterfall during our reconnaissance (Figures 6, 8 and 9).

The cave is found on the upthrown (footwall) block of fault F1, right next to the fault. The SE wall of the cave is the very well preserved polished fault plane of fault F1 (Figures 8 and 9) that dips 81-

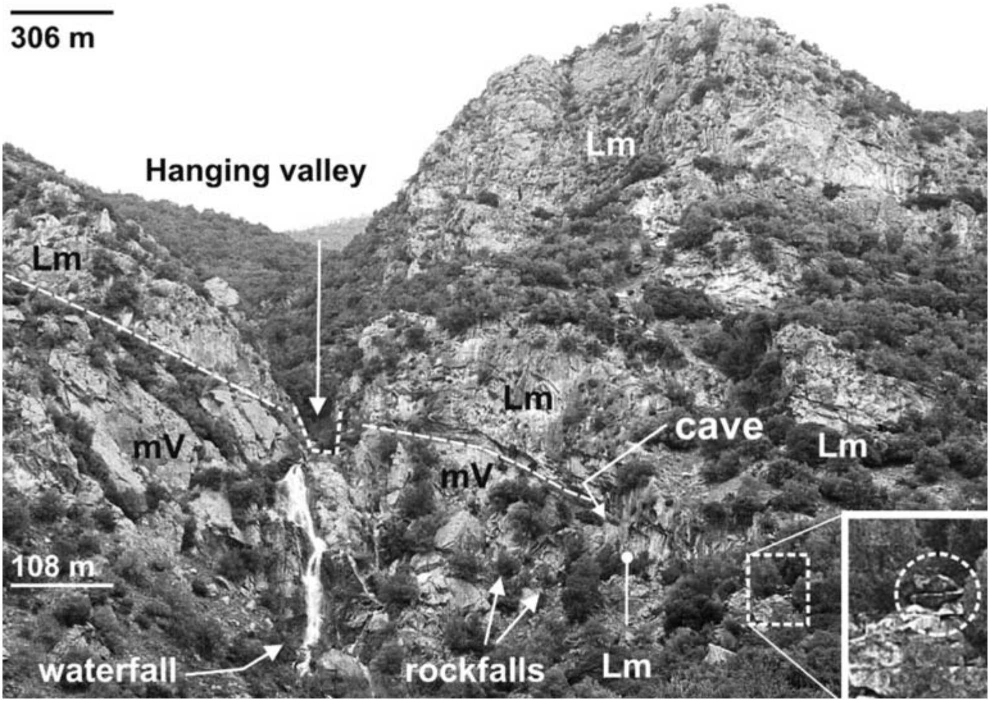

Fig. 6: Photograph of the escarpment where the study site is located (view from the South). Walling remains are visible in the zoomed-in part of the photograph, near a hanging valley and a very scenic waterfall more than 70 m high. The escarpment consists of crystalline limestones (Lm), over metavolcanics (mv), their contact (marked with a dashed line) dipping around 27° towards the NE. Where the cave is located (entrance facing to the left of the photo, not visible in the photo), the contact is downthrown by a normal fault parallel to the escarpment (see text), and only limestones are exposed in the vicinity of the walling remains. Elevations taken from a 1:5.000 topographic diagram of the Hellenic Army Geographical Service are also shown.

85° towards N153-163°E, with striations (70°/226°). A thick travertine deposit occurs along the plane of F1 (Figures 8 and 9b). The ceiling of the cave is the floor of the crystalline limestones of the upthrown fault block, whereas the NW wall consists of the metavolcanics that are found below them, bounded by a succession of at least three discontinuities with more or less the same strike as F1 (Figure 8b). Furthermore, the polished fault plane of F1 is interrupted by a transverse fault (F2 in Figure 8a and 9a, dipping 85° towards N252°E). All these discontinuities pre-defined the shape of the cave, whose formation was initiated by groundwater circulation along the limestone / metavolcanics contact (permeable and impermeable, respectively). The bases of three large stalactites -that are broken today- are found on the cave ceiling (Figures. 8 and 9a), their positions defined by joints cross-cutting the limestones. Dripping water along parts of the cave is still observed today.

The present form of the cave is probably the result of subsequent removal by mass wasting of the metavolcanics under the floor of the limestones on the upthrown block of F1. It is characteristic that, when observing the escarpment from the south, on the western side of the hanging valley and the waterfall the metavolcanics systematically protrude underneath the crystalline limestones above them. On the contrary, in the vicinity of the cave, the limestones are seen overhanging above the metavolcanics, giving to the observer the sense of removal of a significant mass of metavolcanics

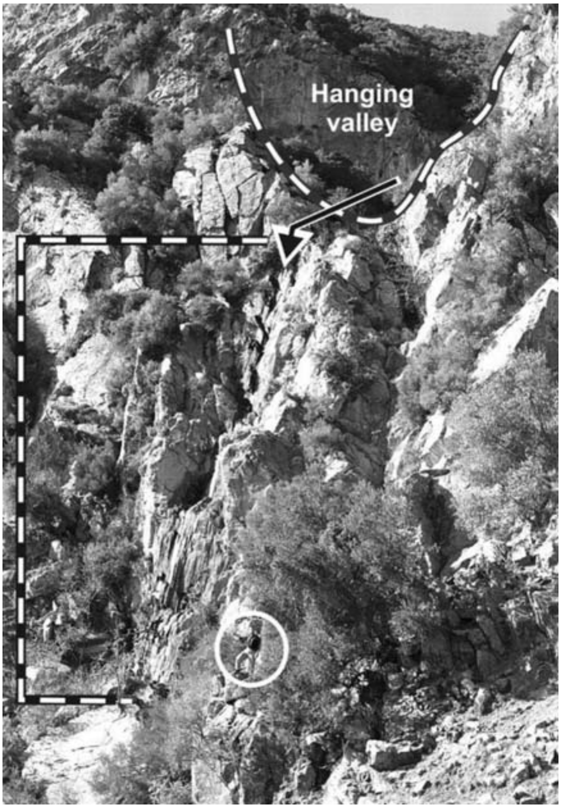

Fig. 7: View of the hanging valley and high waterfall immediately to the West of the wall remains and cave at the study site. The person (in white circle) shown for scale, underestimates the height of the waterfall since he does not stand immediately in front of it.

underneath them (Figure 6 - rockfalls can be seen also on the slope in front of this area). This may be due to more intense rock fracturing because of the intersection of two faults and differences in mechanical behaviour between the limestones and the metavolcanics.

5. Discussion and open questions

Recent works point out the straightforward connection between geological features and phenomena (mostly related to the presence of an active normal fault zone, in specific) and the selection of the particular site for the oracle of Delphi, the major oracle of Apollo in Central Greece (Piccardi, 2000; de Boer and Hale, 2000; de Boer et al., 2001). They discuss Plutarch's and other ancient authors' description of the process of divination over a chasm from which gasses where emitting, provoking a state of 'ecstasy' to the priestess of the oracle, and they provide geological evidence which supports the validity of the ancient sources, proposing that the oracular chasm indeed existed in the form of a fissure related to a ground-rupturing active fault or an associated extensional fracture. Piccardi (2000) identified such a fault (paralleling the general direction of the Delphi fault zone) that runs through the shrine of Athena at Delphi, where the primitive sanctuary of the 14th century BCE was also located. De Boer and Hale (2000) have shown that the shrine of Apollo (at a location different than the shrine of Athena) is located at the intersection of the Delphi fault zone and a conjugate swarm of NNW-SSE fractures, along which a number of springs were found (de Boer and Hale, 2000). Chemical analyses of spring waters and travertine deposits realized by de Boer et al. (2001) have proved that light hydrocarbon gasses were emanating with the spring waters at Delphi, origi-

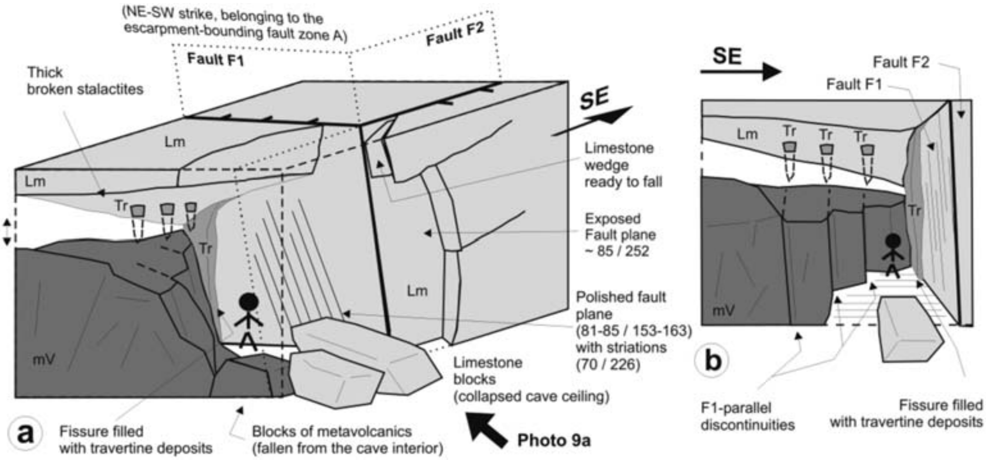

Fig. 7: 3D sketch of the cave lying on the very steep slope immediately West of the ruins. The formation of the cave was directed by a NE-dipping crystalline limestones (Lm) / metavolcanics (mV) contact, which forms the ceiling of the cave, fault F1, the polished fault plane of which constitutes the SE wall of the cave, fault F2 striking transverse to F1, and faults striking parallel to F1 inside the metavolcanics in its upthrown (footwall) block. A fissure along fault F1 is filled with travertines (Tr). Ticks indicate downthrown (hangingwall) fault blocks.

nating from the underlying strata of bituminous limestones. Among these gasses ethylene was detected, which, upon inhalation causes effects that match those described for the prophetic vapours in ancient texts (de Boer et al., 2001).

Taking into account the initial dedication of oracles to Gaia (earth) and Poseidon, the god of earthquakes, and the fact that earthquakes are closely related to myths regarding the Delphic oracle (Polimenakos, 1996; Piccardi, 2000*),* preference to the particular type of environment for the oracle of Delphi may be attributed to the fact that it most vividly reflects the 'underworld' (chthonian) powers, which, in modern terminology would be geodynamic phenomena. In a passage referring to a steep escarpment in the valley of Peneos in Thessaly, Herodotus explicitly states: "In my opinion it is the work of an earthquake" (Her. 7, 129, 26). This is a clear indication that the connection between earthquakes and changes in the landscape (formation of tectonic landforms) was a notion understood at least as early as Classical times (presumably, also even earlier).

Comparing the landscape features at the oracle of Apollo at Delphi and the site of Aghios Taxiarches we can recognize quite similar geological and geomorphic features (similarity referring to types of landforms found in the landscape, but not necessarily similarity in their sizes or details).

- The oracle at Delphi is also located in front of a 500-700 m high fault escarpment facing to the south, with a WNW-ESE normal fault zone running along its base (Birot, 1959; Aronis et al., 1964; Mariolakos et al., 1989, 1991; Pechoux, 1992; Piccardi, 2000; de Boer and Hale, 2000). The fault zone at Delphi is considered active (e.g. Mariolakos et al., 1989, 1991; Piccardi, 2000; de Boer and Hale, 2000), albeit less active –arguably- than the Telethrion fault zone (judging from their geomorphic expressions).
- In both sites the fault escarpments consist of bedrock: limestones in Delphi, limestones and metavolcanics in Aghios Taxiarches. These hard lithologies result in steep and imposing escarpment morphology, "decorated" with steep cliffs and rock fall scars.
- The oracle at Delphi was also constructed at the mouth of a valley with a gentle upper part,

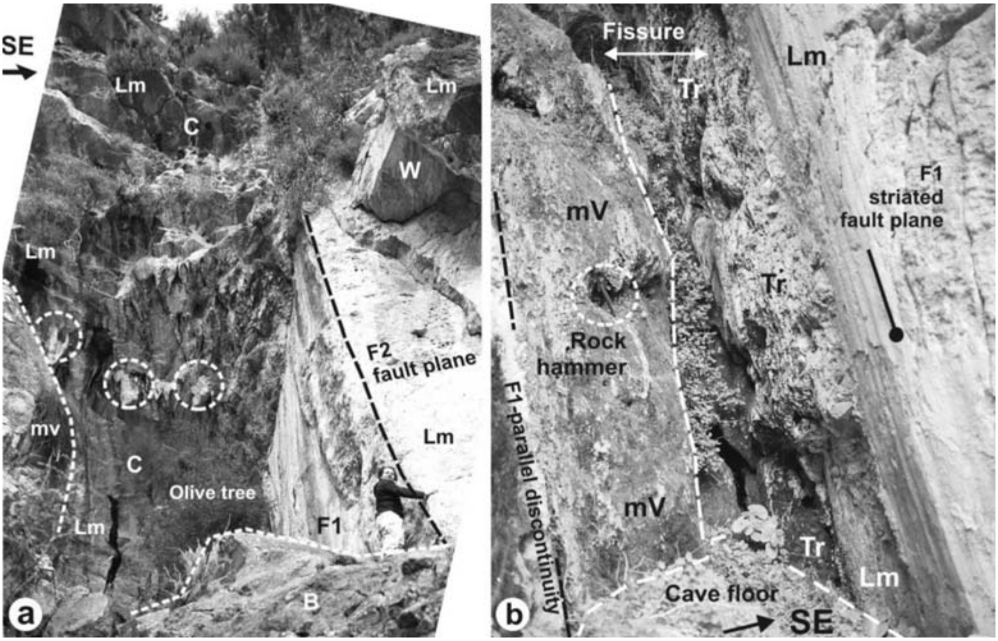

Fig. 8: (a) Oblique view of the cave entrance, looking up from a lower point in the very steep slope in front of it. Lm: Limestone. mV: Metavolcanics. F1/F2: polished fault planes, C: the cave ceiling, dipping away from the reader (=the floor of the limestones, with the metavolcanics –mv- underneath them removed), B: part of a large limestone block fallen from the ceiling. W: large limestone wedge ready to fall off. Thick broken stalactites (dashed-line circles) and newer generations of $CaCO_3$ deposits can be seen on the cave ceiling. (b) The interior of the cave. A large fissure along the polished and striated fault plane of F1 is visible, filled with thick travertine deposits (Tr). The floor of the cave was probably lower during antiquity, now filled with rockfall debris.

hanging above a steep lower part (e.g. Piccardi, 2000). In the case of Aghios Taxiarches the impressive, high waterfall in the lower part of the valley adds to a more “dramatic” landscape; the sacred spring Castallia at Delphi is also typically depicted as a small waterfall.

- In both sites, the presence of carbonates (limestones and crystalline limestones) broken up by joints and fault planes, in combination with impermeable underlying rocks, favoured the presence of springs, spring water being a fundamental element in the process of divination. At the site of Aghios Taxiarches, water is still dripping inside the cave today.
- The oracle springs at Delphi were also associated with thick travertine deposits (e.g. Higgins and Higgins, 1996; de Boer and Hale, 2000).

Considering that studies by Piccardi (2000), de Boer and Hale (2000) and de Boer et al. (2001) have demonstrated that the oracle of Delphi was located in the particular site exactly because of the presence of specific geological features and phenomena, directly connected to the presence of active fault zones, the geological and geomorphological similarities between the site at Aghios Taxiarches and the oracle of Delphi, in our view provide indirect support to the hypothesis that the former can well be the oracle of “Apollo Selinountios” mentioned by Strabo. The cave next to the walling remains should merit consideration as a potential key geomorphological element of the site, considering that use of caves as places of chthonian cult was in fact common in ancient Greece. Some of them were also used as oracles, e.g. the oracle of Trophonios in Leivadeia (Boeotia), which was located at a cave with springs inside it (Higgins and Higgins, 1996). In order for a firm connection between the cave and the archaeological remains (walling) nearby to be established, a test excavation inside the cave and a more systematic work on the site in general is necessary. Such studies will probably require special geotechnical considerations given the slope instability problems and the high rock fall hazard. If the cave is indeed found to be related to the use of the nearby site, detailed geological, geomorphological, geochemical and gechronological study could attempt to help addressing questions related to the type of connection the cave may have had with the function of the site. E.g. how different was the morphology of the cave during antiquity, when the nearby site was operational? Was it more enclosed or open more or less as at present? Limestone blocks fallen from the cave ceiling are blocking the entrance of the cave (Figs. 8 and 9a) but, when exactly this collapse took place is not known. How much lower was the cave floor (now filled with debris) in antiquity? What is the age of the travertine deposits inside the cave, and what was the chemical composition of the fluids that deposited the travertines? Were there gas emissions involved, and if yes, of what gasses?

The origin of the travertine deposits along the fault plane of F1 and their relation or not to hydrothermal activity are questions that refer to whether the cave may have served as the adyton (sanctum) of a shrine, with geological features similar to those described by ancient writers for the Delphic adyton (fissure on the ground & emanating gasses). These questions become very interesting, considering:

- the location of the site within the major hydrothermal field of Northern Evoikos Gulf, the type locality for travertine deposits (of hydrothermal origin) being at nearby Aedipsos (Fig. 5).
- the preferential location of travertine deposits in such fields along normal faults (e.g. Hancock et al., 1999) and especially their intersections, as is the case for the cave.
- the gas emissions associated with hydrothermal springs on the opposite side of the gulf and nearby Aedipsos (e.g. Sfetsos, 1988, Gioni –Stavropoulou, 1998).

Regardless of its exact use in antiquity, given the location of the Agios Taxiarches site in a geodynamically and geomorphologically highly active environment, future detailed studies could also clarify whether geo-environmental factors played a role in its decline (or destruction). Two such possible causes of disturbance of the site's operation could be destructions by strong earthquakes in the broader N. Evoikos graben (nearby Oroviai were devastated during the 426 BCE earthquake (Thuc. 3. 89, Bousquet and Pechoux, 1977), and destructions due to rock falls. Rock falls are greatly favoured by the steepness of the escarpment and the intense dissection of the crystalline limestones and meta-volcanics by numerous joints and fault planes. The talus slopes along the base of the escarpment speak of a long history of rock falls, whereas very recent falls are described by locals (unrelated to strong earthquakes) and evidenced by the large number of fallen boulders in front of the base of the escarpment. Rockfalls could also be related (although not necessarily) to strong earthquakes caused by any one of the fault zones around the N. Evoikos graben, or the Telethrion fault zone itself. Furthermore, strong earthquakes could have caused hydrological disturbances, such as those mentioned for Aedipsos and the broader area in an account of the natural phenomena caused by the large 426 BCE earthquake, given by Strabo (Bousquet and Pechoux, 1977).

6. Conclusions

- Two inscriptions, one dedicated to "*Apollo Selinaios*", and another mentioning a priestess were found at Aghios Taxiarches, 6.2 km NW of modern Rovies (where ancient Oroviai are located). The inscriptions, located next to wall ruins, provide strong indications (if not definitive proof) of a shrine of Apollo bearing the epithet *Selinaios*, unknown from literary and epigraphical sources.

- Given the vicinity of the site to ancient Oroviai and the new epigraphical material, we propose the hypothesis that the site can well be the "oracle at Oroviai " of "*Apollo Selinountios*" mentioned only in a single passage of Strabo (and in no other literary or epigraphic source). Considering that epigraphic evidence is stronger than evidence from historical sources, and that Strabo never visited Euboea, it seems very likely that he may have used a wrong version of Apollo's epithet *Selinaios* (more details in Nikolopoulos, 2005).
- The walling remains at the site are located on the 300m high, steep bedrock escarpment of an active normal fault zone. The presence of the fault zone is responsible for a landscape of particular beauty and imposing geomorphological elements, which include steep cliffs and rockfall scars, a hanging valley with a high waterfall and a small cave that has formed at the junction of two faults and has extensive travertine deposits inside it.
- The site at Agios Taxiarches, when compared to the oracle of Apollo at Delphi, is found to be situated in an environment with similar geological and geomorphic features (this referring to types of landforms, not exact similarity). Considering that recent studies have demonstrated that the oracle of Delphi was located in the particular site exactly because of the presence of specific geological features and phenomena that are directly connected to the presence of active fault zones, the geological and geomorphological similarities between the site at Aghios Taxiarches and the oracle of Delphi, in our view provide indirect support to the hypothesis that the former can be the area where an ancient oracle stood.

Systematic archaeological study of the broader area around the walling remains and of the nearby cave should be undertaken, if the hypothesis we propose is to be irrevocably verified. Such a study will probably be technically demanding, considering the steep terrain and high rockfall hazard. Geological/geomorphological, geochemical, and geochronological studies would be necessary to clarify the connection the cave may had with the site's function.

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MINERALOGICAL, PETROGRAPHIC AND STABLE ISOTOPIC STUDY OF ANCIENT WHITE MARBLE QUARRIES IN THESSALY, GREECE - II. CHASANBALI, TEMPI, ATRAX, TISAION MOUNTAIN

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Abstract

The present study focuses on the identification of marble sources from four ancient quarries in Thessaly, including Atrax, Tempi, Chasanbali and Tisaion and aims in characterizing the variations of the mineralogical and petrographic features, and the stable isotope ratios ($\delta^{13}C$ and $\delta^{18}O$). The results provide additional data and complete the databases presented in previous works from Kastri, Kalochorion and Gonnoi. Microscopy was employed both to evidence the geometrical relationships among the mineral constituents, with particular reference to calcite, and to detect the accessory grains. The studied marbles demonstrate various textures, whereas the maximum grain size of calcites has been used to discriminate the marbles. The geometric relationships of carbonate grains, such as the grain boundary shape, were also evaluated. According to the stable isotope compositions, most of the samples plot in the same area, although some groupings are observed.

Key words: *white marble, ancient quarries, ancient technology, mineralogy, marble textures, C- and O-isotopes, Thessaly, Central Greece.*

1. Introduction

Identifying ancient marbles is of great importance to archaeologists and art historians. Provenance studies provide useful archaeological information regarding contacts, trade and other activities during antiquity. They also help in detection of modern imitations or ancient copies of original works. In addition, location of the quarry from which a damaged marble artefact came, makes it possible to find proper material for the purpose of restorations, reconstructions and replacements (Lazzarini, 2004; Tycot, 2004).

Since many of the marble sources that were exploited in antiquity are of white marble, it is not easy to distinguish among most of them based only on their macroscopical and morphological features, as large variations of the physical properties can be observed even for marbles from the same quarry or quarrying area.

The application of various analytical methods allow many sources to be positively identified (Craig and Craig, 1972; Coleman and Walker, 1979; Lazzarini et al., 1980; Herz, 1987; Mello et al., 1988; Moens et al., 1988; Tsirambides, 1996; Vakoulis, 2000; Attanasio et al., 2003; Capedri et al., 2004; Melfos, 2004; Perugini et al., 2004). In particular, only one method is not enough for recognizing marbles, and so the most recent and effective approaches usually combine different techniques, such as mineralogical composition, petrographic analysis, stable isotopes (^{13}C and ^{18}O) and trace element analysis. Other physical or geochemical methods have been applied in recent years with some success. Examples include the use of thermoluminescence, strontium isotopic distribution, manganese electron spin or paramagnetic resonance (ESR-FPR), porosity, heat capacity, back-scattering or diffusion of light, gamma-ray radiography, dimensional or other geometrical data obtained from thin-sections examination with automatic quantitative image analysis.

The most widely used and accurate procedure for the identification of white marbles involves mineralogical and petrographic studies in combination with C-O stable isotope analyses. According to Gorgoni et al. (2002), this progressive implementation is based on two procedures: i) creating sets of reference data for new marble supply areas of known or potential archaeological interest never previously considered and ii) improving and detailing the database for the most important marbles of antiquity.

The large overlapping of the isotopic data fields from different localities renders $\delta^{13}C$-$\delta^{18}O$ plots often ineffective in discriminating the marble sources. It is therefore evident that additional methods should be applied for a more specific determination of the provenance. Mineralogical composition and petrographic studies could help in distinguishing the different sources (Capedri et al., 2004).

Thessaly in Central Greece demonstrates an impressive history throughout the centuries, since the Neolithic period. It must have played a key economic role in the antique Aegean, and indeed Mediterranean, world. The economy of the region was based on the exploitation of local resources and trade. Among the local resources particular emphasis is placed on the exploitation of the local white marble quarries (Karagiorgou, 2001).

The importance of Thessalian marbles implies that their correct provenancing, as well as the possibility of identifying specific quarrying areas, are both crucial archaeological issues and may provide important information on the economy and art history of classical antiquity. However, only limited studies have been published so far on the quarries and the marbles of Thessaly, by Papageorgakis (1967), Germann et al. (1980), Melfos et al. (2002) and Melfos (2004, 2008). These authors have also published databases on the Thessalian white marbles based on isotopes, but also on alternative techniques, such as mineralogy and petrography.

When identifying ancient marble artefacts by means of petrographic and isotopic methods, sometimes the results do not match well with the sets of comparative parameters for the various supply areas. These discrepancies are possibly due to incompleteness or limited reliability of the databases available.

The present study focuses on four white marble quarries in Thessaly county (Fig. 1) and aims in characterizing the variations of the mineralogical and petrographic features, as well as the stable isotope ratios (^{13}C and ^{18}O). These quarries are located in Chasanbali (Sykourio area), in Tempi, in ancient Atrax (between Larisa and Trikala) and on Tisaion Mountain in Magnesia (Fig. 1). The results of this study provide additional data and complete the databases presented in a previous work by Melfos (2004), which included the ancient quarries in the Kastri village (Aghia area), in Kalochorion (Sykourio area) and in ancient Gonnoi (Tempi area) (Fig. 1).

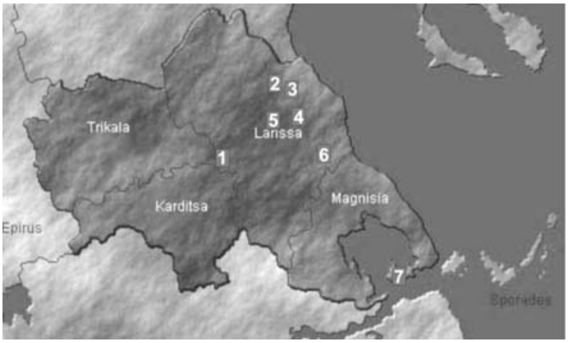

Fig. 1: Map of Thessaly in central Greece, showing the locations of ancient white-marble quarries. 1. Ancient Atrax, 2. Ancient Gonnoi, 3. Tempi, 4. Chasanbali, 5. Kalochori, 6. Kastri, 7. Tisaion mountain.

2. Geological setting

The area of Thessaly belongs geotectonically in the Pelagonian zone, which is composed of several tectonic units, showing different tectono-metamorphic evolution. It is considered as a microcontinent that rifted from Apulia during Permo-Triassic, giving rise to two small ocean basins, the Pindos ocean in the west and the Axios-Vardar ocean in the east (Robertson et al., 1991). After the continental collision in Early Tertiary, these small ocean basins closed.

The pre-Alpine crystalline basement consists of granites, ortho- and para-gneisses of Late Proterozoic to Palaeozoic ages (Kilias and Mountrakis, 1989; Koroneos et al., 1993; Anders et al., 2007).

The basement is structurally overlain by the composite Pelagonian nappe consisting of a basal tectonic mélange, exposed in northern Euvoia and in Koziakas (Danelian and Robertson, 2001; Pomonis et al., 2007), including Triassic metavolcanic series (metarhyolites, amphibolites, mica-schists, greenschists) and Triassic-Jurassic deep-water metasedimentary rocks (mainly schists, prasinites, amphibolites, marbles and dolomitic marbles).

These series were overthrusted during Early Cretaceous by the Axios-Vardar ophiolite complexes of ultramafic and mafic rocks found mainly in Eastern Thessaly and Northern Euvoia, the easternmost parts of the Pelagonian zone (Danelian and Robertson, 2001). They show important Early Cretaceous weathering and are unconformably overlain by Mesozoic to recent sediments, including transgressive Late Cretaceous meso-autochthonous shallow-water crystalline limestones that pass upwards into Palaeocene flysch (Katsikatsos et al., 1981; Caputo, 1990).

3. Analytical Methods

A total of 25 samples of fresh white marble were collected from the studied ancient quarries in Chasanbali, Tempi, Atrax and Tisaion mountain, for mineralogical, petrographic and isotopic analyses, during fieldwork between 2005 and 2009. A total of 14 thin and polished-thin sections of the rock samples were studied mineralogically by optical microscopy at the Department of Mineralogy, Petrology, Economic Geology, Aristotle University of Thessaloniki, Greece. Microscopy was employed both to evidence the geometrical relationships among the mineral constituents, with particular reference to calcite, as well as to detect the accessory grains. The studied marbles demonstrate various textures such as homeoblastic or heteroblastic marbles. The maximum grain size of calcite (MGS), which has been used to discriminate the marbles, was measured. The geometric relationships of carbonate grains, such as the grain boundary shape, were also evaluated under the microscope. These features depend on the metamorphic evolution.

In addition, powders of the samples were processed by X-ray diffraction (XRD) in order to distinguish calcite from dolomite and to verify the related abundances in each sample. Oxygen and carbon isotopic analyses of 16 marble samples were carried out at the Department of Geology of Royal Holloway, University of London. The oxygen and carbon isotope ratios are referred to the standard VDPB (Belemnitella americana from the Cretaceous Pee Dee Formation, South Carolina). The colour and macroscopical characteristics, the mineralogical composition, the textural features, MGS, and a general description of the analysed marbles are depicted in Table 1, which reports also O and C isotopes composition.

Table 1. Macroscopic characteristics, mineralogical composition, textures and isotopic compositions of the marbles in studied ancient quarries of Thessaly.

Locality	Sample	Macroscopic characteristics	Mineralogical composition	Texture	Shape of the crystal boarders	MGS*	C-O isotopes
Atrax	Atr 1 Atr 2	Coarse-grained. White to grayish white colour	calcite, apatite, sulfides, Fe-oxides	Homeoblastic to slightly heteroblastic	Sutured dentate, embayed	4 mm	δ^{18}O: -1.77 - -3.36‰ δ^{13}C: 1.65 - 2.27‰
	Atr 3	Fine-grained. White colour with pinkish tint	calcite, apatite, sulfides, Fe-oxides	Heteroblastic	Straight to curved, commonly embayed	2 mm	δ^{18}O: -4.60 - -7.00‰ δ^{13}C: 2.74 - 4.20‰
Tempi	Tmp 1a Tmp 1b Tmp 2a Tmp 2a Tmp 3a Tmp 3a	Middle- to coarse-grained. Grayish to white colour	calcite	Homeoblastic and in some cases heteroblastic. Elongated crystals	Sutured dentate, embayed	5 mm	δ^{18}O: -1.10 - -6.00‰ δ^{13}C: 1.10 - 3.20‰
Chasanbali	Chas 43 Chas46	Fine-grained. White colour	calcite, quartz	Homeoblastic	Straight or curved	0.5 mm	δ^{18}O: -4.15 - -5.60‰ δ^{13}C: 2.74 - 2.94‰
Tisaion Mount	Triker 1	Very fine-grained. White colour with pinkish tint	calcite, sulfides, Fe-oxides	Homeoblastic	Straight to curved	100 μm	δ^{18}O: -1.79 δ^{13}C: 3.16‰
	Triker 2	Fine-grained. White to grayish white colour Dark coloured stripes	calcite, sulfides, Fe-oxides	Homeoblastic	Straight to curved	100 μm	δ^{18}O: -3.90‰ δ^{13}C: 4.13‰
	Triker 3	Fine-grained. White to grayish white colour	calcite	Homeoblastic	Straight to curved	100 μm	δ^{18}O: -0.45‰ δ^{13}C: 2.98‰

*MGS: Maximum grain size of calcites.

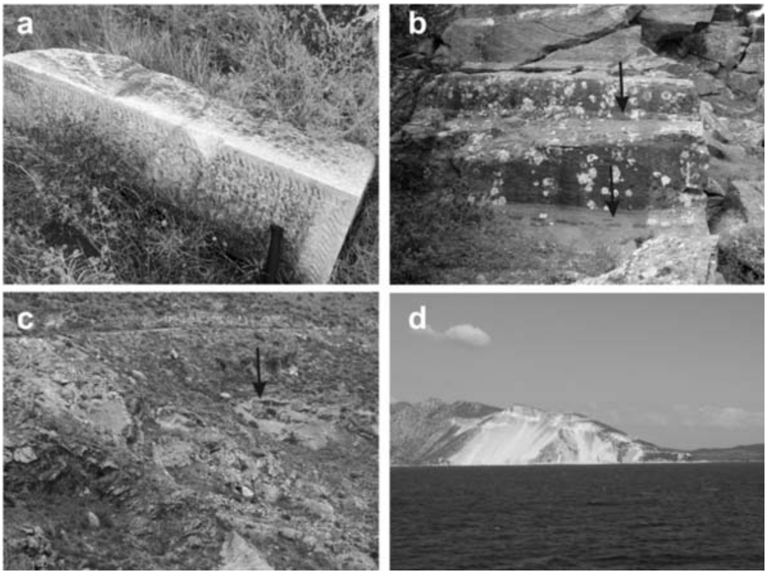

Fig. 2: (a) Unfinished marble block left in the area of the ancient Atrax quarries. (b) Rock faces of an ancient marble quarry in Tempi. The tool traces on the marble and the cavities for the wedges are still preserved. (c) The small ancient white marble quarry in the Chasanbali area. (d) The modern marble quarries at the Tisaion mountain, viewed from the entrance of the Pagasitikos gulf. The extraction works have destroyed all the ancient quarries.

4. Ancient marble quarries: mineralogical, petrographic and isotopic features

4.1 Ancient Atrax

The marble quarries are located near the ancient city of Atrax, on the NE foot of Titanos mountain (Papageorgakis, 1967; Germann et al., 1980; Karagiorgou 2001). The hollows remained after the removal of the stones as well as the numerous unfinished blocks left in the broader area (Fig. 2a), demonstrate an intense quarrying process during antiquity. These quarries produced two types of marble: a coarse-grained marble with a white to greyish-white colour and a fine-grained white marble with a pinkish tint. According to Karagiorgou (2001), the first type was of high quality and was extensively used in Thessaly for constructing mainly grave stelai and a few sculptures.

The marble of Atrax consists mainly of calcite with traces of apatite, sulphides and Fe-oxides. The texture of the coarse-grained white to greyish-white marble is homeoblastic (Fig. 3a) to slightly heteroblastic, indicating that it is made of equidimensional grains and only rarely it may contain calcite crystals with different sizes. The shape of the boarders of the grains is sutured to dentate and only rarely the boarders are curved. The calcite crystals are commonly embayed. The marble consists of twinned calcite crystals of 0.5 to 2.5 mm in diameter which rarely reaches up to 4 mm (MGS). It is a well recrystallized marble resulting in triple-grain junctions of the calcite crystals meeting at about 120° angles.

The fine-grained white marble with a pinkish tint exhibits a heteroblastic texture with very small grains up to 10 μm in diameter, coexisting with larger crystals with a diameter reaching 2 mm. This coarse-grained calcite sometimes is found in the form of veinlets crosscutting the fine-grained crystals. The boarders of the grains are straight to curved and sometimes embayed.

The isotopic results of 3 fresh marble samples collected from the quarry sites are listed in Table 1

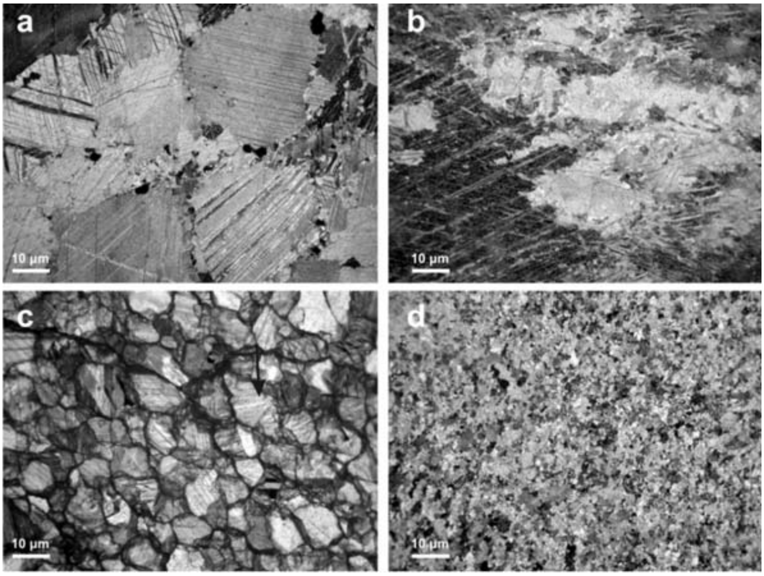

Fig. 3: Photomicrographs (+N) of calcite crystals of the studied marbles showing textural features. (a) Homeoblastic texture of the coarse-grained marble from Atrax (sample Atr1). (b) Marble showing sutured grain boundaries of calcite from Tempi (sample Tmp1b). (c) Homeoblastic texture showing triple junction at 120°, from Chasanbali (sample Chas43). (d) Homeoblastic texture of the very fine-grained marble from Tisaion mount (sample Tis1).

and are plotted in the diagram of figure 4. Seven additional isotopic values for marbles of Atrax are from Germann et al. (1980) and two from Capedri et al. (2004). The C-O isotopes of the Atrax marble are not homogeneous and are plotted in two groups demonstrating the two marble types. The $\delta^{13}C$ values range from +1.65 to +2.27‰ and from +2.74 to +4.20‰. The $\delta^{18}O$ vary from -1.77 to -3.36‰ and from -4.60 to -7.00‰.

4.2 Tempi area

Three big ancient marble quarries are located on the N foots the mountain Kissavos, in the middle of the Tempi valley, at a height around 200 m from the Pineios river, which flows through the valley towards the Aegean sea.

The marbles were quarried from the open pits, the straight rock faces of which rise to a height of up to 5 m above ground level. The extraction proceeded by step, with at least four levels. Tool traces, especially marks of pickaxes, on the rock and the hollows left behind show the extraction methods and techniques (Fig. 2b). These techniques were simple and were influenced by the geological and structural features of the rock, such as fissures and cracks. The stone was quarried in large massive slabs and monoliths, up to 5 m in length, up to 3 m in width, and from 0.70 to 1.10 m in thickness. The quarrymen cut a bench of the length and the width required for the blocks and they disengaged the blocks from the rock mass by digging a channel 25 cm wide around the rock slab. Then they chiselled small cavities at the bottom of the blocks, 10 cm long and 5 cm wide. After that, they put iron wedges in the cavities and by hammering them they split off the rock slab. The technique used in the Tempi marble quarries was similar with this used elsewhere in Thessaly (Kastri, Gonnoi) and generally in ancient Greece.

The material which was extracted from the quarries in Tempi was roughly worked by sculpturing in the quarry area. The quarrymen gave an approximate shape to the block for an easier transportation. This suggestion is supported by the observed heaps of waste material and debris, spread around the working area, as well as by the presence of broken columns, up to 2 m long, left in the quarry.

The marble of Tempi consists only of middle- to coarse-grained calcite crystals. Its colour is from greyish white to grey. The texture is homeoblastic, indicating that it contains equidimensional grains, and only rarely it is heteroblastic. The shape of the boarders of the grains is sutured to dentate (Fig. 3b). The calcite crystals are commonly embayed. The marble consists of anhedral calcite crystals of up to 5 mm (MGS) in diameter, and is characterized by a high degree of preferred orientation. The calcite crystals are flattened and elongated parallel to the foliation plane. In cases marble exhibits a heteroblastic texture with the large calcite grains (> 1 mm) intergrowning with smaller grains (10-100 μm).

The isotopic results of 6 fresh marble samples collected from the quarry sites are listed in Table 1 and are plotted in the diagram of figure 4. Eight additional isotopic values for marbles of Tempi are from Germann et al. (1980). The C-O isotopes are cohesive with $\delta^{13}C$ values ranging from +1.10 to +3.20‰ and $\delta^{18}O$ from -1.10 to -6.00‰.

4.3 Chasanbali area

The Chasanbali area, 12 km northeast of Larisa, is one of the most significant ancient quarrying sites to international cultural heritage. The quarries provided the “green Thessalian stone” which is an ophicalcite comprising a mosaic of green serpentinite and white marble fragments. This stone was used for decorative purposes in Imperial Rome and especially in Byzantium. Sarcophagi, column shafts, facing slabs, tubs, ambones, iconostaseis and baptismal fonts are still found in places stretching from Syria to Britain and from Tunisia to Germany, as well as Rome, Constantinople and Thessaloniki (Melfos, 2008). Besides the “green Thessalian stone” quarries, on the Chasanbali Hill there is also a small white marble quarry (Fig. 2c) at the easternmost border of the site.

The marble in this quarry comprises a slab in the ophicalcite, 50 m long and 7 m thick, and it is an olistolith which was found intercalated among the ophicalcite breccia during Mesozoic (Melfos et al., 2009). It is a fine-grained white coloured marble and consists mainly of calcite with traces of quartz. It has a homeoblastic texture, with equidimensional grains (Fig. 3c). The rims of the grains have straight to curved boarders. The calcite crystals are commonly twinned with a diameter from 100 to 500 μm (MGS). Triple-grain junctions of the calcite crystals, at about 120° angles, is a common feature and demonstrates a well recrystallized marble.

Four samples were collected from the Chasanbali ancient white marble quarry for carbon and oxygen isotopic analyses. The $\delta^{13}C$ values range from +2.74 to +2.94‰ and the $\delta^{18}O$ from -4.15 to -5.60‰ (Tab. 1, Fig. 4).

4.4 Tisaion mountain

A large quarrying area is located at the N foot of the Tisaion mountain, near the site of Zasteni on the east coast of the Pagasitikos gulf, in Magnesia (Fig. 2d). The quarries extend all along the Tisaion mountain and up to 100 m above the sea level. According to Papageorgakis (1963), there were two large ancient quarries at some distance from the coast and numerous smaller ones, hidden behind thick vegetation and for this reason inaccessible. Modern exploitation works, in the last decades, have recently destroyed all these ancient quarries, obliterating crucial evidence of their existence. Only a few ancient marble blocks, with marks of pointed chisels, still exist today, being witnesses of the intense quarrying works in antiquity.

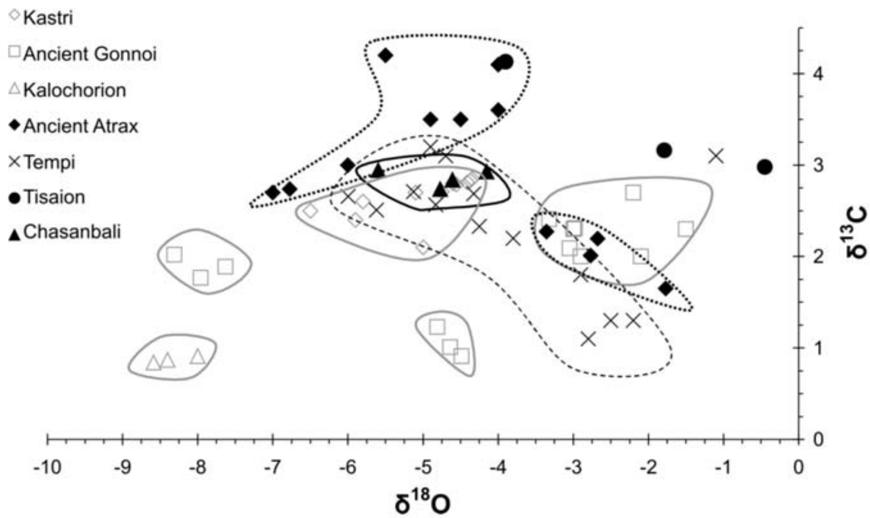

Fig. 4: A $\delta^{18}O$-$\delta^{13}C$ diagram summarizing the stable isotope data of the marbles from the ancient quarries in Thessaly studied here (Atrax, Tempi, Ghasanbali, Tisaion) in combination with the results of Kastri, Kalochorion and Gonnoi, published by Melfos (2004) (data also from Germann et al. 1980, Melfos et al. 2002, Capedri et al. 2004).

The marble in the Tisaion mountain has a white to greyish white colour. This type is called "Lafkos White" today. Sometimes dark coloured stripes exist parallel to the schistosity. Near the sea, at the lower parts, the marble has a characteristic pinkish tint, and so the trade mark of this type of marble is "Lafkos Pink".

The mineralogical composition of the pinkish- and the greyish-white marble is calcite with traces of dolomite, quartz and Fe-oxides. Calcite is the only constituent of the white marble. The texture of all the types is homeoblastic (Fig. 3d), indicating that it is made of equidimensional grains. The boarders of the grains have straight to curved boarders. The marble is characterized as a fine-grained marble, with grain size varying from <10 μm to 100 μm. Only rarely there are calcite crystals with a diameter up to 1 mm (MGS).

Three samples, one of each type, were analyzed for carbon and oxygen isotopes. The results are not homogeneous and so they do not plot as a group (Tab. 1, Fig. 4). The $\delta^{13}C$ values range from +2.98 to +4.13‰ and the $\delta^{18}O$ from -0.45 to -4.13‰. More isotopic analyses are planned for the near future in order to better establish the isotopic signatures of the three marble types at the Tisaion mountain.

5. Discussion-Conclusions

The present study contributes significantly in the updating of the databases of the marbles from Thessaly, used in antiquity. Petrographic and O-C isotopic results presented here, complete the databases published in previous works for ancient quarries from Kastri, Kalochorion and Gonnoi. The mineralogical and petrographic features of the marble coming from four different localities of Thessaly, e.g. Atrax, Tempi, Chasanbali and Tisaion mountain, show distinct differences and with the combination of the isotopic results may be used to identify the provenance of archaeological marbles. Recently this complete reference data was used successfully in identifying the provenance of the marbles used in the construction of the Ancient Theatre A' of Larisa (Melfos-unpublished data) and it is a potential tool in analogous future works from ancient monuments from Thessaly.

According to their stable isotope compositions (Tab. 1), most of the samples plot within the same area, although some groupings are observed (Fig. 4). Globally, $\delta^{18}O$ values in marine carbonates range from -10‰ to +5‰, but most marine carbonate sediments and limestones are in the range of -10‰ to +2‰ (Nelson and Smith 1996). The values of the marbles from this study vary from -7.0‰ to -0.45‰ and fall inside this range. More specific the oxygen isotopes can be compared with the isotopes of the Mesozoic marine limestones which range from -7 to 0 ‰ (Veizer et al. 1999), suggesting that they were relatively affected by very low grade metamorphism, which resulted in the recrystallization of the carbonates without any affect in the O-isotopes.

The carbon isotope values of the studied marbles (+1.10 to +4.20 ‰) demonstrate a relatively narrow range, which probably shows that the C source was rather homogeneous for the carbonates which were incorporated within all the marble occurrences. These values represent seawater composition during carbonate deposition and are comparable to values of the non-metamorphic Mesozoic pelagic limestones worldwide which have $\delta^{13}C$ values mainly from 0 to 3 ‰ (Veizer et al. 1999). This reveals that the marbles preserved their protolith carbon isotope ratios, although the subsequent metamorphic event of low grade caused a recrystallization to most of them, mainly from Atrax and Tempi.

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MINERALOGICAL DIFFERENCES BETWEEN ANCIENT SHERDS AND EXPERIMENTAL CERAMICS: INDICES FOR FIRING CONDITIONS AND POST- BURIAL ALTERATION

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Abstract

Results are reported regarding laboratory-scale experimental work aiming to reproduce ceramic specimens with macro and micro characteristics similar to ancient sherds. Small differences in mineralogical composition between ancient sherds and experimental ceramics elucidated the effect of the firing conditions and the degree of post-burial alteration of ancient ceramics. Scarsity of gehlenite ($Ca_2Al_2SiO_7$) in sherds for which firing temperature has been estimated between 800 to 950°C, led to higher Fs/Gh (fassaite/gehlenite) ratio in respect to that recorded for the ceramic specimens. This fact is attributed to the dissolution of gehlenite during the post-burial alteration, the ancient ceramics were subjected to, but also due to the short sintering duration (i.e. higher heating rate and/or low soaking time) applied by the potters in some cases.

Key words: *ancient ceramics, gehlenite, post-burial alteration, short firing cycle, Plio-Pleistocene sediments.*

1. Introduction

The mineralogical transformation of calcareous clays during firing for the manufacture of ceramic products have been discussed by many authors (González-García et al. 1990; Dondi, et al. 1999, 1998; Riccardi et al. 1999; Cultrone et al. 2001; Bauluz et al. 2004). The formation of free CaO, after the thermal decomposition of calcite which starts at ~600ºC and completed around 800-850ºC, promotes nucleation of high temperature crystalline phases through reactions with the dehydroxylated phyllosilicate minerals. A series of phases including Ca-silicates of Ca-Al-silicates such as wollastonite ($CaSiO_3$), gehlenite ($Ca_2Al_2SiO_7$), anorthite ($Ca_2Al_2Si_2O_8$), fassaite or "ferrian aluminian diopside" according to the IMA, (Morimoto, 1988) ($(Ca,Na)(Mg, Fe^{2+}, Fe^{3+}, Al, Ti)(Si, Al)_2O_6$) could be formed. Their presence in ancient sherds could aid to make inferences about the chemical composition of the raw materials employed by the ancient potters as well as the firing conditions (i.e. the maximum firing temperature, heating rate, soaking time and kiln redox atmosphere) they have followed. This information is essential for the establishment of the ancient technology.

However, the susceptibility of ancient ceramics to chemical weathering during their burial conditions must be carefully assessed. Dissolution phenomena and/or precipitation of minerals during post-burial alteration affect the mineralogical and geochemical composition of sherds, creating difficulties to establish, in a straightforward manner, the provenance of their raw materials and the determination of manufacturing technology (Heimann & Maggetti, 1981; Owen & Day 1996; Buxeda et al. 2002).

This paper is focused on the assessment of the reasons which affect the formation and stability of melilite phase (gehlenite) in ancient fine wares, a crucial mineral for the archaeometric investigation. Results are drawn by comparing mineralogical and petrographic data of ancient sherds with ceramics produced in the laboratory. The experimental ceramics are made of clay-rich raw materials which exhibited the best mineralogical and chemical affinity to the raw materials used in the ancient ceramics (Rathossi et al., 2003; Rathossi et al., 2004; Rathossi, 2005; Rathossi & Pontikes, 2010a, b).

2. Materials and Methods

The ancient ceramic sherds are representative of Roman lamps (second half of the 1st c. A.D. to early 4th c. A.D.) derived from three excavations in the city of Patras which unearthed two workshops (A and B) and one Lychnomanteio (Fig. 1a). Lamps were found and collected from a depth of 1 to 1.5 m. They are characterized as fine wares due to their fine grain size (<0.2mm). Petrographic, mineralogical and geochemical study of 107 lamp sherds and 59 clay-rich samples collected from the prevailed Plio-Pleistocene sediments in the neighbour of the archaeological sites (Fig. 1b), established the local origin of raw materials for Roman lamps production (Rathossi et al., 2003; Rathossi, 2005). Detailed information concerning their sampling location and geology is provided in the aforementioned references. Three clay-rich samples from the Plio-Pleistocene formation (sampling location 1, 3, 4, Fig. 1b) were chosen, as they exhibited the highest degree of similarity with the ancient raw materials. The firing tests at the laboratory were performed at different conditions, in an effort to mimic the firing procedure applied in Roman times as reported in archaeometric investigations (Rathossi, 2005).

For the preparation of experimental ceramics, the clay-rich raw samples were gently crushed by hand in an agate mortar, without any refinement. The powder was mixed with water and the plastic mass was shaped by hand in discs, of 5cm dia. by 1.5cm height, approximately. After drying at room temperature for five days, the discs were placed in a resistance oven at 50 °C for 24h. Firing was performed in a resistance and a propane–firing kiln up to 850, 950 and 1050 °C. Heating and cooling rates in all firing experiments were 3 °C min^{-1} and soaking time was 1h. Twenty-seven experiments were conducted; for each sample, three firing temperatures, in static air, oxidising and reducing atmosphere, were tested. The firing atmosphere in gas kiln was controlled by regulating the primary and secondary air flow; Bernoulli–type burners were used. Firing initiated in oxidising atmosphere and the transition to reducing atmosphere, where applicable, took place at 800 °C and throughout the soaking period. During cooling, the firing atmosphere was maintained and was inverted to oxidising for a temperature below 800 °C. The measurement of the firing atmosphere was performed using a flue gas analyser employing electrochemical cells, measuring O_2 and CO and calculating CO_2 (Testo 335, Germany). A sample of hematite powder was placed next to the clay body during the firing tests in order to be used as diagnostic for the specific firing conditions. For oxidising firing, the ratio CO/CO_2, %, ranged from 0.2 to 4.4 and for reducing firing, the ratio CO/CO_2, %, ranged from 11.2 to 23.0.

The chemical composition of the major elements for the ancient ceramics and clay-rich samples was determined by Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) at ACT-LABS, Ancaster, Ontario, Canada. Detection limit for major elements is 0.01%. The analytical precision calculated from replicate analysis of one sample is better than ±1%.

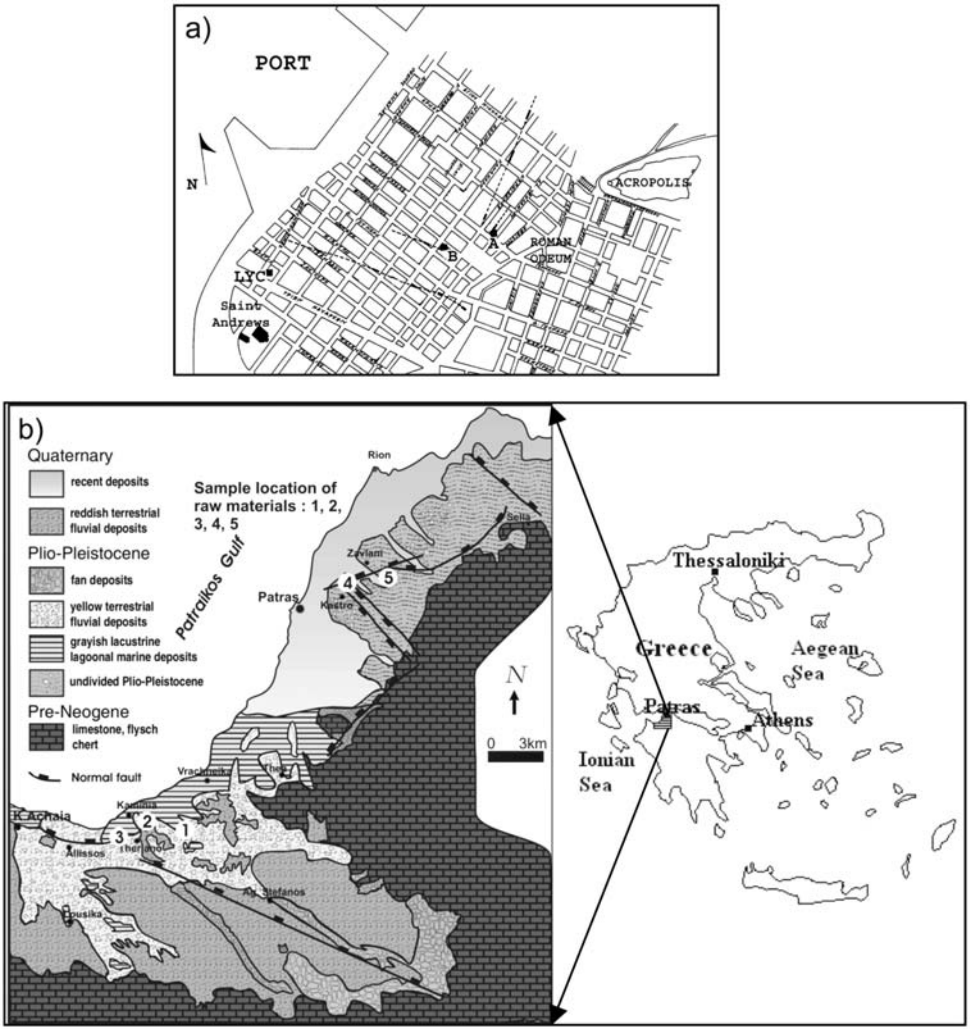

Fig. 1: a. Part of the town-plan of the city of Patras with the location sites of excavations, the two workshops (A and B) and the Lychnomanteion (LYC). Dashes lines indicate ancient roads (Petropoulos, 1999); b. Simplified geological map of Northwestern Peloponnese. Numbers refer to sampling locations. Lithofacies after Loftus & Tsoflias (1971), Zelilidis et al. (1988) and tectonic data after Doutsos et al., 1988.

Cross-sections of the ancient sherds, clay-rich samples and their ceramic specimens were mounted on glass, sectioned to a thickness of 30–40μm, and polished for analysis by polarizing and scanning electron microscope (JEOL 6300). Powdered samples were also subjected to X-ray diffraction (Bruker D8 Advance, equipped with a LynxEye® detector) studies to determine the high-temperature crystalline phases formed during firing in both ancient ceramics and test samples. The scanning area covered the 2θ interval 2–70°, with a scanning angle step of 0.015° and a time step of 0.3s. Qualitative analysis was performed by the DIFFRAC^{plus} EVA® software (Bruker-AXS) based on the ICDD Powder Diffraction File. The mineral phases were quantified using a Rietveld–based quantification routine with the TOPAS® software (DIFFRAC^{plus} TOPAS Ver. 3.0 Tutorial, Bruker-AXS).

3. Results and Discussion

Roman lamps were made by Ca-rich raw materials with a significant Fe_2O_3 content (CaO≈10 wt%, Fe_2O_3≈7 wt%). Plotting the bulk chemical composition of ancient sherds on the ternary diagram (Ca, Mg, Fe)O–(Al, Fe)$_2$O$_3$–SiO$_2$ falls in the field of Quartz-Anorthite-Diopside+Wollastonite, suggesting that during firing the mineralogical transformations include gehlenite as a metastable new-phase (Fig. 2a). Hence, gehlenite is expected to have been crystallized in higher amount than clinopyroxene in low fired lamps (T≈800°C). In lamps fired at temperature higher than 1000°C or for prolonged retention at the maximum temperature, the gelhenite content is expected to have been diminished as it is reacted with residual quartz towards anorthite and wollastonite (Peters & Iberg, 1978; Riccardi et al., 1999; Traoré et al., 2000).

The above-mentioned expected trend, well documented in the literature, seems to be in contradiction with the mineralogical results recorded for ancient sherds. X-ray diffraction analyses of Roman lamp sherds fired at low temperature 800-900°C show higher amount of clinopyroxene (fassaite) compared to gehlenite. The latter mineral, in the studied sherds, is present as a minor constituent, even if at these temperatures the formation of gehlenite in Ca-rich ceramics is expected to be intense. The estimation of the firing temperature of the ancient sherds is based on the preservation of the basal reflections (001, 110) of white mica and their low content in new high-T mineral phases (Maggetti, 1981; Cultrone et al. 2001; Rathossi & Pontikes 2010a). The preservation of mica suggests that the neo-crystallization is in early stages.

The very low amount of gehlenite in Roman lamps at low temperature (T≈800-850°C) is predominantly attributed to the mineralogical/chemical composition and the grain-size distribution of their raw materials. In detail, to the:

(i) very fine grained calcite (micrite and/or sparite) in the majority of samples,
(ii) homogeneous dispersion of calcite in the micromass and
(iii) CaO content, which ranges between 5 and 15wt%

These reasons favour the crystallization rate of clinopyroxene (fassaite) at the expense of gehlenite, already from 800°C (Peters & Jenni, 1973; Noll, 1978; Maniatis & Tite, 1981; Veniale, 1990).

In addition, three more hypotheses are being forward:

1. *The burial conditions of ceramics have an impact on the alteration phenomena.*
According to Heimann & Maggetti, (1981), Nomura & Miyamoto, (1995) and Wang & Becker, (2009) during burial processes, ambient conditions, i.e. CO_2-charged solutions of pH 6, could lead to the complete breakdown of gehlenite and the subsequent formation of wairakite ($Ca(AlSi_2O_6)22H_2O$), calcite and probably small amounts of Ca-montmorillonite or to the formation of scawtite ($Ca_7(CO_3)(Si_6O_{18})2H_2O$). Gehlenite could be decomposed also under the conditions of a humid climate (humid acid, sodium salt, with CO_2-charged solutions, pH 8.5) or under the presence of a Na_2CO_3 solution. Ca could be extracted from gehlenite due to a high chemical potential of CO_2 and metastable vaterite and small traces of aragonite are formed. Both gradually transform to calcite, the most stable polymorph. Al and Si (residue of decomposed gehlenite by the Ca extraction) could react with Na in a fluid to form analcite or (hydro) sodalite.

Alternatively, according to Nomura and Miyamoto (1998), organic carbon might react with O_2 in the fluid to generate CO_3^{2-} under oxidising conditions. Then gehlenite is attacked by the CO_3^{2-}-rich fluid to generate a Ca^{2+} rich fluid from which calcite crystallized. The dissolution of gehlenite by the fluid also releases Al and Si ions (into the fluid), and together with Na, which may dissolve from the glassy matrix, could form (hydro) sodalite or other aluminosilicates.

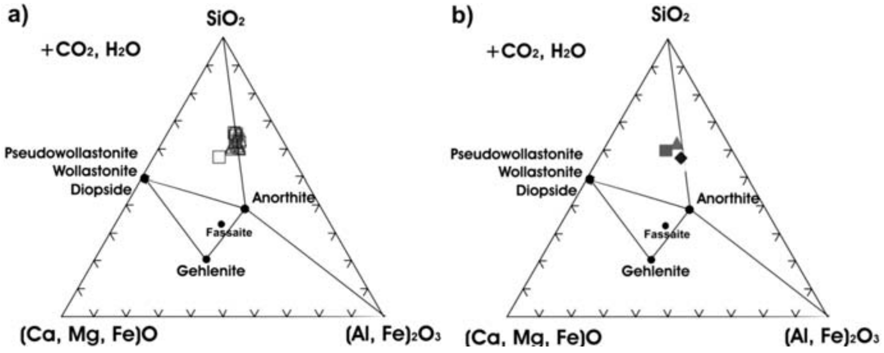

Fig. 2: (Ca, Mg, Fe)O–(Al, Fe)$_2$O$_3$–SiO$_2$ plot of chemical composition of : (a) Representative Roman lamps from the three excavations (open square= workshop A; open triangle= workshop B; open rhomb= Lychnomanteion; see also Table 1a) and (b) three clay-rich raw materials used in experimental work (full square= sampling location 1; full rhomb= sampling location 4; full triangle= sampling location 5; see also Table 1b).

Except of calcite, no reflections of wairakite and Ca-montmorillonite or analcite and (hydro)sodalite have been detected in X-ray patterns of ancient ceramics considered in this study, whereas the presence of scawtite can not be resolved because its basal peak (3.02Å) overlaps with the basal peak of calcite (3.03Å). As gehlenite seems to be more susceptible to aqueous alteration compared to clinopyroxene and anorthite and in combination with the detection of calcite in Roman lamps, it cannot be precluded the possibility of a slightly chemical weathering of lamps during burial processes.

2. *The thermal stability of gehlenite is affected by the redox atmosphere in the kiln.*
Concerning the influence of firing conditions on the thermal stability of gehlenite, a plausible hypothesis is the effect of redox atmosphere in the kiln. Indeed, the crystallization of Al-Fe-rich clinopyroxene (fassaite) in ancient sherds indicates a high oxygen fugacity fO_2 approaching or slightly exceeding the HM buffer (Hijikata & Okuma, 1969; Onuma & Yagi, 1975; Oba & Onuma, 1978; Onuma et al., 1981; Onuma, 1983). Thus, it could be assumed that the oxidising conditions

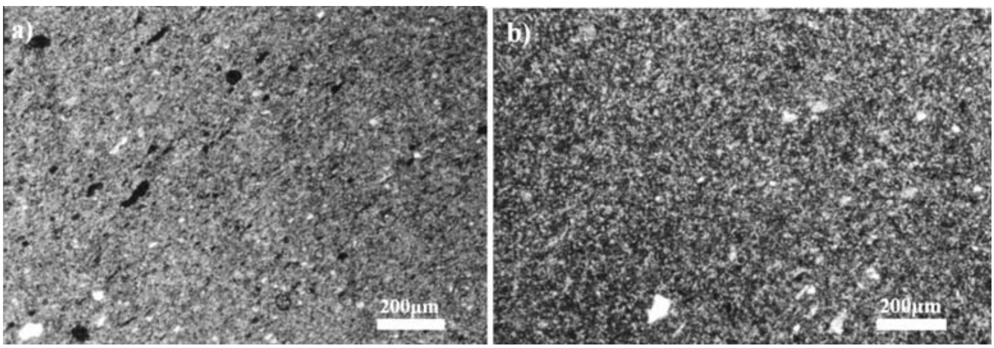

Fig. 3: Representative photomicrographs displaying the similarity of the petrographic fabrics between (a) a very low fired roman lamp (T ≈650ºC) and (b) a local clay-rich sample (from sampling location 4 in Fig. 1b), representative of the raw material of ancient sherds, which was used in the experimental work. The lighter colour of ancient sherd micromass results from the firing procedure.

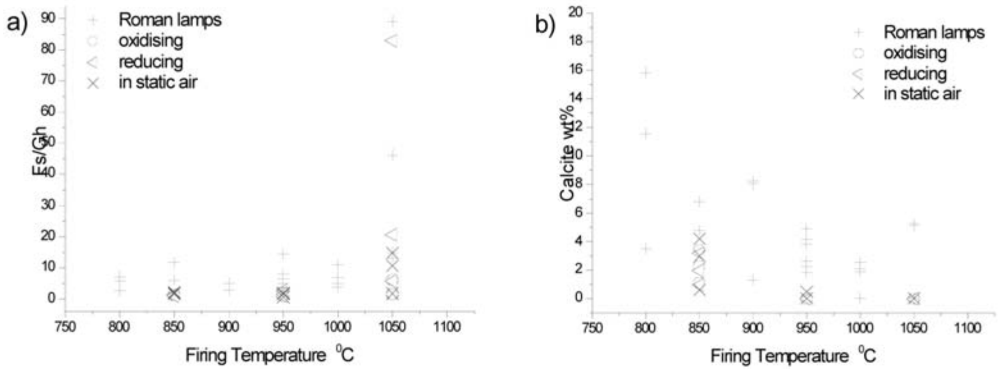

Fig. 4: Variation of the Fs/Gh (fassaite/gehlenite) ratio (a) and of wt% calcite content (b) in respect to various firing temperatures in Roman lamps and in experimental ceramics at the three atmosphere conditions considered in this study.

which prevailed in ancient kilns influenced the formation of gehlenite. However, the firing experiments on the three local clay-rich samples best representative of Roman lamps' raw materials in relation to chemical composition, mineralogy and grain-size distribution, (Fig. 2b, Fig. 3), did not result to a clear correlation between firing conditions tested and degree of formation for gehlenite. Specifically, the X-ray diffraction analysis of experimental ceramics fired at 850°C, determined that gehlenite is formed at considerable amounts (Rathossi & Pontikes, 2010a, b), contrary to the lower amounts in ancient lamp sherds fired between 800 and 900°C (Fig. 4a).

3. *The duration of firing cycle influences the thermal stability of gehlenite.*

The petrographic observation was a powerful tool in combination with X-ray diffraction analysis to clarify better that the sintering duration is one of the reasons for the low amount of gehlenite in ancient sherds. During petrographic and mineralogical analyses, the presence of calcite (Fig. 4b) is detected even in samples fired at high temperatures (T=1000-1050°C) where fassaite and anorthite dominate. The simultaneous coexistence of calcite with high-T minerals practically eliminates any hypothesis of primary calcite, strengthening the assumption of a secondary's origin calcite, i.e. formed by:

(i) filtration of calcareous aqueous solutions during burial conditions, followed by the recrystallization of secondary calcite,
(ii) secondary calcite formed by the decomposition of gehlenite under post-burial chemical leaching and
(iii) the recarbonation of portlandite [$Ca(OH)_2$] generated by the hydration of unreacted lime (CaO)

In particular, analysis on the petrographic fabric of several high fired sherds (T=1000-1050°C), revealed either pores filled with calcite crystals forming blocky aggregates and/or needles of calcite with chaotic spatial orientation (calcitic hypo-coating, Fig. 5a) or concentration features (i.e. speckled, striated b-fabric, Kemp 1985) formed by calcite dispersed in a optically inactive micro-mass (Fig. 5b, 5g). In the latter case, calcite could be derived from either the alteration of gehlenite or the unreacted lime.

In lamp sherds fired at lower temperature, between 800 and 900°C, residual lime and/or incompletely dissociated calcite have been observed (Fig. 5c, 5e, 5f). Moreover, X-ray diffraction analysis of sherds

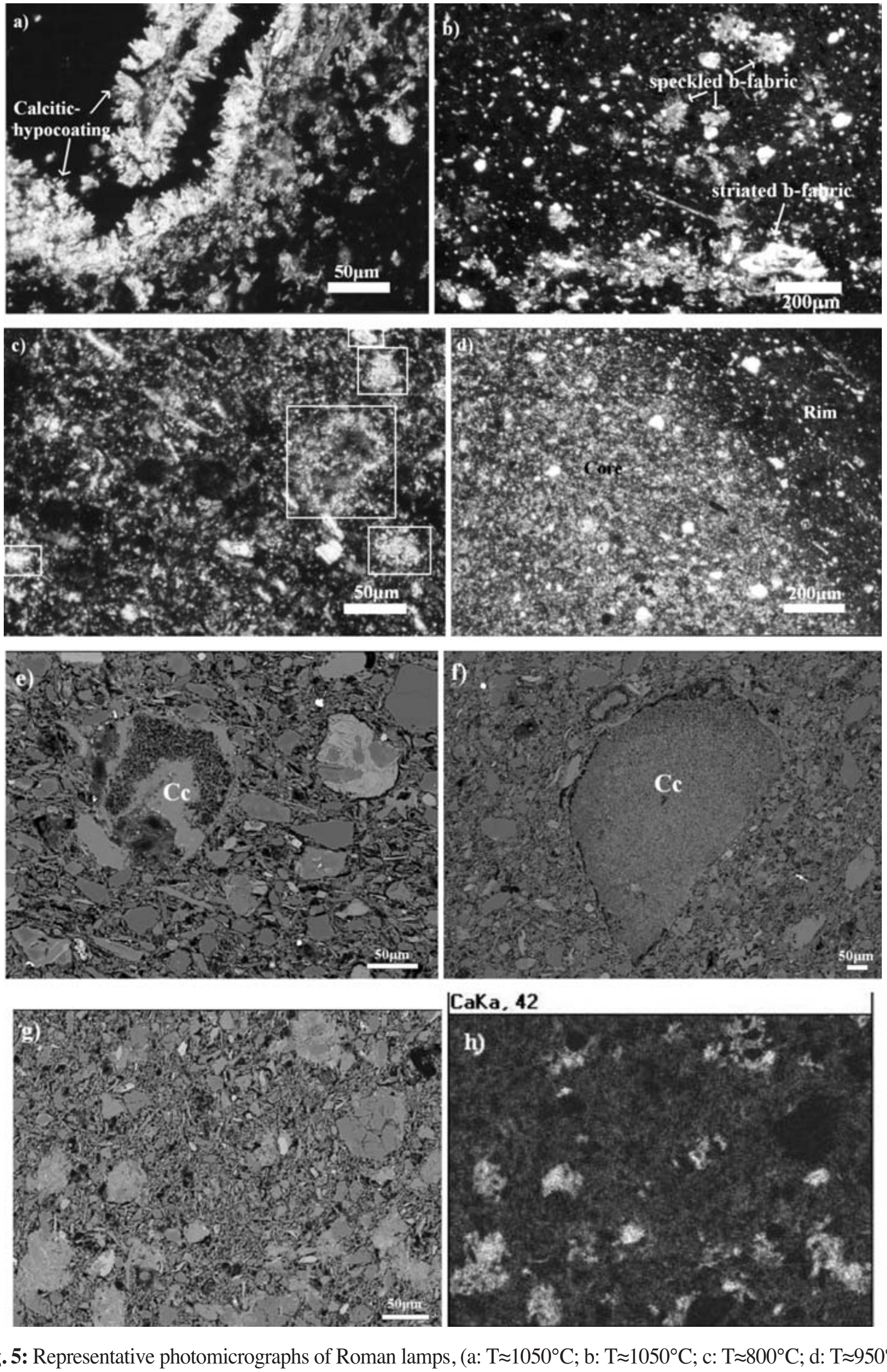

Fig. 5: Representative photomicrographs of Roman lamps, (a: T≈1050°C; b: T≈1050°C; c: T≈800°C; d: T≈950°C; all in crossed polars). Representative back scattered electron micrograph (e: T≈900°C; f: T≈900°C; g: T≈1050°C; h: mapping of Ca in sample g). Rectangular shape and (Cc) indicate residual lime and partially decomposed calcite.

indicated that calcite content at those temperatures reached up to 16wt%, when in experimental ceramics fired at 850°C the concentration did not exceed 4wt% (Fig 4b). In these low fired sherds, the ratio Fs/Gh is very high compared with that in experimental ceramics at 850°C (Fig. 4).

Additionally, optical observation showed that ceramic bodies of lamps often exhibit zoning with an optically inactive rim (the firing has been completed) alternating with an optically active (high birefringence) core in which primary micrite calcite grains and/or residual lime dominate (Fig. 5d). Their firing temperature is estimated around 950°C as evidenced by the higher content of new phases (fassaite, anorthite) and the absence of white mica, suggesting that its dehydroxylation has been completed. For these sherds, gehlenite content is also lower than that in experimental ceramics at the same temperature (Fig. 4).

These specific features in the lamp sherds fired between 800 and 950ºC, which were not detected in the experimental ceramics, suggest a shorter overall firing duration (i.e. higher heating rate and/or shorter soaking period) in the ancient kiln. This fact led to a limited progress of mineralogical transformation across the ceramic body (partially decomposed calcite and/or residual lime). According to Moroni & Conti (2006) at 850°C the lime amount increases significantly at high heating rate and short soaking period whereas quantities of gehlenite tend to decrease drastically when heating rate increases. This happens due to the crystallization of new phases is governed by the kinetics of dehydroxylation and decarbonation reactions which in turn are controlled by the heating rate and soaking time.

Another factor which affects ceramic transformation is the shape of lamps (closed form), since this geometry hinders the entrance of hot gases to the interior (zoning, primary calcite preserved in core). Finally, the efficiency of kiln is one more reason which must be taken into account for the uncompleted decomposition of calcite or unreacted calcite. Modern kilns reach an efficiency of 30-85% whereas the efficiency of kilns in antiquity reached 20% at best, therefore the energy required for the decarbonation reaction was not readily available in ancient kilns (Freidin & Meir, 2005).

All these factors, during the firing of lamps, provoked the limited decarbonation reaction released CaO in the system which was sufficient to participate in the crystallization of fassaite rather than gehlenite. For the latter mineral the content of CaO in its structure is around 30wt% (Deer et al., 1986).

4. Conclusions

The comparison between Roman lamps and experimental ceramics gave a very good correlation in petrography, mineralogy, microstructure and microchemistry (Rathossi, 2005; Rathossi & Pontikes, 2010a,b). The only difference lies in the lower rate of gehlenite's crystallization in Roman lamps. A higher proportion of Fs/Gh ratio results in comparison with that in experimental ceramics which could be ascribed to the following two basic reasons :

a) the post-burial alteration of ancient sherds, which led to the dissolution of gehlenite and the formation of secondary calcite and

b) the shorter sintering duration (i.e. higher heating rate and/or lower soaking time) applied by the ancient potters. Such a practise would prevent the complete mineralogical transformations in the ceramic body. Calcite has been detected in lamp sherds fired up to 950°C suggesting either the artial decomposed calcite or residual lime as the sintering duration was not enough to complete the neo-crystallization.

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SELECTION OF THE PATH OF THE EUPALINOS AQUEDUCT AT ANCIENT SAMOS ON THE BASIS OF GEODETICAND GEOLOGICAL / GEOTECHNICAL CRITERIA

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Abstract

The tunnel of Eupalinos at Samos (Greece) is certainly one of the most admirable works in antiquity, but several questions concerning its plan, and especially the selection of its path, leading to an 'S' type curve, a longer tunnel and a longer aqueduct remain without an answer. In this paper we try to provide an answer to the question 'why Eypalinos selected the specific path for the aqueduct?' on the basis of geotechnical and geodetic evidence.

Two basic criteria should have been satisfied for the tunnel planning: first, that it had to be excavated through rocks with mechanical properties suitable for a safe underground excavation, and second, that the portals should have been in areas permitting accurate geodetic orientation and guidance of the excavation.

The overall selection of the tunnel path indicates that Eupalinos had an excellent understanding of the theory of errors and an ability for geological and geotechnical evaluation of the mechanical characteristics of the ground, i.e. a primitive system of the rock strength classification, with remarkable similarities with the modern GSI method.

Key words: *Aqueduct, Geodesy, GSI, Tunnel.*

1. Introduction

The Eupalinos Tunnel was constructed as part of an aqueduct to provide water to the town of Samos (eastern Aegean Sea) in circa 530BC (Figs. 1 and 2). This tunnel, more than 1000m long, is the first tunnel known to be excavated from both portals using strict geotechnical and geodetic techniques. It was functional for about 1000 years, but subsequently blocked, buried and forgotten for about 1500 years. It was found in the late 1800's, following the precise description of Herodotus, a 5th c. BC historian, in an effort to provide water to the town of Samos.

The whole aqueduct system consists of three parts, with the tunnel representing its middle part (see Fig. 3). The northern segment, ~895m long, between the spring and the northern tunnel portal consists of a buried channel ('cut-and-cover') and a qanat (a channel excavated at the bottom of wells, see Stiros, 2009a), while the southern part, from the southern tunnel portal to the town cistern, ~620m long, consists of a qanat. Although the aqueduct, and especially the tunnel, have been recognized as a masterpiece of engineering at several studies - culminating with the publication of a volume by Kienast (1995) - there are still some questions concerning its overall design.

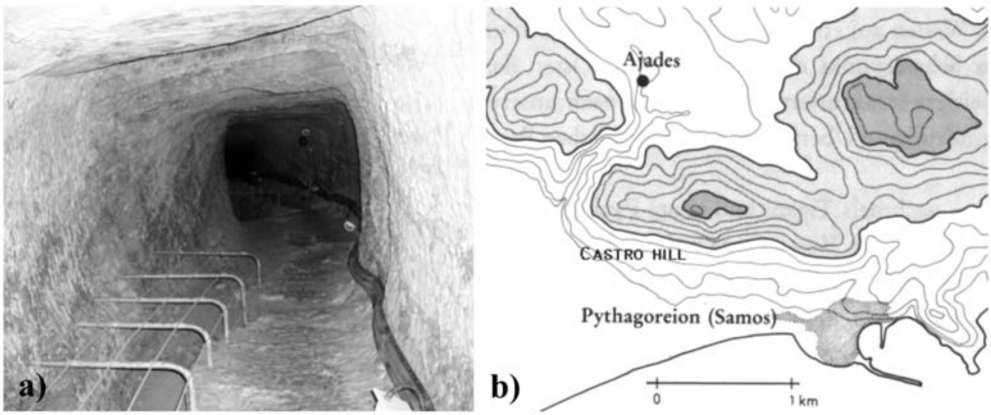

Fig. 1: (a): Inside view of the Eupalinos tunnel (b): Topography in the Eupalinos tunnel area. The aqueduct provides water from the Ajades Spring to the Samos town (modern Pythagoreion) cutting through the Castro Hill.

A main question concerns the selection of the overall aqueduct path. Since it was argued by Kienast (1995) and previous investigators that a main constraint for the tunnel was the need to bring water at the maximum possible elevation, an aqueduct of minimum length, approximately along a straight line would be required.

Such a hypothetical aqueduct would have been only 1500m long, i.e. 1km shorter than the constructed one, and apart from the fact that it would deliver water at a level about 2m higher, it would correspond to a less expensive and less time-consuming project. In addition, it would obviously correspond to a lower-cost and shorter-duration project.

Still, Eupalinos, the chief engineer, selected a longer, curved path delivering water at a lower elevation. Which were the reasons for the selection of a specific route and rejection of other alternatives?

In a previous article (Stiros 2009a) it was shown on the basis of geodetic evidence that the tunnel path selected by Eupalinos represented one of the two possibilities: the selected path and the alternative path #3 (see Fig. 3). In this article we examine the possible reasons for the selection of the overall aqueduct path, and conclude that this selection was dictated by the local geological and geotechnical conditions. This indicates that even in the 6th c. BC Eupalinos was aware of the variations of geological strength of rocks, and probably he was successfully applying a primitive but effective rock strength classification system, in principle not very different from those used in our days (for instance the GSI classification system, Hoek and Brown, 1997; Marinos and Hoek, 2000).

2. Possible alternative routes for the Samos aqueduct

Figure 3 summarizes the existing path of the Samos aqueduct plus three alternative routes. Among them routes #1 and #2 were proposed or summarized by Kienast (1995), while #3 was examined by Stiros (2009a). It is astonishing that the selected route corresponds to the longer tunnel (approximately 1040m) and the longer overall aqueduct (1515m). Alternative tunnel #1 would lead to a tunnel of nearly equal length but to a shorter aqueduct, avoiding an about 200m long qanat. Alternative tunnel #2 would lead to an about 925m long tunnel but a longer overall aqueduct (~400m longer), while alternative tunnel #3 would lead to a less than 900m long tunnel and a minimum aqueduct length, since section 4-5 could have been constructed as a qanat.

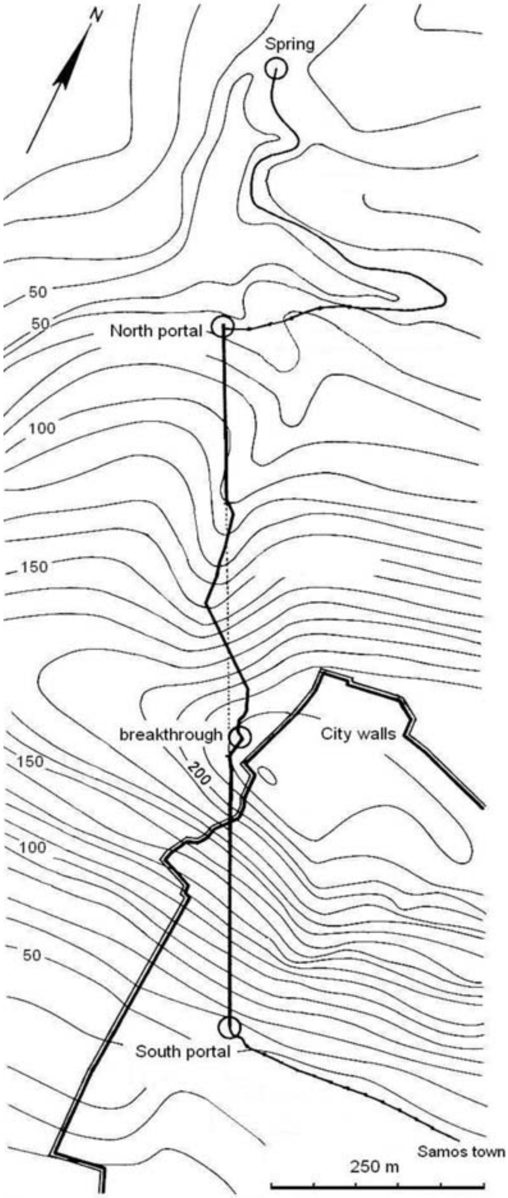

Fig. 2: Plan of the ancient Samos aqueduct, consisting of three segments: (a) a channel bringing water from the spring to the northern tunnel entrance (portal), (b) the tunnel and (c) a channel conveying water from the southern tunnel portal to a main cistern in the Samos Town (after Kienast, 1995).

Selection of the aqueduct route would be easily explained if a long aqueduct was combined with a short tunnel, given that the latter represents the most difficult, time consuming and expensive part of the project, and represented an innovative engineering practice at the time. In fact, the Samos tunnel was the first tunnel ever constructed from two portals using strict geodetic techniques, while qanats or buried channels ("cut-and-cover') were quite usual in antiquity (Grewe, 1998; Stiros, 2009b). Still, the selected aqueduct path corresponds to the *maximum* possible tunnel length, >1040m, in comparison to alternatives as low as 930m (#2) or even <900m (#3) (see Fig. 3)!

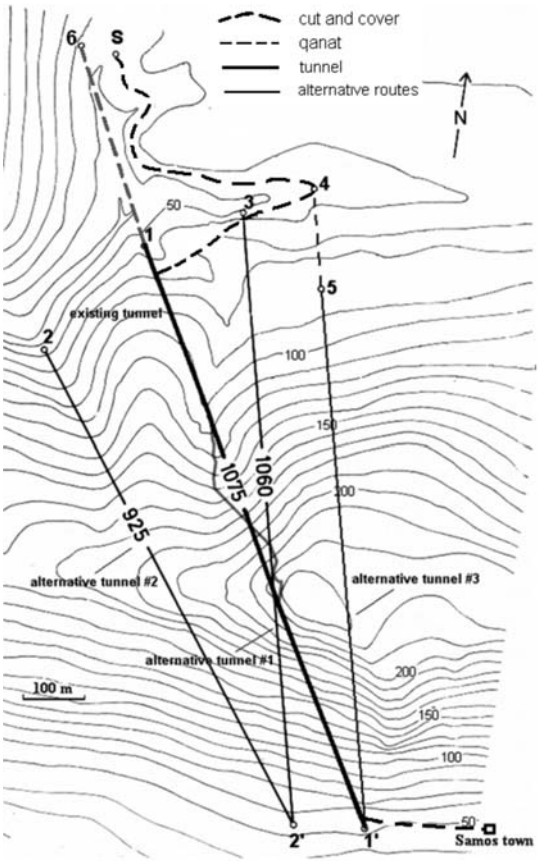

Fig. 3: Plan view of the Eupalinos tunnel and of the three alternative paths of shorter length. Partly after Kienast (1995).

3. Rationale for the aqueduct path selection

Discarding the possibility of an intentional construction of a longer aqueduct either for draining more money for the construction or as a matter of proud (a tunnel superior to any other existing), we can think of the following possible reasons for the aqueduct path selection:

First, a survey gross error. This explanation can readily be rejected, given that Eupalinos proved able to align a tunnel opened from two portals.

Second, technical constraints, in particular geodetic and geotechnical. Geodetic constraints are important for the safe orientation and guidance of a tunnel opened from two portals even for modern tunnels (Kontogianni, 2005, Stiros, 2009b), while geotechnical data constraint a tunnel cutting through rocks that can easily excavated without causing stability problems and require costly and time-consuming support measures. This seems to be the only reasonable explanation.

In fact, Stiros (2009a) noticed that on the grounds of geodesy there were only few alternative paths for the tunnel fulfilling the requirement of long baselines in free spaces at the two portals. Such baselines are absolutely necessary for the geodetic orientation and guidance of the excavations.

The problem of geotechnical constraints is for the first time examined in this paper, although the geology along the tunnel path have been studied by other investigators as well (see Kienast, 1995).

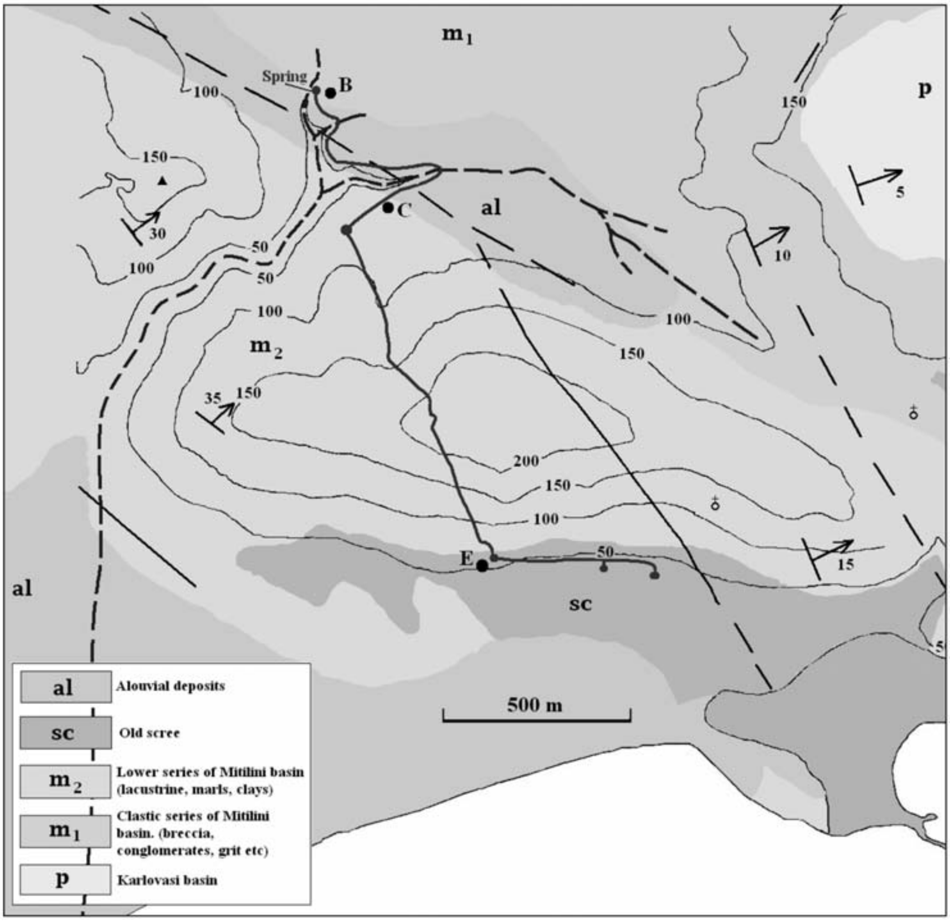

Fig. 4: The geology of the area consists of a NE-dipping monocline incised by a stream leading from the Ayades spring to the sea (simplified after Theodopoulos, 1979). GSI values are reported for locations B, C and E.

4. Geological and geotechnical characteristics of the aqueduct area

The morphology of the area is dominated by the Castro hill, ~200 m high, and an incised valley through which the Ayades spring is discharged to the sea (Fig. 4). The geology of the Castro hill corssed by the tunnel, is rather simple, and consists of the Lower series of the Mytilini formation, lacustrine medium to thick-bedded travertine-type limestones strata, forming a monocline tilted 30^o N on the average. Near the Ayades spring, geologic formations consist of clastic series of the Mytilini basin (Pontian), fluvio-lacustrine deposits consisting of alternating beds of breccia, conglomerates, sandy marls and marly limestones, with intercalations of travertine limestones. At the south portal of the tunnel strongly cemented old scree and talus cones are found (Fig. 4).

The incised valley through which the Ayades spring is discharged to the sea cuts the monocline dominating the geology of the area and permits an easy understanding of the stratigraphy of the tunnel area in a natural section; additional observations can be made in ancient quarries near the 150m high peak, at the NW part of the map.

A careful field study permitted to understand the structure of the area around the tunnel, as well as the geotechnical characteristics of the rocks.

First, it was found that the strength of the rocks of the sequence of the Kasto hill decreases upwards, and since this represents a monocline, strong rocks are found near the south portal and weak rocks near the Ayades spring.

Second, we tried to find a measure of the strength of these rocks adopting the Geological Strength Index (GSI) classification (Hoek and Brown, 1997), which has been widely used in Greece (Marinos and Hoek, 2000). Using the typical GSI criteria, we estimated the GSI index for rocks in several representative areas and summarized these results in Table 1.

Table 1. GSI values of rocks for selected locations (see Fig. 4) near the Samos tunnel.

Location	*GSI*
B	35-40
C	30-40, locally <20
E	80-90

Third, it is evident that the results of the geotechnical (GSI) approach is consistent with the results of the structural/geological study, and hence it puts some constraints to the selection of the tunnel path: The area around point C was not suitable for tunnel construction in antiquity (low strength rocks), and the north portal should have been shifted to the SW. This is schematically shown in Figure 5.

5. Constraints for the tunnel path selection

Previous discussion reveals that Eupalinos had to reject any plans for a tunnel near point C (incompetent rocks, unsafe excavation); in order to meet competent rocks he had to shift the north tunnel portal as long as possible to the SW, for instance till path #3 in Figure 3. This would lead to a >10% shorter tunnel (see Fig. 3), and this advantage would counteract any problems caused by a longer aqueduct.

Still, Eupalinos selected an intermediate solution, fixing the north portal at the boundary between weak and relatively strong rocks. For this reason he had to support a part of the tunnel, and this support was extended in Roman times (Kienast, 1995).

What are the characteristics of this path? As Stiros (2009a) noticed, free space to fix a long survey base line necessary for the orientation of the tunnel and guidance of its excavation exists only at the extension of the selected tunnel path (see Fig. 3). In all points farther SW, where lithological conditions are more favourable, the incised stream does not permit fixing any long baseline. Since the length of such a baseline was critical for the success of the tunnel orientation, Eupalinos had to make a compromise between geodetic requirements and geotechnical requirements. The selected path proved that his overall rationale was correct, and this proves an excellent under-

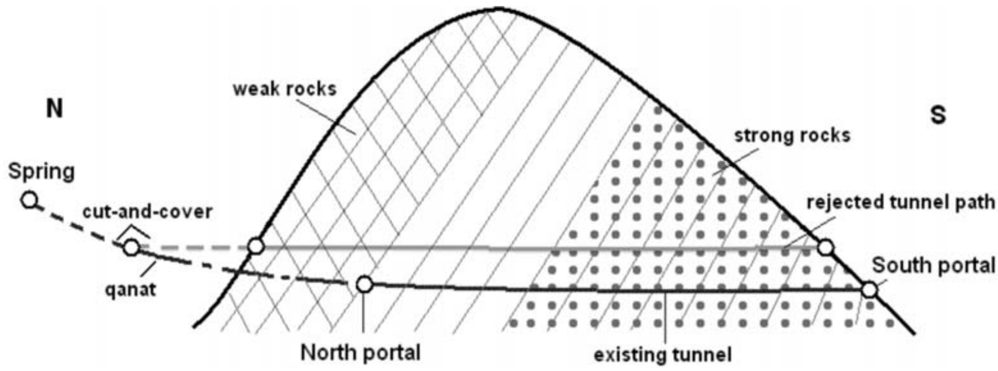

Fig. 5: Sketch of the longitudinal section of the Castro hill along the Ayades stream. Competent rocks are found in the lower parts of the sequence and non-competent in its upper parts, close to point C in Fig. 4. Superimposed on this sketch are the approximate tunnel path #3 (rejected) and the tunnel path selected by Eupalinos. It is obvious that the criterion for the path selection was the strength of rocks in the north portal.

standing of the geodetic requirements for such a magnificent project and of the geology and of rock strength conditions. The latter required a detailed understanding of the rock mass strength characteristics, permitting comparisons between rocks of different types, and obviously costly decisions. Most probably a primitive Geologic Strength Index was used for this task.

6. Conclusions

Planning of the Eupalinos tunnel path was definitely far from being a random choice. All available data indicate that the path was selected as a *compromise* between the geotechnical and the geodetic design. Eupalinos had at least an excellent empirical understanding of the geology and an ability for characterization of the rock mass quality, reminiscent of the modern rock mass classification systems such as GSI, as well as an excellent understanding of the techniques, requirements and limitations for alignment and guidance of underground excavations. Without such knowledge it would be absolutely impossible to complete such as demanding project.

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ΓΕΩΤΟΠΟΙ / GEOSITES

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INVESTIGATION OF THE FORMATION OF SPELEOTHEMS IN THE AGIOS GEORGIOS CAVE, KILKIS (N. GREECE)

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Abstract

The Agios Georgios cave at Kilkis (North Greece) contains a large variety of speleothems and it is considered as one of the most decorated caves of Greece. For this study a coordinated geochemical and textural investigation of the speleothem was carried out. This stalactite was cut along its growth axis and a transverse slab of it shows parallel calcite layers of varying thickness and colour, whose regularity and spacing suggest an annual origin. Microscopic investigation of polished-thin sections resulted in a detailed description of several fabric types. Scanning Electron Microscopic study and microanalyses revealed that pure calcite is dominant; local Mg-bearing calcite occurs, too. In some pores among the faceted crystals there is a variety of clay minerals that, along with the development of Mg-bearing calcite, are interpreted as the result of microbiological or/and climatic changes. Numerous changes in environmental conditions in caves (particularly changes in water flow rates) cause variations in the degree of perfection of crystallite lateral growth and inclusions may trapped by their advancing growth surface. The speleothem is studied in order to generate archives of climate change (aridity, flow rates etc.) and indentifying shifts in climate system. The successive laminae in the studied speleothem from Agios Georgios suggest alternative cool and warm periods in the past climatic conditions of northern Greece.

Key words: *speleothems, microfabrics, Agios Georgios Cave, North Greece.*

1. Introduction

Caves are formed by different processes in many rock types and unconsolidated sediments. They can be classified according to their origin and the lithology of host rock or the type of sediment (Ford and Williams, 1989). The most common type of caves is limestone dissolution cave, which forms as a slightly acidic fluid (carbonic acid) erodes the limestone. Caves that form in this way can be very deep and contain substantial number of chambers or rooms. Chemical reactions under these very precisely controlled conditions permit the growth of unusual minerals and the growth of crystals of exceptional size. Mineral deposits take on the form of stalactites, stalagmites, flowstones, and other forms known collectively as speleothems. Because these deposits are nourished by water seeping down from the surface, changes in the climate and vegetation on the surface leave their signatures in the growth bands of the speleothems. The deposits of caves have become an important source of paleoclimatic information (e.g. Fairchild et al., 2006). Use of cave speleothems has been proven to be a powerful tool for the study of past climate and environmental changes. The noteworthy properties of climate recording by these cave formations result from their mineralogy and fabric, as well as from their mode of occurrence (Bertaux et al., 2002). Similar to corals, tree rings, annual laminations in maar lakes and annual layers in ice cores speleothems may present an annual and subannual laminate that can be used

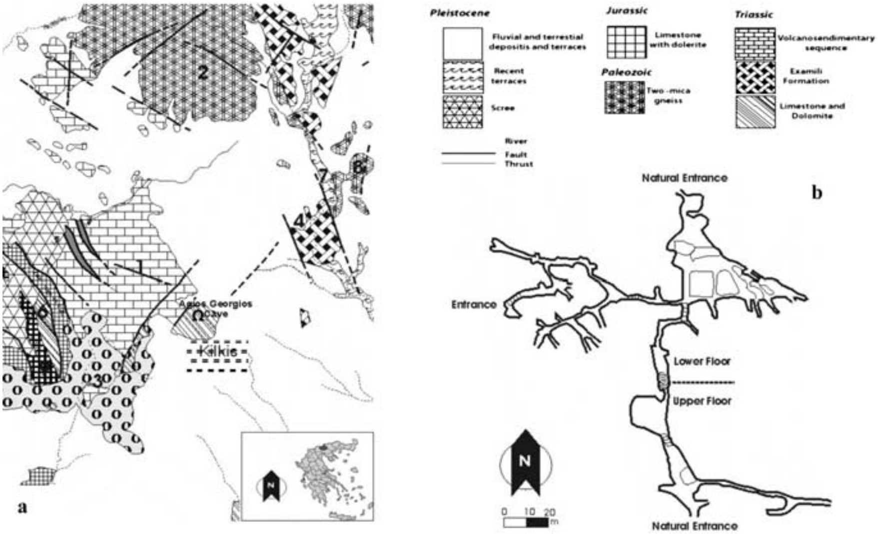

Fig. 1: (a) Geological map of broader area of Kilkis (after Kockel and Ioannides, 1979) Ω: Agios Georgios cave (b) Map of Agios Georgios cave (mapping from Hellenic Speleological Society).

in studies of climate reconstructions (Genty and Quinif, 1996; Kaufman et al., 1998; Baker et al., 2008).

The aim of this study is to present a detailed description of the fabrics present in a 181mm long stalagctite from the Agios Georgios Cave, Kilkis, N. Greece, to relate their development to different climatic conditions and to suggest possible climatic changes that have been imprinted in the speleothem texture. Interpretation of fabrics and the collected data serve to demonstrate that the petrographic characteristics may have recorded a climate signal.

2. Geological and Speleological Setting

The Agios Georgios cave (Latitude 40^{o}59'32''N; Longitude22^{o}52'20''E) is located at the south-west of Agios Georgios hill in Kilkis (47 km north of Thessaloniki, Greece), Central Macedonia Valley. It is a limestone cave developed in the limestone with local dolomite of Middle- Upper Triassic part of Deve-Koran Sequence (Kockel and Ioannides, 1979) (Fig. 1a) which belongs to the circum Rhodope zone (Kaufmann et al., 1976).

The Agios Georgios cave has an extent of 1000m^2 with a visiting path about 500m long. The cross-like pattern is developed in east-west and south-north directions (Fig. 1b). It has two natural entrances the northern, at the lower level and the southern at the upper level; both of them are blocked from aggregates. The passages are narrow and high, looking like clefts. Most of them have a north-south or an east-west direction, obviously depending on the direction of tectonic structures in the limestone. The Agios Georgios cave is developed in the "upper floor" and the "lower floor". The first is decorated with stalactites, stalagmites and flowstones with typical dark brown colour, sometimes with a little reddish tinge. The "upper floor" consists mainly of coral forms.

2.1 Present Climate Conditions

The available data on the climate of Kilkis come from the Halkidona station 37 km to the south and

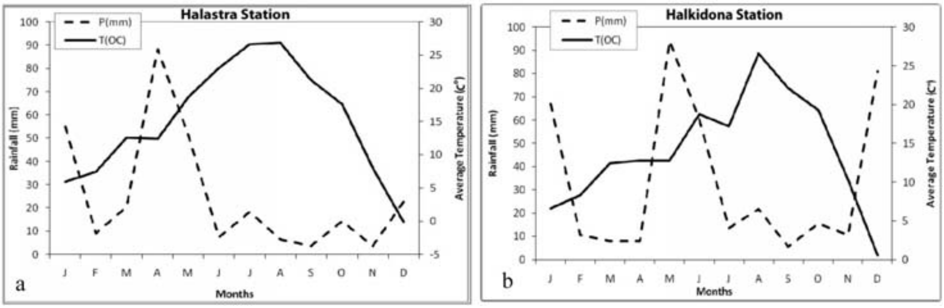

Fig. 2: Plot of average monthly rainfall (P) and temperature (T) from Halastra (a) and Halkidona (b) meteorological stations.

the Halastra station 26 km to the north of Agios Georgios cave. Average annual rainfall at these two sites is 343 mm and 454 mm, respectively. The average annual temperature at Halkidona is 16 ^{o}C and at Halastra is 15.5 ^{o}C (Fig. 2a, b). The hottest month is typically August, when mean monthly temperature is about 27 ^{o}C, while the coldest month is December when mean annual temperature approaches 0 ^{o}C. The local present-day climate at the Agios Georgios site is sub-humid Mediterranean, characterized by strong seasonal contrasts. The two instrumental records yielded a mean annual precipitation of 424 mm/year and a mean annual temperature of 15-17 ^{o}C for the period 1992–2006. Evaporation commonly exceeds precipitation from June to early September. The mean annual temperature in the cave is 16±1 ^{o}C and the humidity is about 95%.

3. Sampling and analytical methods

Sampling and study of the Agios Georgios speleothems were licensed to us by the Greek Ministry of Culture and Tourism, Ephoreia of Paleoanthropology and Speleology of Northern Greece (Licence No. ΥΠΠΟ/ΣΥΝΤ/Φ44/ 3898/88161). Three speleothems were sampled from different galleries of the the Agios Georgios cave. When cut vertically in sections parallel to the growth axis, they present well developed laminae zones. The AG1 sample is a stalactite (181mm long and 56mm wide, Fig. 3) which was chosen for further chemical analysis because it grew in a place without episodic flood. Twelve polished -thin sections were prepared along the stalagmite axis in order to observe the carbonate fabrics and the laminae under an optical microscope. Scanning electron microscope (SEM) equipped with EDS and WDS, at the Laboratory of Electron Microscopy and Microanalysis, University of Patras, was employed to examine crystal microstructure as well as to perform quantitative electron microanalyses. All elements were analyzed by an electron-dispersive X-rays (EDX) using EDS and WDS detectors attached to a JEOL JSM-6300 SEM. Operating conditions were accelerating voltage 15 kV and beam current 3.3 nA with 4 μm diameter beam. EDS and WDS spectrum information with the ZAF correction software information was used. The total counting time was 60 sec and dead-time 40 %. Synthetic oxides and natural minerals were utilized as standards for our analyses. Detection limits are ~0.1 % and accuracy better than 5 % was obtained.

4. Petrography of Speleothems

4.1 General

Each speleothem is consisted of multiple layers which have an annual or a subannual origin (Frisia et al., 2000). The layers may comprise either a single or various fabrics. Factors like chemistry and flow of par-

Fig. 3: AG1 stalactite cut vertically in section parallel to growth axis.

ent waters, the supply of ions to growth sites and the rate of CO_2 outgrassing are related to the crystal morphology of speleothems. Kendall and Brougthon (1978) pointed out that stalagmite are composite crystals from individual crystallites. The surface of crystals could be smooth or show steps and kinks, crystal defects stems from the incorporation of foreign ions, misfits at implying growth surfaces and condensation of vacancies (Wenk et al., 1983). Other misfits may originate from fluctuating flow rates, exposure of the growing crystal faces to the cave air, rapid outgrassing or dissolution (Fairchild et al., 2007).

4.2 Fabrics observed in the Agios Georgios speleothem

The collected sample cut along it axis show alternations of multicoloured laminae of variable thickness (Fig. 3). Notably, shows any asymmetric development with its axis to be shifted towards the stalactite periphery.

Columnar fabric consists of composite calcite crystals with length to width ratio ≤ 6:1 (Fig. 4a). Each composite crystal is made up of innumerable crystallites. The crystals have straight boundaries, uniform extinction and their long and optic axes oriented more or less normal to growth surfaces. In the studied samples crystallites are stacked in order, which is characteristic of columnar fabric, along with the lack of ring diffraction patterns in the composite crystals. The most common orientation of crystallite boundaries is parallel to the facet (1014) and crystallite habit is {1014} rhombohedron, and frequently the boundaries of crystallites are marked by micropores. The crystallites usually terminate with euhedral tips with flat faces (Fig. 4b). This fabric rarely shows competitive growth phenomena but the crystallites that form columnar fabrics are characterized by few dislocations, and it is probable that they grew through the spiral growth mechanism. At Agios Georgios stalactite columnar fabric forms translucent layers, which show annual lamination.

Another textural type observed in sample AG1 is *fibrous fabric*, which is characterized by calcite crystals with length to width ratio ≥ 6:1 and irregular crystal boundaries due to competitive growth phenomena (Fig. 4c, d, e). Competitive growth results in selective elimination of those crystals whose c-axes are not perpendicular to the substrate. Local Mg-bearing fibrous calcite crystals intergrow with pure calcite (Fig. 4f). In some cases, this type of fabric is characterized by the presence of patches of dolomite. Fibrous fabric layers are translucent and alike to columnar fabric.

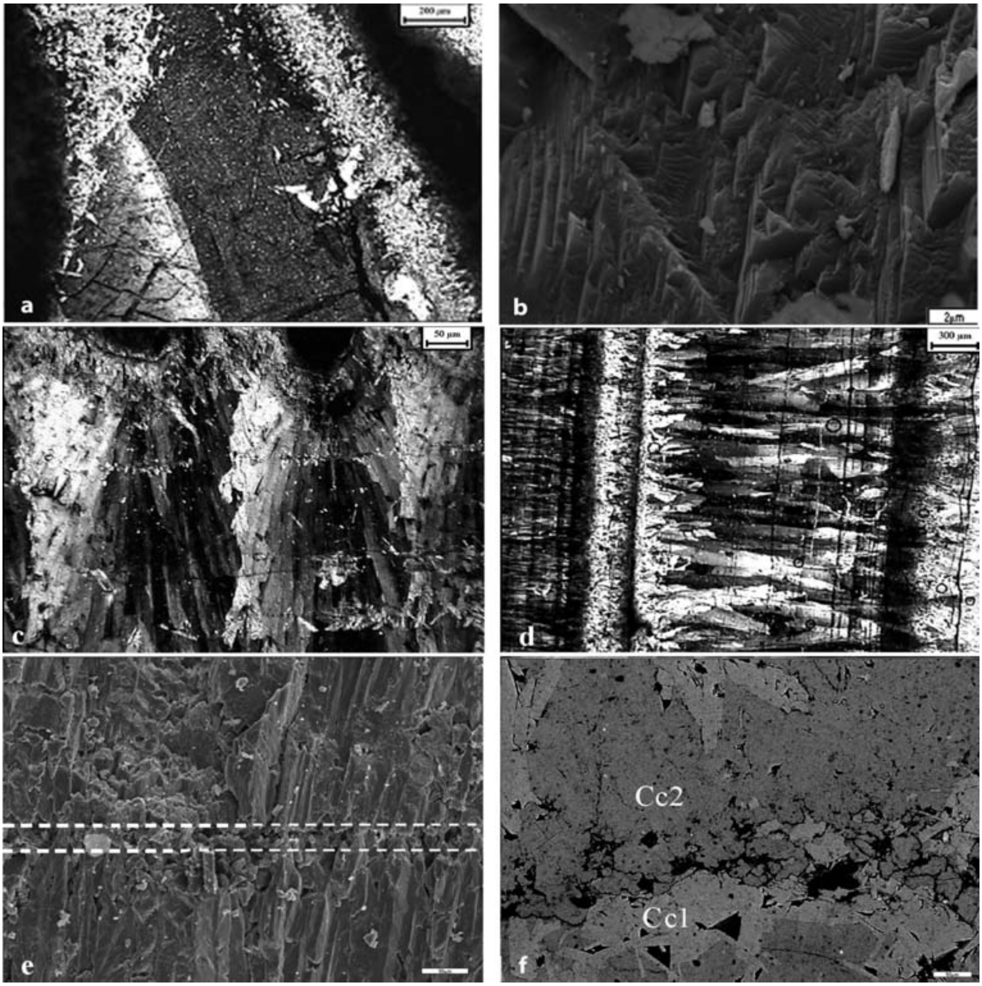

Fig. 4: Types of fabric and inclusion patterns from the stalactite of Agios Georgios Cave (a) Columnar Fabric photomicrograph, showing straight composite crystal boundaries and lack of visible laminae. The composite crystals have uniform extinction (Nicols +) (b) Secondary electron image showing trigonal crystallites with step surfaces. (c) Fibrous Fabric. Photomicrograph from AG1 shown competitive growth phenomena which result from those crystals whose c-axes are not perpendicular to the substrate. (d) Each layer of fibrous fabric is marked by microsparite (Nicols +) (e) Secondary electron image of two fibrous fabric calcite layers separated by thin layer of microsparite (f) Backscattered electron image of pure calcite (Cc1) interlayered with Mg- bearing calcite (Cc2); scale = 50μm.

Calcite with *microcrystaline fabric* in AG1 sample stalactite (Fig. 4g) form laminae layers with alternations between white and dark laminae and in places porous layers. Few crystallites grow in optical continuity with substrate, commonly in different orientations. This misorientation yields the serrated to interfingered boundaries typical of extinction, which may crosscut each other. Detrial muscovite grains up to 50μm and Fe-oxides exist in voids mainly in the dark laminae of microcrystalline calcite. In places halloysite and gibbsite occur, too; preliminary investigation of these clays suggested that they are resulted from microbial activity (Fig. 4h).

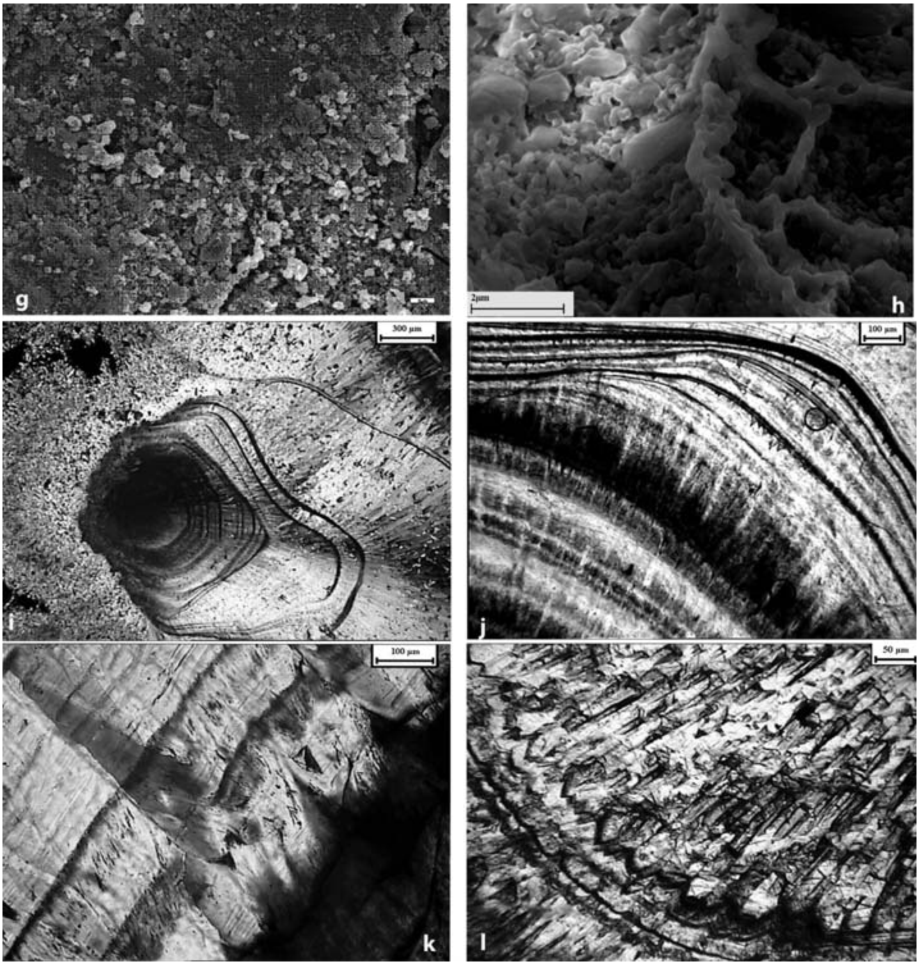

Fig. 4 (continued): Types of fabric and inclusion patterns from the stalactite of Agios Georgios Cave: (g) Secondary electron image showing crystallites exhibit rugged surfaces with macrosteps (scale = 5μm). (h) Secondary electron image of a void where microbial activity forms clay minerals. (scale = 2μm) (i) Bulbous mass of pseudopleochroic calcite. Type 1 growth layers contain large thorn like inclusions. Crossed polarized light (scale=300 μm). (j) Microcrystalline fabric. Photomicrograph showing dark drowns and white lamina. (k) Type 3 growth layers where former crystal terminations are defined by bands of pseudopleochroic calcite; crossed polarized light (scale = 300 μm). (l) Very well defined former crystals terminations by pseudopleochroic calcite; plane polarized light (scale = 50 μm).

4.3 Laminae Types

In thin sections cut normal to the stalactite long axis five type of growth layering were recognized. The layers of the first type are smooth curves with parallel to subparallel linear inclusions (*Type 1*). Another type of layers similar to *Type 1* (Fig. 4i) form smooth curves, which are defined by the concentration of inclusion. These inclusions are not visible with a light microscope so they impart pseudopleochroism to the calcite (*Type 2*, Fig. 4j). In *Type 3* layers are also defined by pseudo-pleochroic calcite but, instead of being smooth curves, they define former positions of rhombohedral (rarely scalenohedral) crystal faces (Fig. 4k). Such terminations may be complete or incomplete. In the latter case the growth layers combine the features of layer *Types 2* and *3*. Some inclusion-defined crystal terminations are not now associated with crystal boundaries. *Type 4* layers also define former calcite crystal faces like *Type 3* but are themselves defined by concentrations of linear inclusions (Fig. 4l). Layers characterized by the presence of impurities commonly separate layers with different crystal habit (*Type 5*).

5. Mineral Chemistry

Microanalytical work was carried out in carbonate crystals from each fabric of stalactite. The most common phase in all types of fabrics is pure calcite. In places with fibrous fabric, Mg-bearing calcite is also present with MgO ranging from 0.45 to 2.10 wt %; local dolomite patches were also analyzed (Fig. 4f). Representative results are given to Table 1.

Table 1. Representative chemical microanalysis of crystals from the AG1 stalactite sample.

Analysis No.	*AG1_1*	*AG1_2*	*AG1_3*	*AG1_4*	*AG1_5*
Mineral	***Calcite***	***Calcite***	***Mg-Calcite***	***Mg-Calcite***	***Dolomite***
FeO	-	-	-	-	0,68
MnO	-	-	-	-	-
MgO	0.06	0.14	2.10	1.58	19.95
CaO	55.85	55.83	53.87	53.7	32.93
Total	**55.91**	**55.97**	**55.87**	**55.28**	**53.56**
Stoichiometric formulae on the basis of 2 oxygens					
Fe^{2+}	-	-	-	-	0.017
Mn^{+}	-	-	-	-	0.000
Mg^{+}	0.003	0.007	0.103	0.079	0.907
Ca^{2+}	1.997	1.993	1.897	1.921	1.076

6. Discussion

Visible lamina thickness and repeated pattern of fabrics from AG1 stalactite reflect climate variations through the relationship between growth rate, climatic and geochemical parameters. Variations of seasonal alteration of fabric and/or mineralogical defining couplet and as, well as impurities during infiltration events have been shown generally to occur on an annual scale (Genty et al., 2001; Baker and Genty, 2003). In different environment settings depositions of different phases of $CaCO_3$ occur and as a result visible laminae could be interpretated as regular alteration of arrangement in space of crystals with the well defined morphology (texture or fabric, Onac, 1997; Frisia et al., 2000; Frisia et al., 2002). In sample AG1, connection between thickness of lamina and the environment variation could be achieved by the fact that in wet period and in high flow rates the thickness of layers increases. In contrary, at dry periods the thickness of visible layers decreases. If, during these periods, evaporation exceeds precipitation, which is related to the modern summer period in the area, then it is probable that this factor may additionally determinate the type of thin layers. Another connection between visible laminae and fabrics has occurred in this study. It is noticeable that during periods of infiltration (in seasonal high flow rates) the input of detrital and colloidal materials is more often (Borsato et al., 2007) and fibrous fabric is more likely to appear. In dry seasons where drip rate is slow lamina thickness is fine and columnar fabric is dominant. Also chemical variations in the water are reflected by chemical differences in the precipitated calcite, thus explaining the occurrence of both Mg-bearing and pure calcite crystals with microcrystalline fabric.

The calcite crystals of columnar fabric lack diffraction patterns and are crystals with low density defects. This is because the crystallites are stacked in order and all of them have the same orientation with respect to substrate (Kendall, 1993). The crystallite surfaces and sizes may vary, while the only crystal defects are few dislocations that grew with spiral mechanism. Spiral growth is more common at low supersaturation and can continue even if the fluid is close to saturation (Sunagawa, 1984). Therefore, it is considered as the dominant growth mechanism for columnar fabric crystallites (Frisia et al., 2002). The crystallites that formed in summer are characterized by evolution from smaller grains with rough surfaces to larger grains with flat faces; the winter crystallites are commonly characterized by rough surfaces. Columnar fabric forms in an environment of constant discharge, low and fairly constant degree of supersaturation and negligible impurity content. Accordingly, the layers with columnar fabric observed in the collected samples suggest formation under similar conditions.

Two factors are responsible for acceleration of fibrous fabric: 1) the larger number of crystallites due to more nuclei present and 2) faster growth rate induced by higher flow velocities (Frisia et al. 2000; Frisia et al., 2002). Both of these factors will result in faster achievement of parallel compromise boundaries and hence fibrous fabric. Fibrous fabric is generated only when flow rates accelerate crystal growth rate and increase heterogeneous nucleation, suggesting that the relevant layers in the Agios Georgios sample were formed under higher drip rates than those forming columnar fabrics.

Microcrystaline fabric usually forms under conditions of mean discharge, higher than those related to columnar fabric, low supersaturation and where the air flow is absent (Frisia et al., 2003). It is associated with insoluble residue like clay minerals (Huang et al., 2001). Clay minerals in AG1 sample can be found in void spaces, pores and bulbous masses which are compatible with their association to the microcrystalline texture (Fig. 4i). These microfabric evidences suggest that microorganisms have actively participated in the genesis of speleothem (Baskar et al., 2007). The formation of the clay minerals stems from the alteration of silicates and is probably related to microbe activity. The role of microbes is important because they act as nucleation sites to calcite precipitation and in many cases appear to control the types of crystals that form (Jones, 2001; Baskar et al., 2009). Different types of layering and inclusion patterns from AG1 stalactite steams from the perfect or less perfect coalescence between crystallites. If crystallites have the same orientation and identical lattice orientation with the substrate will combine to give a single crystal, and thus an inclusion-free calcite layer. Less perfect coalescence allowing the entrapment of impurities and will give rise to inclusion bearing layers (Kendall and Broughton, 1978). The variations in either the supply or the rates of absorption of impurities give rise to variations in impurity concentration which thus comes to define a growth layering.

All the above fabrics have been formed under isotopic equilibrium and stable isotopes (^{18}O and ^{14}C) suggested that fibrous calcite developed during cold environment episodes whereas microcrystalline and columnar fabrics have been crystallized under warm conditions (Antonelou, 2007).

7. Conclusions

Stalactite AG1 from Agios Georgios cave, Kilkis, N. Greece, is a calcite laminated stalactite with visible laminae, which are due to different chemical and environmental conditions. Three types of calcite fabrics have been detected. Columnar and microcrystalline fabrics formed during warm climate episodes while calcite crystals that show fibrous fabric have grown under conditions of rapid fluid discharge and low temperatures. The interpretation of fabrics can give as a clue about the paleoclimatic conditions during the formation of stalactite and alternations of warm and cold climatic episodes that influenced the area of N. Greece can be suggested.

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PLEISTOCENE PALAEOCLIMATIC EVOLUTION FROM AGIOS GEORGIOS CAVE SPELEOTHEM (KILKIS, N. GREECE)

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Abstract

Palaeoclimatic reconstruction in N. Greece has been investigated in this study, using stable isotope analyses and U/Th dating of a speleothem (stalactite) from the cave of Agios Georgios (Kilkis). Sampling sequence was followed in detail in order to obtain high resolution analysis of the proxy. Speleothem $\delta^{18}O$ entirely depends on two factors: changes in the $\delta^{18}O$ of the percolation waters (a proxy for local rainfall $\delta^{18}O$) and the temperature of water-calcite fractionation inside the cave (a proxy for outside air temperatures). During periods of relatively stable temperatures, $\delta^{13}C$ shifts are caused principally by variations in soil CO_2 input and physico-chemical processes inside the cave. More important processes affect the $\delta^{13}C$ signal of speleothem inside the cave are length of flow path and rates of CO_2 degassing.The lower $\delta^{13}C$ calcite values indicate greater respiratory activity of soils under wetter conditions. The stalagmite layers were dated through U/Th geochronological method, which places the carbonate precipitation in Middle Pleistocene (630-300ka BP). The isotopic composition of the layers was used in combination with the dating results to reconstruct the evolution of the area of Kilkis. Correlation with global climatic records shows that major climatic transitions that influenced northern hemisphere seem to have also affected the region of N. Greece.

Key words: *speleothem, stable isotopes, palaeoclimate, Pleistocene, Macedonia, Greece.*

1. Introduction

Speleothems are probably the most interesting formations of limestone caves, because they hold a remarkable archive of palaeoclimatic data describing local and global events for the period of time in which they grew. As calcite nucleates on the surface of the growing cave formation, trace elements and certain isotopes are sealed in place, in concentrations that may bear similarity to the environmental conditions under which they have formed. A climatic record can be derived from the relative contents of ^{13}C and ^{18}O in the lattice. Support for a palaeoclimatic record based on growth frequencies of speleothems can be obtained from the dated deposits themselves, by variations in ^{13}C and ^{18}O

of calcite along the growth axes of deposits that formed in isotopic equilibrium with the groundwater (Gascoyne, 1992).

Our understanding of palaeoclimatic transitions has been considerably increased by the many recent studies of global climatic change (e.g. Imbrie et al., 1984; Chappell and Shackleton, 1986; Bond et al., 1993; Dansgaard et al., 1993; Bar-Matthews et al., 1997). Eastern Mediterranean region is a transition zone between humid climate in the north and arid climate in the south. As in other climatic transition zones, the region of north Aegean Sea was sensitive in the past to changes in natural environmental parameters, such as temperature, amount of rainfall, origin and pattern of storm tracks, vegetation type, and location of the desert boundary (Street and Grove, 1979; Bar-Matthews 1999; Tzedakis et al., 2003; Geraga et al., 2005; Hughes et al., 2007; Psomiadis et al., 2009).

It has long been appreciated that, at least for the last 450 ka, the many stages and substages into which the deep-sea isotopic sequence is divided are also appropriate for viewing the continental record (e.g. Shackleton, 1969; Tzedakis et al., 1997, 2001, 2003), although marine and terrestrial boundaries may not be precisely isochronous. With regard to the amplitude of climate variability, research focusing has been developed over some prominent transitions during the Middle Pleistocene, like the so-called Mid-Brunhes Event (MBE) at the MIS 11/12 transition ca. 430 ka (EPICA community members, 2004), the most severe glacial period correlated to MIS 12 (Tzedakis et al., 2003), the moderate variations during MIS 13-15 etc. Regarding palaeoclimatic data for the region of Greece during Middle Pleistocene, studies have been applied to pollen analysis (Tzedakis et al., 2003, 2006) and geomorphological and sedimentary data (e.g. Hughes et al., 2007). These studies have indicated that the most severe tree population contractions of the last 450 ka occurred during the glacial maxima of MIS 12 and less intense MIS 10 (Tzedakis et al., 2003, 2006). These results were in agreement with the relative extent of ice sheets as estimated from marine benthic isotope records (e.g. Shackleton, 1987; Waelbroeck et al., 2002) and reconstructed from field evidence from Europe (e.g. Ehlers, 1996). During the most extensive Skamnellian Stage glaciation (MIS 12), climate would have been even colder and/or wetter than was the case for both the later Vlasian and Tymphian cold stages (Hughes et al., 2007). MIS 16 appears to be the most extensive glacial period of the last 1.35Ma, not in terms of intensity but rather of the prolonged suppression of tree populations (Tzedakis et al., 2006).

Early middle Pleistocene faunas seem to be missing from Greece. In central-western Europe this period is characterized by a new warm phase of alternations of mild glacial intervals with warm interglacial ones (Agusti and Anton, 2002). From middle Pleistocene onwards, the establishment of the bipolar climate in the North Alpine areas forced the south European environment to alternate between Mediterranean arid and mild-temperate (Kostopoulos and Vasileiadou, 2006).

In the present work, a ca. 250ka $\delta^{18}O$ and $\delta^{13}C$ record that was obtained from a stalactite from northern Greece (Agios Georgios Cave, Kilkis) are discussed for palaeoclimatic interpretation during the period from MIS 9b to MIS15e.

2. Setting of the area

Agios Georgios cave is located near the city of Kilkis (Fig. 1), approximately 50km north of Thessaloniki (Macedonia, N. Greece). The total length of its hallways is 500m and its total surface reaches up to 1000m^2. The internal environment is typical of a karstic cave, with stable temperature all year round (16±1^{o}C) and high humidity (95%). Mean annual precipitation in the region is 386mm and mean annual temperature is equal to 15.1^{o}C.

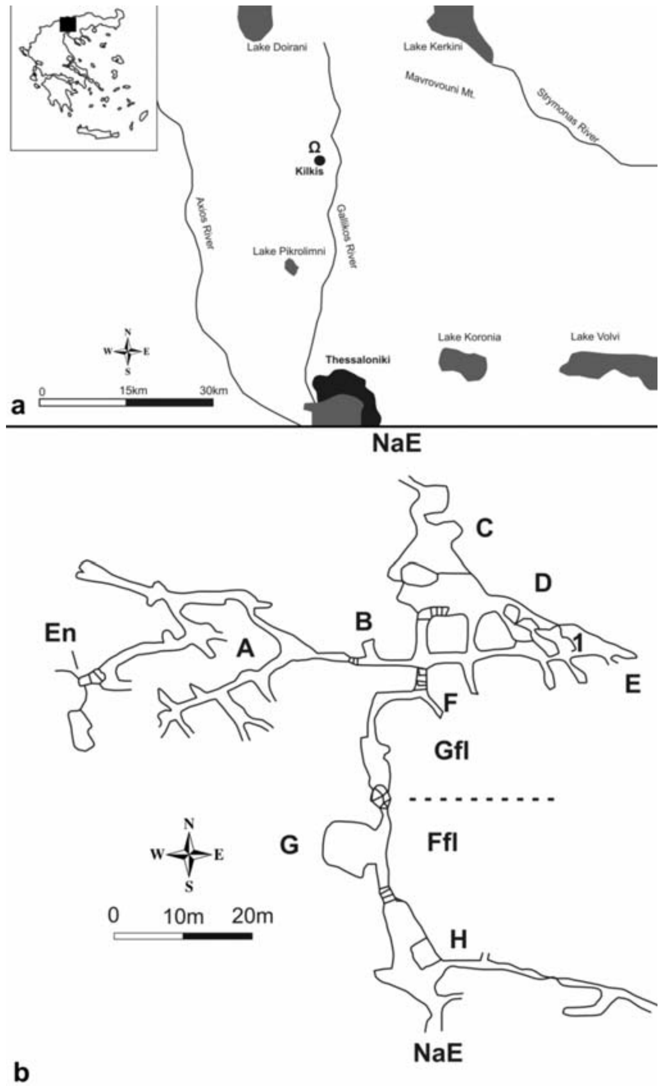


Fig. 1: Location of the study site (a) and ground plan (b) of Agios Georgios cave (Ω). NaE: Natural Entrances; En: Entrance of the cave; Gfl: Ground floor; FFl: First floor; A-H: Chambers; 1: Sampling position of stalactite SP4.

The karst has been developed in the M.-U. Triassic limestone (Kockel and Ioannides, 1979). Palaeontological evidence recorded several species of mammals and micromammals of the last 15ka (Tsoukala, 1991).

3. Methods

3.1 Sampling and isotopic analyses

The cave conditions and processes render the specific environment as a partly active (humid) karst setting (Woodward and Goldberg, 2001) with on-going drip-flow in only some of the cham-

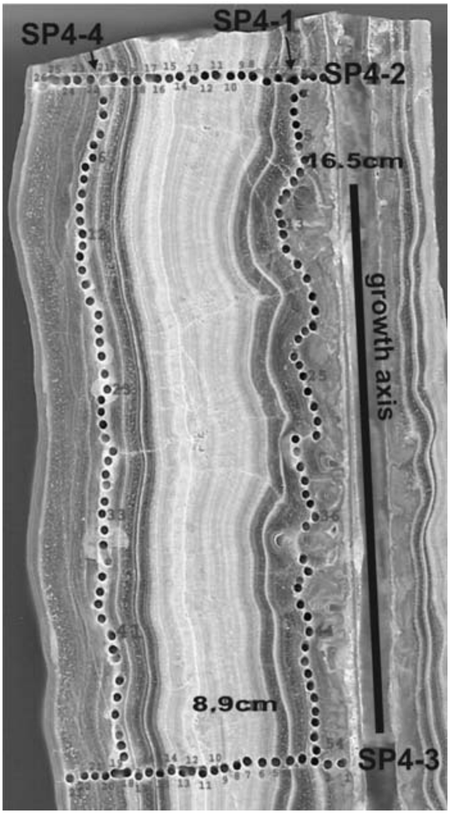


Fig. 2: Cut section of SP4. SP4-2 and SP4-3 are perpendicular subsampling sections to the growth axis. SP4-1 and SP4-1 are parallel subsampling sections, respective to layers 3 and 21 (dating samples and Hendy tests).

bers. A stalactite (SP4, 181mm long and 56mm wide) was selected for isotopic analysis from deep within the cave (chamber D, Fig. 1). SP4 generally kept to all necessary conditions for isotopic analysis (Hendy, 1971) which mainly are a deep spot in the cave, not very close to air-circulation exits (i.e., cave entrance) and not in very high chambers (the distance of the drip water during its falling from the cave ceiling may induce isotopic fractionation). The sampled stalactite was cut perpendicular to its length in order to expose their growth laminae and to permit observation and subsampling. To obtain high resolution $\delta^{18}O$ and $\delta^{13}C$ records, the laminae were sampled every 2mm by means of microdrilling, using a 0.7 mm diameter drill bit (Fig. 2) providing approximately 300-500μg of carbonate powder.

Two subsampling sections parallel to the growth axis (SP4-2 and SP4-3) were used in order to examine the palaeoclimatic variability during the growth of the stalactite, whereas two other subsampling sections perpendicular to the growth axis and representing specific laminae (SP4-1 and SP4-4) were used for the radiometric datings and for the application of the so-called Hendy tests (see below). In total, 126 subsamples were extracted for isotopic analyses and dating. $\delta^{13}C$ and $\delta^{18}O$ isotopic ratios of the calcitic stalactite layers were measured (vs. PDB standard) on a Thermo Delta V Plus isotope ratio mass spectrometer equipped with a GasBench II device at Stable Isotope Unit, I.M.S., NCSR Demokritos, Athens, after addition of H_3PO_4 for CO_2 production at 72°C (Fig. 3). The standards used for comparison were NBS 19 and NBS 18 carbonates and an internal Carrara marble standard.

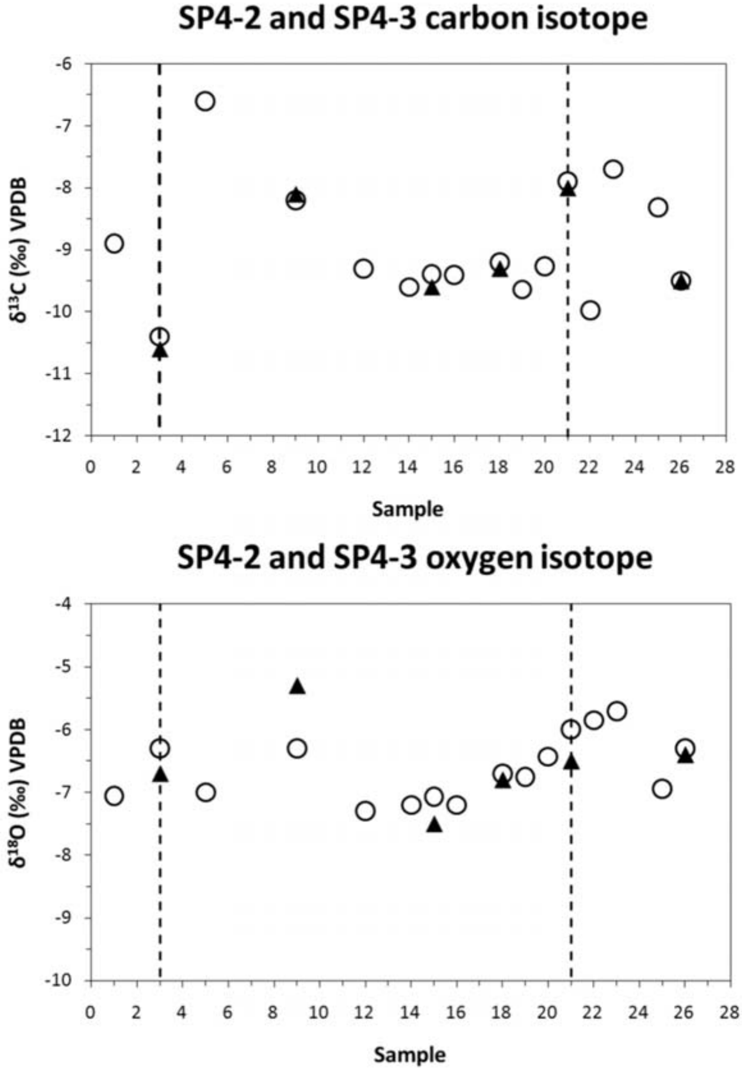
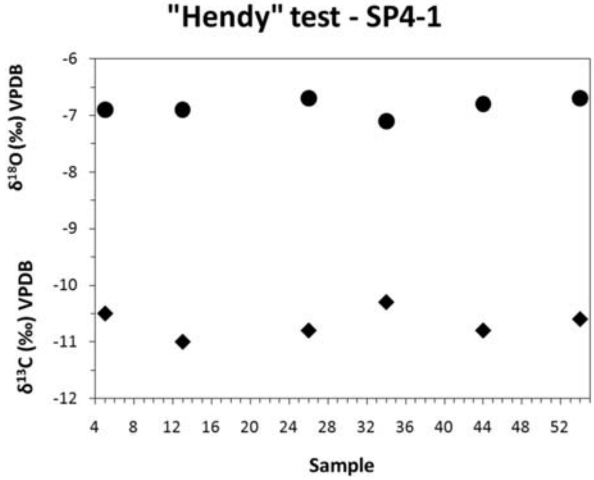


Fig. 3: Results of isotopic measurements (VPDB): variation of carbon and oxygen isotopes across sampling sections. Circles: SP4-2; Black triangles: SP4-3. Dashed-lines represent the U/Th datings of laminae 3 and 21.

Analytical reproducibility is better than 0.1‰ for $\delta^{13}C$ and $\delta^{18}O$. Uranium-series dating was performed using thermal ionization mass spectrometry (TIMS). For the analyses, approximately 200mg samples were used from the two sections (SP4-1 and SP4-4). Ages for each position were determined using a Fisons VG Sector 54-30 mass spectrometer equipped with a WARP filter and an ion-counting Daly detector. Full analytical details of the TIMS method are provided in Zhao et al. (2001).

Isotopic fractionation was excluded after conducting the proposed tests by Hendy (1971) along two specific layers of the stalactite (SP4-1 and SP4-4), which showed negligible kinetic effects (Fig. 4). The $\delta^{18}O$ values along individual laminae are generally constant, whereas $\delta^{13}C$ values vary up to 1.8‰ and are not correlated with $\delta^{18}O$.



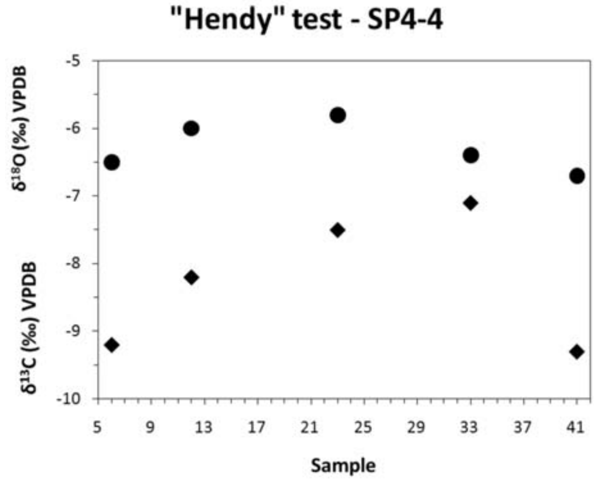


Fig. 4: Plots showing the $\delta^{18}O$ and $\delta^{13}C$ variations (VPDB) for representative different laminae (SP4-1 and SP4-4) of SP4 stalactite as measured along the length of the laminae (see also figure 2). The isotopic trends indicate minor variations in $\delta^{18}O$ and wider variations in $\delta^{13}C$. These trends are in accordance with suggested criteria for isotopic equilibrium (Hendy, 1971).

3.2 Results and discussion

Variations in $\delta^{13}C$ of cave deposits could be attributed to: i) length of flow path and rates of CO_2 degassing which favour speleothem $\delta^{13}C$ enrichment when the surface recharge is low under drier environment; ii) greater respiratory activity of soils under wetter conditions resulting in lower $\delta^{13}C$ calcite values; iii) biogenic CO_2 (lighter values-warmer climate) vs. atmospheric CO_2 (heavier values-cooler climate; McDermott, 2004). Respectively, oxygen isotopic composition of stalagmites may vary due to: i) evaporation effect during arid climatic conditions accompanied by enrichment in $\delta^{18}O$; ii) amount effect i.e. augmented rainfalls, resulting in $\delta^{18}O$ decrease in meteoric water (Rozanski et al., 1993; Bard et al., 2002; Straight et al., 2004); iii) lower deposition temperatures resulting in higher $\delta^{18}O$ values in carbonate precipitations (Gascoyne, 1992; Bar-

Matthews et al., 1996; McDermott, 2004).

It has long been established that for the last 900ka the many subdivisions into which the deep-sea isotopic sequence is divided are reliable for viewing the continental record like speleothems (e.g. Shackleton, 1969; Tzedakis et al., 1997, 2003, 2006), although marine and terrestrial boundaries may not be precisely isochronous. U-series dating of SP4 indicates that the formation of this stalactite started after the Middle Pleistocene Transition (920-640ka BP) and ceased during MIS 9 (ca. 300ka BP). Inspection of figure 5 reveals a close correspondence between variations in global marine isotopic data and the isotopic signature of SP4. In this study, the composite $\delta^{18}O_{benthic}$ record from the equatorial East Pacific (Shackleton et al., 1983; Ninkovich and Shackleton, 1975; Shackleton et al., 1990) and the EPICA Dome C record in Antarctica (EPICA community members, 2004) have been used for intercomparison. These data series have been well correlated to climatic variations in the region of Greece by Tzedakis et al. (2006). Minor discrepancies are at all occasions within the analytical error (2σ) of dating results. However, although major climatic events recorded in marine records seem to have influenced also the region of N. Greece, some well-established climatic periods do not correspond to alterations of the isotopic composition of SP4 calcitic laminae. The latter may be attributed either to the absence of these phases in the region or to depositional factors related to rates of carbonate accumulation or to cave conditions.

The palaeoclimatic interpretation of SP4 isotopic record (Fig. 3 and 5) shows high resolution correlation with five interglacial and four glacial periods during the Middle Pleistocene. The earliest stage corresponds to MIS 15e (lamina 1, 630-610ka BP) with moderately warm conditions, followed by the cooler short stadial MIS 15d (lamina 3, 610-600ka BP). MIS 15d have influenced N. Greece with lower temperatures but as it seems by the depleted $\delta^{13}C$ the climate was rather humid than permafrost. MIS 15a (lamina 5, 580-570ka BP) restored warmer conditions in the region but the recorded enriched $\delta^{13}C$ indicates absence of soil coverage and biological activity, which probably renders this lamina to the transition between MIS 15a/15b. Lamina 9 clearly represents low temperatures and arid conditions (enriched $\delta^{18}O$ and $\delta^{13}C$) and correlates well to MIS 14 (540-500ka BP), which influenced temporally the region in accordance to global records. SP4 laminae 12-19 show an explicit climatic stability in both $\delta^{18}O$ and $\delta^{13}C$. According to U-series dating, these laminae correspond to the time window between 490-390ka BP and indicate warm and wet climate. The effectual correlation of this period with MIS 13 (ca. 480ka BP) and MIS 11 (ca. 400ka BP) is opposed to the absence of isotopic record in SP4 correlated to the most severe Middle Pleistocene glacial MIS 12 (ca. 450ka BP) or to the so-called Mid-Brunhes Event at ca. 430ka BP, also recorded in Greece. During MIS 12, the coldest mean summer temperatures and the local glacier maximum were recorded in the region (Hughes et al., 2007) and also arboreal pollen reached their minimum in N. Greece (Tzedakis et al., 2006). However, the absence of MIS 12 climatic transition in SP4 could be attributed to ceased stalactite growth due to permafrost conditions in the soil surface, which is a typical factor of speleothems hiatuses due to the crucial decrease of water flow and drip rates.

A mild alteration of the climatic conditions took place in lamina 20 (390-360ka BP) which probably corresponds to the transition between MIS 11 and MIS 10, indicated by the slightly enriched $\delta^{18}O$ (cooler climate). The establishment of the glacial conditions of MIS 10 seems to have happened at 360ka BP and held until 340ka BP (laminae 21-23). This period is characterized by cool and dry climate, interposed by a cold and wet phase at 350ka BP (lamina 22), which by any means does not change the glacial character of MIS 10 in N. Greece, but it rather indicates a short abatement of the frost coverage of the epikarst. This interruption is also indicated in arboreal pollen from N. Greece (Tzedakis et al., 2006) and also in isotopic records from Antarctica (EPICA community members,

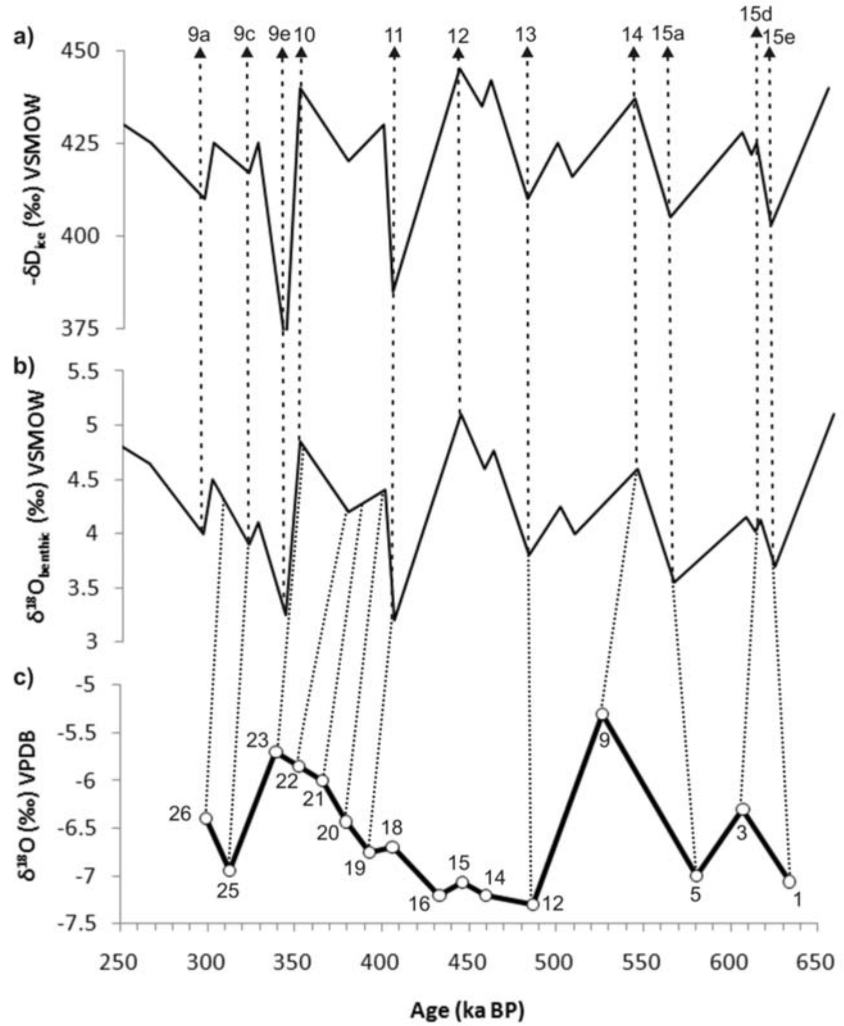


Fig. 5: a) EPICA Dome C (EDC), Antarctica, Deuterium (-δD) record (EPICA community members, 2004); b) δ^{18}Obenthic composite record from sites in the equatorial East Pacific (Shackleton et al., 1983; Ninkovich and Shackleton, 1975; Shackleton et al., 1990); c) SP4 δ^{18}O record, with the respective sampling laminae. On top of the diagram, the Marine Isotope Stages are indicated. Dense-dashed lines connecting b) and c) represent the palaeoclimatic correlation of SP4 with global records (see text for interpretation).

2004). The following warming occurred at 320-310ka BP (lamina 25). This stage, although it should be expected to meet with MIS 9e due to sequence, probably corresponds to the milder MIS 9c with warm and arid climate. This assumption is based on the fact that lamina 25 does not show the acute transition of climatic conditions that characterizes MIS 9e and also on the age position in SP4 stratigraphy. The absence of MIS 9e intense warming in SP4 is attributed to subsampling resolution, as it was quite short in duration and therefore may have not been isolated in laminae distinction. SP4 isotopic record ends with a cooler (enriched δ^{18}O) and rather humid (depleted δ^{13}C) stage, which corresponds well to the transition between MIS 9c and 9b (lamina 26, ca. 300ka BP).

4. Conclusions-Results

The isotopic record of SP4 stalactite from Agios Georgios cave, Kilkis, N. Greece, has indicated several climatic transitions in the region. These alterations correlate well with marine records from around the world as well as with terrestrial palaeoclimatic data from Greece. According to these variations, SP4 record mirrors two cold and dry stages (MIS 14 and 10) and two warm and wet periods (MIS 11 and MIS 13). Among the above, several stadials and interstadials have been isotopically fingerprinted, showing that global climatic changes, which influenced mostly the northern hemisphere, have also influenced the area of N. Greece. The absence of two distinct climatic events in SP4 record, the severe cold MIS 12 and the intense warm MIS 9e, is attributed to different factors. The permafrost soil coverage during MIS 12 probably caused growth cease of the speleothems in Agios Georgios cave, while the short duration of MIS 9e may have caused slipping during subsampling. In any case, although higher resolution of subsampling and denser datings would offer the opportunity to distinguish shorter and more detailed climatic transitions, the study of SP4 isotopic record encourages the application of palaeoclimatic interpretations in speleothems around Greece.

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EVALUATING THE INFLUENCE OF GREEK GEOPARKS TO THE LOCAL COMMUNITIES

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Abstract

The European geoparks are new and effective instruments for the interpretation, protection and promotion of geological heritage aiming to a sustainable local development. Since 2000 the two Greek geoparks, the Lesvos Petrified Forest and the Psiloritis Natural Park have developed a great number of activities. Because of their differences, these two geoparks can be used as good examples to evaluate contribution of geoparks to local economy. In Psiloritis geopark operation is supported by the AKOMM –Psiloritis SA Development Company and significant funds have been raised for geo-protection and geo-tourism through European projects, a certain operational budget from local funds has been established and a new action plan has been developed under the forthcoming Leader+ project. In Lesvos Petrified Forest geopark operation is supported by the Natural History Museum of the Lesvos Petrified Forest which is responsible for research activities, protection and promotion of this protected natural monument. Main activities were funded by the North Aegean Regional Operational Framework as well as by INTERREG and LEADER initiatives to promote geoconservation, geotourism and local development. Furthermore, in both areas exchange of know how and best practices assisted local stakeholders and staff of local authorities to develop skills on the nature protection and promotion of geoheritage. Additionally, a great number of publications, environmental education programs and promotional activities contributed to the information and education of local communities, as well as of visitors on their geological and natural heritage. All the above mentioned activities have significant impact in local economy through the development of geotourism.

Key words: geoparks, Psiloritis Natural Park, Lesvos Petrified forest, geoconservation, local development, geoheritage.

1. Introduction

Geoparks are territories aiming to conserve and promote their significant geodiversity and natural heritage for the benefit of science and local communities. The term was first introduced in the early 90' by UNESCO presenting an initiative, called UNESCO *Geoparks* to enhance the value of the nationally important geological sites, but it was established in 2000 with the creation of the European Geoparks Network with the support of the European Union. The International Union of Geological Sciences - IUGS in collaboration with UNESCO launched in 1995 a project named *Geosites* to compile a global list of the world's most important geological sites (Murray 2004). The latter has recently resulted to a list of the most important geological sites of south-eastern Europe (Theodosiou-Drandaki et al. 2004). This project failed to gain continuous support and it was abandoned by UNESCO and IUGS in 2004.

Geodiversity on the other hand was more recently induced in the international literature in an effort to describe, in the same way that biodiversity does, the wide natural range (diversity) of geologic (rocks minerals, fossils), geomorphologic (landform, processes) and soil features (Murray 2004), including their assemblages, relationships, properties, interrelations and systems. However, geological and geomorphological conservation efforts in Europe, Australia and other places worldwide started a century ago focusing on either landforms and geological formations or structures (Sturm 1994; Murray 2004).

Till recently Lesvos Petrified forest and Psiloritis Natural Park were the only geoparks in Greece, participating in the European and Global UNESCO's Geoparks Networks. The European Geoparks Network (EGN) was established in 2000 by four territories, Lesvos Petrified Forest, Reserve Geologique de Haute Provence in France, Vulkaneifel in Germany and Maestrazgo in Spain, aiming to promote and conserve their geological heritage, educate people and support local development activities (Zouros & Martini 2003). The initiative was under the umbrella of UNESCO, which later in 2004 adapted and used EGN as model to create other continental networks globally, establishing the Global Network of Geoparks (GGN). After the Madonie declaration in 2004 EGN became the only mechanism for the integration of new territories from Europe in GGN (Fassoulas et al 2007). In 2009, the Helmos – Vouraikos National Park became member of the EGN and GGN which today comprise 34 and 63 territories respectively.

A European Geopark has to manage both abiotic and living nature, including cultural heritage, in order to achieve high standards of conservation, promotion and finally true economic development (Zouros & Martini 2003). According to the European Geoparks Network convention (charta), it must present a significant geological heritage and cover a substantial area where an economic strategy, funded by EU programmes, occurs. It must comprise of geological sites of special value and sites with special ecologic, archaeologic, historic and cultural value. The geopark has to enforce local population to re-evaluate their heritage and encourage them to play an active role in economic revitalisation of their territories through certain actions that promote geotourism, education and other nature-friendly activities. The structure of the European Geoparks Network is relatively simple and comprises an Advisory Committee (11 members, including representatives of UNESCO, IUGS and IUCN) and a Coordination Committee (comprising of two representatives from each member). Decisions concerning the network are only taken by the Coordination Committee. As part of the Coordination Committee, there is an elected EGN Coordinator and Vice Coordinator to represent the whole Network. Membership in EGN has to fulfill certain quality criteria and is evaluated every 4 years through a strict and open process curried out by independent reviers selected by the EGN and UNESCO – GGN (UNESCO 2006).

Despite other international associations, EGN is a very active network of territories which collaborate together, exchange experiences and good practices in many scientific and applied topics, implement researches and studies for the conservation and promotion of nature in general and develop activities to support local economy in a sustainable manner. Networking is thus the strongest tool to transfer knowledge and experience between participating territories, from those having long tradition on nature protection and/or successful examples on sustainable ecomonic growth and strong local participation in territorial management to other less developed or weaker in protection of natural heritage.

To examine the true influence of European Geoparks in local communities and especially the benefits for the conservation of nature and sustainable local economy, we use two examples from the operating geoparks in Greece. The Lesvos Petrified Forest and the Psiloritis Natural Park are both hosting high quality geosites but two quite different territories; the first being a coastal area while the second is representing a mountainous area. Both lying far away from big domestic areas, but close to already developed tourist areas have the potential to develop sustainable tourism and associated

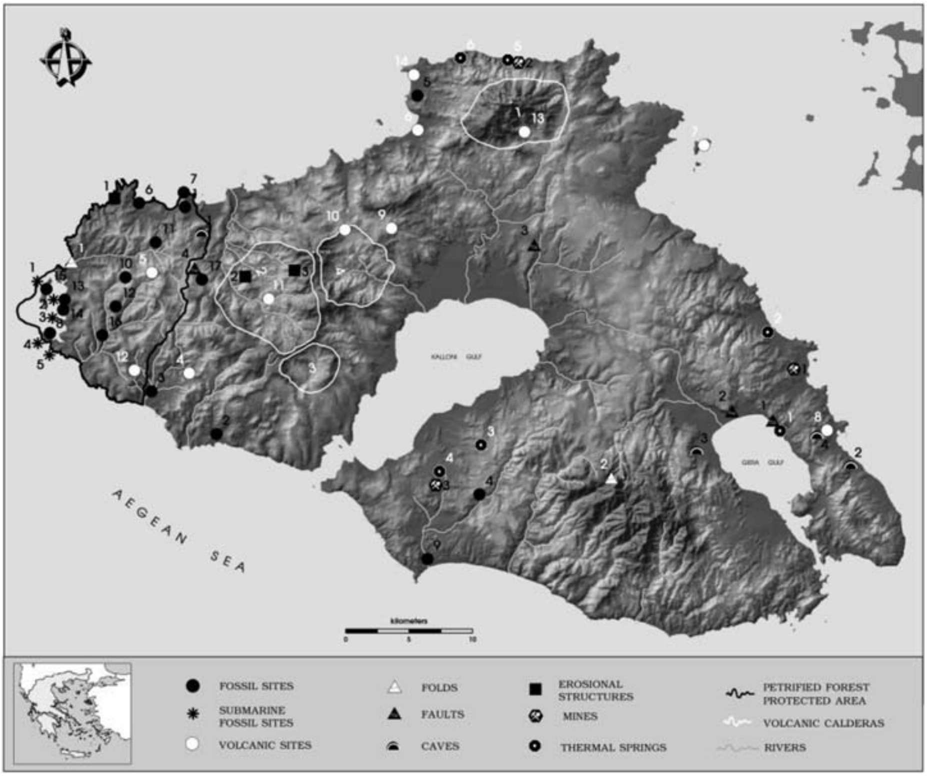

Fig. 1: Lesvos geopark and the main geosites.

economic activities. Hereby we examine the influence of certain activities and initiatives, developed so far in these geoparks, especially under the topics of scientific and educational progress, conservation of geological heritage and local, economic development.

2. Study Areas

2.1 Lesvos Petrified Forest

Lesvos Island, located in the NE of the Aegean Sea, is dominated by Neogene volcanic rocks, forming characteristic landforms and landscapes. Related to the volcanic activity is the formation of the well-known "Petrified Forest of Lesvos" which has been declared as a protected natural monument (Fig. 1). The protected area lies within the Municipality of Eresos – Antissa which comprises by seven small towns and 13 settlements has an area of 291 km^2 and a population of 5.530 inhabitants. In the Municipality there are about 2500 beds in the hotels and in the rooms to let. Aiming at protecting and efficiently managing the Petrified Forest, the Natural History Museum of the Lesvos Petrified Forest was founded in 1994. It is a non-profit, public (?) organisation and defines the management structure of the Lesvos Petrified Forest Geopark. Its seven-member board encompasses representatives of the central government, the local authorities, universities and the local community. Its scientific, technical and administrative staff includes 8 permanent and 25 temporary employees. The Lesvos Petrified Forest Geopark comprises a core zone (15,000 hectares of the Petrified Forest protected area) and a broad buffer zone (more than 20,000 hectares of the central volcanic terrains). The Petrified Forest

Fig. 2: Guided tour at the Lesvos Petrified Forest Geopark. More than 90.000 visitors every year visit the Museum and the open air parks.

protected area is included in the Natura 2000 network, basically due to the presence of the Petrified Forest, the high endemism of flora and fauna and the variety of natural habitats.

A strategic plan for the sustainable development of the area has been carried out by the Lesvos Geopark in order to link the protection and promotion of geosites with the development of geotourism. This plan takes into consideration the results of the research and excavations in the Petrified Forest area, the presence of important geosites (i.e. volcanic structures, domes, craters, and thermal springs) and biological reserves, the existence of spot interventions and infrastructures as well as the local economic activities.

A broad range of activities combine the main components for the operation of Lesvos Geopark, including scientific research, the creation of the geosite inventory and map, the protection, interpretation and promotion of geosites, the conservation of fossils, the creation of visiting parks, the establishment of a network of walking trails linking geosites to ecotourism infrastructures, the development of environmental education programmes on geosites, the organisation of scientific and cultural events, and the promotion of monumental geosites.

2.2 Psiloritis Natural Park

Psiloritis Natural Park is located in the island of Crete (Fig. 3) and since 2001 is member of the European and Global Geopark Networks. It has an area of 1159 Km^2, with 157 settlements and towns and a population of about 42234 inhabitants (population density 36.4 inh/Km^2). The Park comprises the Psiloritis mountains and its northern coastal zone, and combines the unique natural environment, the long history, the individual customs and the outstanding civilization with the fascinating geology (Fassoulas 2004). Psiloritis Mountain is not only the highest mountain in the island (2456 m) but also a place of high environmental variety and diversity. Intense geological processes have sculptured for millions of years a unique and complicated bedrock over which life migrated and developed, adapting its features and behaviours to the changes of surface and landscape. Life had to adapt to the geological changes and a high endemism was developed due to isolation of certain species or adaptation of others to the new environmental conditions. Most of the mountainous area is thus included in the Natura 2000 network, basically due to the high endemism of flora and fauna and the variety of natural habitats that have to be conserved.

Within the territory of the Geopark, the whole nappe pile of Crete and the majority of the rock types of the island are presented in excellent outcrops and sections (Fassoulas 2004). In the geopark, all kind of geological structures are visible from small to regional scale. Big faults with excellent and imposing fault

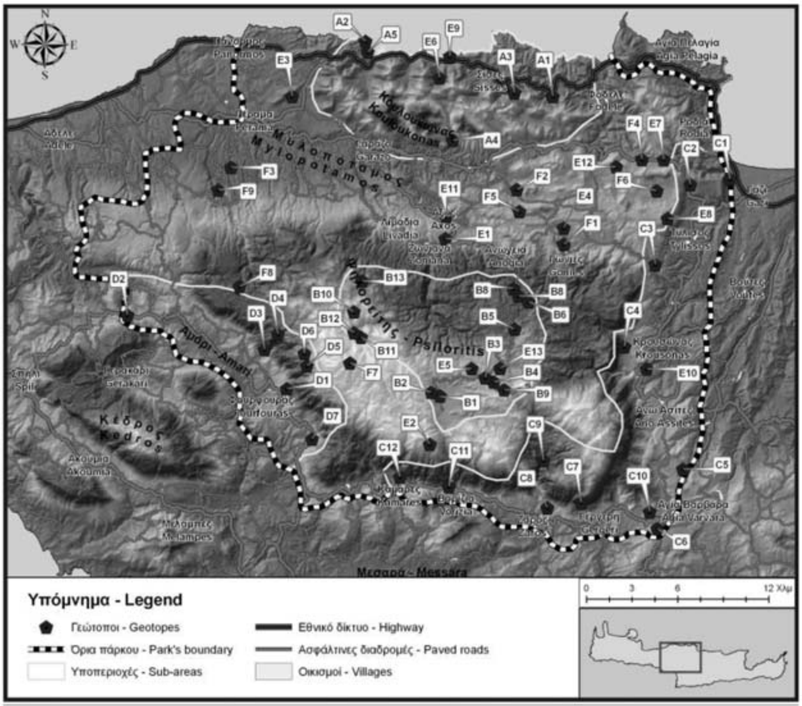

Fig. 3: The area of Psiloritis Natural Park and the most important geosites.

surfaces, fossil sites, caves, impressive gorges and mountainous plateaus that host many endemic species of the island, unique fold associations and geomorphologic structures are feeding for thousands of years the culture, tradition and customs of the inhabitants (Fassoulas 2004). Of the most outstanding attractions are the two open to public caves, Sfentoni and Melidoni, with facilities to host visitors.

The Psiloritis Natural Park has no official designation and is only supported by local authorities and community. It is managed by the Geopark's Management Committee which has been given special authorities by the council of AKOMM Psiloritis Local Development S.A., the company responsible for the local development of the area. Representatives from regional and local authorities, the scientific institutions and NGOs constitute the Management committee, whereas the Natural History Museum of Crete is the scientific coordinator of the Park. A Strategic plan for the development of geotourism and other sustainable development activities has been developed and has been included in the local LEADER Action Plan, implemented hereupon through different, European and National, finance instruments. With the creation of the Management committee and the new authorities that were privileged by the Local Authorities, a new 5-years Management Plan is under preparation now.

The performance of Psiloritis Geopark in geoconservation is weak and is mainly caused by the lack of official recognition and the restricted authorities of the Management committee in these topics. However, the inventory, mapping and evaluation of the geosites of the park was the first step for the conservation of the geological heritage (Fassoulas et al. 2007). All municipalities of the park are obliged to protect and conserve the geological monuments of their territories, whereas recently, in collaboration with the Regional authorities the geosites of the park are included in all Special Zoning Plans of the Municipalities implemented under the new Layout Planning Law of the country. Furthermore, instructions and announcements for the maintenance and conservation of geodiversity appear in many publications and panels all over the area.

3. Countable Results

Participation of the two geoparks in the EGN offers many opportunities for international collaboration, promotion and funding through European and national funds and thus EGN had a significant contribution to geopark's operation and activities. Both geoparks developed many initiatives, projects and actions in order to achieve the geopark's goals. The results of these activities over a decade are now quite recognisable and can be evaluated for their influence to local development. The main fields of activities can be distinguished in scientific and educational activities which help in raising public awareness for geoconcervation and geotourism and promotional activities that contribute to the territorial sustainable development.

Some of these results are countable and tangible and refer to infrastructure development, promotional activities, educational activities, improvement of financial parameters, raised funds, job creation etc. Other activities however, have resulted in improvement of knowledge, adaptation of policies for the management and conservation of nature, support of local production and activities that are less recognisable and can be regarded as intangible.

3.1 Lesvos Petrified Forest

The creation of Lesvos Geopark is based legally on the establishment of the Lesvos Petrified Forest as a protected natural monument by the Presidential Decree 433/1985. An early recognition and identification of the geological heritage and the specific geotopes of the park (Zouros 2005). Further scientific study resulted in the mapping and identification of 80 individual geosites that were further analysed and evaluated using modern methodologies and practices (Zouros 2005, 2007, Zouros and Valiakos2007). More than 60 scientific articles in journals and scientific meetings have been published for the geological heritage of the area, together with several books, field guides and popular publications. A series of national and international scientific congresses have been organised by the geopark in Lesvos between 2000 and 2009 for the promotion and management of geological heritage, and proceedings and abstract volumes were also published. The geopark is supporting in many ways four Phd thesis (Thomaidou, Valiakos, Gumus and Mourouzidou) and five master thesis on the geological structure and geoheritage management in Lesvos (Lambaki 2007, Gribilakos 2007, Alevra 2009, Mantzouka 2009).

Educational activities lie at the core of the Lesvos Geopark's operation. Environmental education programmes organized for elementary and high school students cover a broad range of activities aiming at raising the awareness of the local inhabitants diffusing of geoscientific knowledge at large on various issues such us: understanding of natural processes, geoforms and landscapes, the importance of the environmental protection and management, the conservation of the Earth's heritage and natural hazards. Thematic exhibitions accompanied by educational programmes introduce young students to the "secrets" of geo-scientific research and geoconservation through a variety of activities accompanied by educational tools and publications. Further educational projects were recently developed in collaboration with the Evergetoulas Environmental Education Center. Several field trips were organised almost every spring for the students of University of the Aegean as well as for graduate and post graduate University courses from Greece and abroad. Many lectures and presentations are given to University classes or tourist groups.

In 2000 the Vocational Training Centre of the Natural History Museum of the Lesvos Petrified Forest was founded with the aim of training young unemployed people in the techniques of conservation, excavation and preservation of fossils, as well as in methods of dealing with visitors and promoting Geoparks. Till now five courses were delivered and 108 young people living in the area of the Lesvos Petrified Forest Geopark, were trained. Thirty four of these trainees are, or were employed in the Lesvos Petrified Forest Geopark.

The International Intensive Course on Geoparks is co organized annually since 2007 having a different subject each year. The organization is curried out by the Lesvos geopark and the University of the Aegean in close cooperation with the Global Geoparks Network, the European Geoparks Network. The course is open to 30 participants, geopark staff members with a degree in Geosciences, to PhD and Master Students working on geopark, geotourism, geosite, geomorphosite and landscape topics, as well as to Geoscientists having a special interest on the topic.

Furthermore, a series of scientific and cultural events is organized and hosted every year in the Petrified Forest to attract the attention of the broader public to this unique natural monument. The range of events includes scientific lectures, slide projections, documentary films, natural science oriented temporary exhibitions, book presentations, painting – sculpture - photo and video-art exhibitions, music and dance events, theatrical plays and happenings. Through these events the Geopark draws large audiences of people who may have low or no interest in natural heritage, thus creating new opportunities for sensitisation.

An important component of the Lesvos geopark management plan is the support of the local economy. The geopark has created links with local tourist enterprises, restaurants and small hotels in order to provide the necessary infrastructure to meet the needs of the increasing number of park visitors. The majority of visits to the geopark occur during the summer period (July – September), but the aim is to extend the visiting period to the spring and autumn seasons. In the village of Sigri, the number of "Bed and Breakfast" accommodations has doubled over the last few years in order to meet the increasing demand. More importantly, visitors have increased the duration of their visit to the geopark area. As a result the majority of the new enterprises established in western Lesvos are connected with the activities of the Lesvos geopark. The geopark also supports the making of local handicrafts such as the production of fossil casts and souvenirs by local enterprises. These items are on sale in the Museum shop along with a variety of other locally made products. Lesvos has a long tradition in pottery and wood carving and the geopark promotes these products to its visitors.

The Lesvos geopark also collaborates closely with women's agrotouristic cooperatives and local organic food producers to offer its visitors the opportunity to taste and buy local food products (pasta, organic olive oil, wine, ouzo, liquors, traditional sweets and marmalades etc). The catering for all geopark events (conferences, meetings etc.) is supplied by the women's cooperatives using the local traditional recipes. Their products are also sold in the Museum snack-bar. Every summer the geopark organizes an Agrotouristic festival (attended by 28.000 visitors in 2007), which promotes quality local products, food and drinks prepared by the women's cooperatives. The Agrotouristic festival includes a variety of presentations, events and happenings as well as an exhibition fair of local products.

Lesvos geopark through his activities have become an important factor of the economic, educational and cultural development of the protected area. The geopark contributes significantly to territorial development by directly and indirectly creating new jobs. Since 1995 people have been finding employment within its activities, such as the 25 seasonal positions (8 months per year) and 8 permanent positions. This has to be added to the 5 existing positions in the Petrified Forest Park. But what is even more important for the employment in the area is the number of other employment oppor-

Fig. 4: Some of the activities of Psiloritis geopark. a) Educational field trips on biodiversityy, b) Participation in the First International Geopark's fair in Germany, c) Various publications and promotional material, and d) Information panels.

tunities which have been created in tourist enterprises, small hotels, guest houses, restaurants and other activities connected with the increase of tourist flow in the geopark area. Several other local artisans, such as makers of handicrafts and ceramic fossil casts, carpenters, and blacksmiths, are permanent collaborators with the geopark.

3.2 Psiloritis Natural Park

The establishment of Psiloritis geopark was based on an early inventory and identification of the geological heritage and the specific geosites (geotopes) of the Park (Fassoulas 2004). Further scientific study resulted in the mapping and identification of 64 individual geosites that were further analysed and evaluated using modern methodologies and practices (Fassoulas & Skoula 2006, Mouriki & Fassoulas 2009). More than 15 scientific articles and announcements in scientific meetings have been published for the geological heritage of the area, together with several popular publications. An international scientific congress was held by the geopark in Anogia in 2004 for the promotion and management of geological heritage, and an abstract volume was also published. The park has supported in many ways one Phd thesis on the bats of Psiloritis (Georgiakakis 2009) and two master theses on Geopark's Risk Analysis (Staridas 2006) and Sirenian fossils (Svana 2007, Illiopoulos et al. 2009).

Educational activities (Fig. 4) were mainly undertaken by the Natural History Museum of the University of Crete in collaboration with local schools. Two educational projects have been developed at the early stages focused on the karstic features of the mountains and the endemism of flora and fauna, where later, two other projects resulted in the preparation of two Educational Suitcases that were given to all schools of the geopark. The projects were dealing with water cycle and landscape development and also with the biodiversity of Psiloritis (Fassoulas et al. 2006). Further projects were more recently developed in collaboration with the Anogia Environmental Education Center (AEEC). Several field trips are organised almost every summer for children and families in specific areas of the park under the guidance of the Natural History Museum or the AEEC. Finally, many popular or scientific talks were given to University classes, target groups, or tourist groups (Skoula & Fassoulas 2006).

Very often foreign Universities visit the area to study the bio- and geodiversity of Psiloritis implementing in collaboration with the geopark field trips, mapping courses and sampling. Also, Psiloritis is an important area for local Universities and schools and many scientific articles have been published on several geological, geographical and biological disciplines. An ongoing demand for information on the sustainable development and eco-touristic activities in the broad Psiloritis area is observed recently. Only last year one University and one college classes were introduced and guided to the geotouristic activities of the park and two more summer schools on sustainable development and agrotourism were also hosted in the territory.

The economic contribution of the Psiloritis geopark is visible in several occasions. Certain activities were undertaken and a basic infrastructure has been established for visitors. One of the activities of AKOMM to promote local gastronomy based on traditional recipes and local products is the project “Land of Psiloritis”. It is curried out in cooperation with local stakeholders (taverns, accommodation places, agrotouristic enterprises etc.) who formed a non-profit organisation that uses the logo of geopark as the brand name for a network of cooperating enterprises. Members have to fulfil certain quality standards that have been set in collaboration with the geopark and are evaluated every year by a common group of specialists.

During the last years the geopark has participated in two international tourism fairs promoting the area and the local products, it has developed local workshops and events to promote culture and local production. The geopark has organised many public events for the promotion of local products and artists, for the exchange of knowhow and improve the level of information for the geopark. The most important is the big public exhibition organised in Heraklion and Rethimnon in 2008 to promote local artistic craft making by earth materials which met great success, as more than 20000 people attended the exhibition. In the exhibition participated also artists from other geoparks.

The contribution of the geopark in to the tourist product of the area can not be easily evaluated as there is lack in central accomodation places. The two open caves of the park that are managed by other stakeholders, ie. the Sfentoni Cave in Zoniana and the Melidoni cave accept around 30.000 visitors per year each with an increasing trend the last four years. The caves are in close collaboration with the Geopark for the improvement of their equipment and operation, while 4 employees of the caves have participated in exchange projects with other geoparks on cave management. Generally, an increased demand for information from many countries globally, placed as requests at the Park’s webpage, is recorded.

The Park has participated in two LEADER and one INTERREG II projects, whereas a special regional plan for geotourism development was implemented during the LEADER II initiative securing funds for many individual activities. The last three years about 500.000 € were used for the geopark activities, like the three local geotouristic investments, two local information centers, four geological and natural trails, and more than one hundred information panels that were placed in all important geosites and many other natural or cultural features of the park. For the implementation of these projects five new staff, out of the existing of AKOMM and Natural History Museum of Crete were hired.

4. Conclusions-Results

It is apparent that geoparks, although not yet officially recognised as in other European countries, are the only local structures in Greece to promote and conserve geological heritage, having set their geodiversity as an important economic and scientific value. Combining all aspects of natural and cultural environment geoparks have created a strong economic product which can assist local communities to improve their economic level and have thus the ability to protect and conserve their earth heritage. Many of their activities can be easily assessed in economic terms, presenting the influence the geoparks have in the establishment of sustainable development activities, creation of a geotouristic product, support of local products, raising funds, and creation of new jobs and opportunities. The most important however, is the increase of knowledge and sensitization both for inhabitants and visitors, on their geological and natural heritage.

More specific, geoparks address the strong need for effective management of important geosites and sustainable development of rural areas through the development of geotourism which enhances the value of the Earth heritage, its landscapes and geological formations, key witnesses to the history of life. A broad range of activities combine the main components for the operation of the Lesvos and Psiloritis geoparks, including scientific research, the creation of the geosite inventory, the protection, interpretation and promotion of geosites, the geoconservation, the establishment of a network of walking trails linking geosites to ecotourism infrastructures, the development of environmental education programmes on geosites, the organisation of scientific and cultural events, and the support of local products through the collaboration with local stakeholders.

Geoparks especially act for the benefit of local communities through geotourism development and educational activities in rural areas. The results of their operation prove the potential of all geoparks across Europe to be powerful, new tools for holistic nature conservation and sustainable rural development through geotourism.

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GEOCONSERVATION LEGAL STATUS AND GEOPARK ESTABLISHMENT IN GREECE

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Abstract

Under Greek (and EU) law, geo-conservation (geological conservation) is an issue not being dealt with in an organized and systematic way, in contrast with bio-conservation (nature conservation). Therefore geo-conservation approaches, as the 'geopark' concept, are not recognized under Greek legislation and elements of geological heritage can only be granted protection in isolation and in limited extension, mainly as playing a role to the biotic environment. However, to date, geoparks have been established and recognized by the European Geoparks Network (E.G.N.), in Greece. Those geoparks are protected under the Forestry Legislation, the Archeological Legislation or/and the Environmental Legislation. In view of the plans of the Institute of Geology and Mineral Exploration (I.G.M.E.) to expanding the Geoparks Network in Greece, a thorough examination of the available legal tools to protecting elements of geological importance in geoparks is required, with a view to proposing a legal protection regime that would realistically deal with the conservation of geosites and the establishment of geoparks focusing on overlapping with nature conservation areas, namely "Natura 2000 sites". In addition, building on the experience of the administration and management of national parks and Natura 2000 sites, the available management options will be examined with a view to providing the optimum management alternatives.

Key words: *geopark, geoconservation, geotourism, legislation, Natura 2000, management, administration, Greece.*

1. Introduction

Geosites are (1) the geological and geomorphological sites that mark important phases of the Earth history and environment and have been created by various natural, physical, chemical, biological, geological and geomorphological processes which left their mark on the earth's surface in the past and of an age from some billion or million years ago (volcanoes, caves, sinkholes, dolines, stromatolites, rocks, hot springs, faults and important sites of mineral or fossil interest) and (2) important metallurgical, mineral and extractive centers or remnants that combine geological, cultural and archeological interest.

Geoparks are areas in need of protection whose principal aim is geoconservation, research, education, training and contribution to the socioeconomic development of the wider region by the development of sustainable forms of tourism, namely geotourism, providing major direct and indirect economic benefits to local, regional or national economy (Frey, 2003, UNESCO, 2006a, Eder, 1999, Brachou, 1996) through the inclusion, protection and management of a significant number of geosites representative of the area and of its geological history.

The purpose of this article is firstly to present the available legal tools of protection, conservation and management of geoparks that are available at International, European and National level. Next, the available national legislative framework, namely the environmental legislation, will be evaluated in terms of its compatibility to the establishment of geoparks and the case of overlap of potential geoparks with existing protected areas will be examined. Particular emphasis will be given to the management alternatives in case of an operation of a management authority of an already established protected area where the geopark is to be established where protection and sustainable management can only be achieved through strong local involvement and public authorities, local communities and private interests acting together (Eder, 1999), protected areas without a management authority, protected areas whose Special Environmental Study is being developed, and geoparks within Natura 2000 sites that do not have a management authority. As a conclusion, proposals will be presented to improve the legal status of geoparks at an international and national level.

2. International and European context

2.1 The UNESCO Convention Concerning the Protection of the WorldCultural and Natural Heritage

The only international "hard" law text that provides explicitly for the protection, conservation and management of elements of geological and physiographical/ geomorphological heritage and has been ratified by Greece is the UNESCO Convention Concerning the Protection of the World Cultural and Natural Heritage of 1972 (the Convention) (L.1126/1981 (HOG. A 32). Under article 2 of the Convention as world Natural heritage is defined "geological and physiographical formations **[…] of outstanding universal value from the point of view of science or conservation".** The Convention provides a series of appropriate measures, as the adoption of a general policy so that functionality is given to Natural heritage within social life, the establishment of management authorities, the development of scientific and technical studies especially in relation to dealing with risks that threaten cultural and Natural heritage, to take appropriate measures (legal, technical, administrative et.c.) for its designation, the protection and management and the use of such places for the encouragement of education in the field of conservation, development and encouragement of scientific research (article 5). In addition, each State Party will submit "in so far as possible" an inventory of property suitable to be inscribed in the List (article 11). If the property meets a number of criteria, then it is inscribed in the List as "**Monument of World Heritage**".

The protection of geosites under the above legislation is exceptional, and so since, the Convention concerns places that "**outstanding** Natural phenomena or areas of **outstanding** Natural beauty and aesthetic" and that must be "**exceptional** examples of major phases of the history of the earth, the archive of life, important in general geological processes for the development of geoformations or important geomorphical or physiographical characteristics". In addition, the almost 35 years of operation of the Convention system, very few places have been included primarily due to their geological and geomorphological physiographical interest. However, many places that have been included due to their biological interest present remarkable geological and elements. Anyway, the number of such places falls short of those with a cultural value. IUCN proposes the encouragement of geoscientists to participate in the relevant procedures – where architects and Natural scientists dominate, the publication of a relevant Guide focused on geological/ physiographical criteria and the encouragement of other initiatives, and in particular the Global Geoparks Network (Dingwall, et. al. 2005).

2.2 The Barcelona Convention

Geosites that lie in the seabed, or coastal areas of the Mediterranean Sea can also be protected by the 1995 Barcelona Protocol concerning Specially Protected Areas and Biological Diversity in the Mediterranean of the 1976 Barcelona Convention on the Protection of the Mediterranean Sea (L. 1634/86 HOG 104 A). Under article 4d, in addition to sites of biological importance, the Protocol provides for "**sites of particular importance because of their scientific, aesthetic, cultural or educational interest**." The Protocol stipulates that the Parties develop guidelines for establishing and managing protected areas and lists a certain number of appropriate measures, which the Parties must adopt in order to ensure the identified areas are protected. These measures include: prohibiting the discharge or unloading of waste, regulating shipping operations, et.c. The Petrified Forest of Lesvos, one of the two recognized Greek Geoparks, is listed as a Specially Protected Area of the Protocol.

2.3 The Global Geoparks Network of UNESCO

The Geoparks Initiative of UNESCO is based philosophically on the Declaration of *Digne-les-Bains* of 1991 "for the rights of the Memory of Earth" that was adopted by the 1st International Symposium for the Conservation of our Geological Heritage. (Digne, France 1991) Whilst such geoparks are not included in an adopted programme of UNESCO, they are in line with the objectives of the Bioshere Reserves, of the Programme "Man and the Biosphere" of UNESCO. Geoparks are treated by UNESCO as complementary to the World Heritage List in order for an appropriate mechanism to exist in such a way for the recognition of internationally important places that are recognized in national and international geological charts.

The directions for geoparks highlight their role and the objectives of their designation and management. Six principles have been adopted for the recognition of geoparks in relation to their volume, their composition, the socio-economic objectives, the conservation objectives, the education and research objectives, the legal status and their contribution to the international network. In particular in relation to the legal status, UNESCO leaves entirely the choice of appropriate protection means depending on local traditions and choices, but notes that there must be a minimum protection of the elements of geological interest, a management authority and the absence of trading of minerals generally geological elements except exceptional and justified cases. Their success is guaranteed through strong local involvement (Eder, 1999).

The role and the aim of the protection of geosites that is materialized through the geoparks initiative is different than that of the Convention Concerning the Protection of the World Cultural and Natural Heritage. The reason is that taking into account that it is practically impossible to include more than 150 places of geological and geomorphological interest in the World Heritage List the system of the Convention is inadequate to represent the totality of the internationally important places of geological interest (Dingwall et. al, 2005). The initiative is developing at a fast pace in different areas of the earth. Despite the fact that the Initiative recognizes the value of legal protection of the area, does not consider its previous designation, or its proclamation as "protected area", the prohibition of particular activities or the official establishment of a management authority as a precondition for recognition of a geopark (UNESCO, 2008).

2.4 The European Geoparks Network

The European Geoparks Network was established in 2000 and aims at the protection of geodiversity, the promotion of geological heritage to the public and the support of sustainable development in the areas of the geoparks in particular through the development of geotourism in Europe. (Zouros, 2004) The Network has brought close areas from all over Europe that share those objectives and are working together to achieve them. In 2001 the Network signed an official agreement with the Directorate of Earth Sciences of UNESCO with which UNESCO expressed its support. (UNESCO, 2006b) With another agreement with UNESCO in 2004 (the declaration of *Madonie*) the Network assumed responsibility for the management of issues that concern the inclusion of areas in the International Geoparks Network in Europe. (Madonie, Italy, 2004) In accordance with the Charter of the European Geoparks Network "The sites […] must benefit from protection and management measures. No loss or destruction, directly or via sale, of the geological values of a European Geopark may be tolerated. The European Geopark must be managed by a clearly defined structure able to enforce protection, enhancement and sustainable development policies within its territory." (European Geoparks Network Charter, 2000) In addition, in the dossier that the applicants must provide for inclusion in the network are "C.3 Policies for the protection, enhancement and economic development of the geological heritage present in the territory. Existing policies and those under preparation, existing and future actions" and "D.2 The provisions for the protection of the territory" (www.europeangeoparks.org).

The legal protection of the area of the European Geopark or /and the presence of a management authority with decisive competences is simply one of the dimensions to be evaluated for inclusion of the particular Geopark in the Network. Therefore, geoparks of the network could be both areas that are under a strict protection regime and areas whose protection regime is being designed, or even areas without established or under establishment legal protection framework. In any case, however, in comparison with the prerequisites for inclusion in the Global Geoparks Network of UNESCO, the specifications of inclusion in the European Geoparks Network explicitly stress, *inter alia*, the need of existence of a local, regional or national legal framework, the lack of which, however, is not necessarily a hindrance to the inclusion of an geopark in the network.

3. National Framework

3.1 Protected areas under L. 1650/86

Law 1650/86 (HOG A 160) "for the protection of the environment" is the principal legal tool for nature protection and conservation. It provides for the procedures and the means of categorization and designation of protected areas. In accordance with article 18 of L. 1650/86, nature and landscape are protected and are conserved so that Natural processes, the Natural resources' production, balance and evolution of ecosystems in addition to their uniqueness, diversity and individuality are maintained. Both land and marine areas or particular elements or group of elements of nature or landscape can be objects of protection and conservation due to their ecological, geomorphological, biological, scientific or aesthetic value. It should be noted that the law does not explicitly provide for designation of areas with geological, mineral, extractive or metalourgical interest, but only areas with important geomorphological elements.

Out of the categories of designation provided under article 19 of L. 1650/86 (nature reserves, nature protection areas, national parks, protected Natural formations, protected landscapes and landscape elements, and eco-development areas) only national parks and protected Natural formations include a geoconservation dimension, as national parks may be designated if a considerable number of geomorphological elements is present and in the indicative list of potential protected Natural formations are listed including formations of interest for geoconservation as gorges, caves, rocks, petrified forests, paleontological findings, geomophological formations. If the above are of a monumental character they are designated as "conservable monuments of nature".

Under article 21 of L. 1650/1986 the designation of protected areas takes places through the issue of a Presidential Decree following a Special Environmental Study that will document the elements under protection and the purpose of the proposed protection measures. It should be noted that a special legal tool (a Ministerial Decision) is needed to determine the specifications for the elaboration of studies for geoparks either by expert offices or agencies. The above Presidential Decree provides for the necessary terms, prohibitions, and limitations to land use, to construction and the establishment and performance of operations and works. With the same Presidential Decree a Management Authority may be established under the terms and conditions of article 15 of L. 2742/1999 "Planning and Sustainable Development and other provisions" (HOG A'207) that is a Legal Person of Private Law with a series of scientific, coordinating and consultative competences relevant to the management of the protected area.

3.2 Geo-conservation interest in caves and constructions

In the special case that in the potential geopark there is mineral, extractive or metallurgical interest in **caves**, Natural or artificial, the protection status is described by the combined application of article 2 aa of L. 3028/2002 "on the protection of Antiquities and Cultural Heritage in general" (HOG A 153) and M.D. 34593/1108 (Culture) of 23.6/8.7.83 «Protection of Caves» (HOG B` 398). In particular, the caves, either Natural or artificial, are considered Monuments (no other designation is required) and every activity in them is forbidden. Competent authority for the protection, research, excavation and study of caves that are interesting from a Natural archeological view and the guarding, presentation and exhibition of any kind of findings that come from caves is a competence and duty of the State and especially the Ministry of Culture through its special unit i.e. the Paleoanthropology - Speleology Units. However, any activity (intervention, exploration, exploitation, utilization) that is relevant to caves is forbidden, except if there is a prior approval of the above Units. This protection system, even if it was not established for the protection of caves (natural or artificial) from the point of view of their geological value, is compatible with the designation of a geopark that includes caves.

In relation to **constructions** that have extractive, metallurgical or historical interest, both from the point of view of industrial archeology and from the point of view of charting the continuity of the art of extraction (i.e. ancient laundries, air shafts, industrial buildings et.c.), their protection is guaranteed through their declaration as archeological sites, historical monuments, conservable monuments et.c. in accordance with L. 3028/2002 "for the protection of Antiquities and Cultural Heritage in general" (HOG A 153).

3.3 Protection of geoparks through town and country planning law tools

In accordance with article 7 of L. 2742/1999 "Planning and Sustainable Development and other provisions" (HOG A΄ 207) is established the possibility of issuing Special and Sustainable Development Plans that are a series of texts and diagrams with which the guidelines of the General Sustainable Development Plan that deal with the development and organization of the national space are specified, *inter alia*, on issues of special planning of some sectors or branches of production activities of national interest. In the General Sustainable Development Plan of 2009 (HOG A 128) it is mentioned that the basic aspects of tourism, that have been developed until today in Greece have exploited only part of the diversity of the available tourist resources. However, the Special Plan for Tourism of 2009 (HOG B 1138) provides an explicit reference to geotourism (article 6 par. H), that it is expected to encourage the designation of geoparks that would be the destination of such tourists in Greece. At a town and country planning level, the legislation gives the possibility of indirect protection of geosites with the framework of approval of the General Town and Country Plans (GTCP) and the Open City Town and Country Plans (OCTCP) in accordance with L. 2508/1997 "Sustainable housing development and other provisions (HOG A 124).

In accordance with article 4 par. 4 of that law " through the GTCP are established **areas of special protection (ASP)** that are not destined for housing development in contact or not with already developed or areas to be developed, as **in particular** archeological sites, of architectural, historical, folkloric interest, zones next to the sea or to rivers, biotopes and places of outstanding Natural beauty, forests of forest areas. In addition through the GTCP areas around cities and settlements are designated where control of housing expansion is required. For the areas of the present paragraph the GTCP may determine the allowed land use, the maximum surface under which the fragmentation of property is not allowed and other measures of special protection." The above provision is applied accordingly to OCTCPs (see article 5 par. 2). The citation of special areas that may be designated as ASPs from the relevant studies and then approved is indicative and therefore it is possible in line with the town and country planning legislation to award protection status to areas that have the characteristics of a geopark within the framework of elaboration and approval of GTCPs and OCTCPs.

In addition, to this end, it is a positive coincidence the fact that within the elaboration of the above plans a general geological survey is the whole area of the study area takes place, aiming at the exploration of the in principle suitability of every kind of development that requires construction, and the protection of the area from catastrophes and disasters". [see article A.I.A.3.4. of Decision 9572/1845/00 «Technical specifications of GTCP and OCTCP studies and engineers' revenues for the elaboration of such studies" (HOG D΄ 209)]. This study, even though its aim is not the identification of geosites, **can contribute with its findings to the location of geosites suitable for protection within geoparks that could be designated as areas of special protection** (see Theodosiou, 2004).

3.4 Evaluation of the national legal framework in relation to the protection and management of geoparks.

3.4.1 General evaluation of the legal framework

In Greece there is no special regulatory framework for the legal recognition of geoparks as an independent legally recognized designation. Ideally, with an appropriate amendment of article 19 par. 3 of L. 1650/1986 the criteria for the designation of "National Parks" could be expanded to include geological, metallurgical, extractive and mineral elements, in addition to geomorphological, that are already mentioned. In addition, as with "marine park" and "national forest parks" to include the term "geopark" in the law. In order for a geopark to be designated as "national park" the relevant article must be amended as follows: «3. As national park are designated extended land, marine or areas of a mixed nature that are left intact or are barely influenced by human activities and in which a large number and a variety of exceptional biological, ecological, **geological, metallurgical, extractive, mineral**, geomorphological and aesthetic elements. When the national park, or a large part of it is covered by a marine area or forest or extensive areas of **geological, metalourgical, extractive, mineral** or geomorphological interest it can be more specifically be named a marine park, a forest park or a **geopark** accordingly."

However, today, it is possible only to use selectively the legislation in vigor in order to protect geological, geomorphological, metallurgical, extractive and mineral elements that will be integrated into geoparks using piecemeal legislative provisions i.e Areas with many elements of **geomorpho-**

logical value can be designated as 'national parks". Geosites with elements of **particular paleontological and geomorphological value** can be designated as "**conservable monuments of nature**" in accordance with the forestry legislation (e.g. petrified forest of Lesvos). Single Natural creations that have particular scientific value as gorges, caves, rocks, petrified forests and geomorphological creations can be protected by the environmental legislation and be designated as "**protected Natural formations**". Protected Natural formations that have monumental character are designated as "conservable monuments of nature". The fact that the list is indicative gives the opportunity for more elements of geointerest to be designated. **Elements in caves** are protected without further designation, and any positive management actions are subject to the approval of the Paleoanthropology – Speleology Units of the Ministry of Culture. **Constructions** of geointerest are protected through their declaration as archeological sites, historical monuments, conservable monuments et.c. in accordance with the archeological conservation legislation. Indirectly the designation of geoparks could be promoted with the provision of **geotourism in the Special Plan for Tourism 2009**. Geoparks could be designated as areas of special protection (ASP) within the GTCPs and OCTCPs, while the documentation could be supported by the envisaged **general geological survey**. In this way there could be imposed measures of special protection to geosites that do not meet the requirements under the forestry or environmnental legislation.

3.4.2 Management Authority

Management of geoparks that are designated as "protected Natural formations" or "conservable monuments of nature" can be assigned [in accordance with article 15 of L.2742/1999 "Planning and Sustainable Development and other provisions" (HOG A'207)] to **management authorities established to that end** (that will be incorporated in the P.D. of designation) or (in the absence of a management authority) to existing public authorities that are established for this purpose, to local authorities of both degrees, to Universities and public research centers or other not for profit legal persons of public or private law of the wider public sector that have been distinguished for their work in the area of nature protection or generally that have the necessary technical and scientific capacity, and proven experience for the materialization of relevant projects. Caves lacking any designation in principle enjoy general negative protection. However, if an organization wishes to take management measures for the promotion of the cave for its geological/mineral value (i.e. access, lighting et.c.) this is possible following an approval of the Paleoanthropology – Speleology Units of the Ministry of Culture. Finally, the management of Geoparks – ASP, in accordance with the town and country planning legislation, can be performed by the municipalities in whose areas they lie. Such management can be performed by the Municipal Development S.A.s if existing, or a Multi-Municipal Development S.A. in case of smaller municipalities sharing a wider geopark area. The latter is taking place in the case of the Psiloritis Geopark, the second recognized Greek Geopark (www.psiloritis-natural-park.gr).

Therefore, it is possible to perform managerial interventions and without the necessity of amending the legislation, it is possible to have adequate recognition and management of geoparks, in accordance with the standards for their international recognition. So, in case **there is no other parallel/ conflicting uses and designation (i.e. Natura 2000 areas)** the following actions should take place:

- For the already listed areas to encourage their designation as "protected Natural formations" and if they have a monumental character to "conservable monuments of nature" (in accordance with articles 19, 20 and 21 of L. 1650/1986 & article 15 of L. 2742/1999) with the issue of a relevant Presidential Decree.
- The geoscientific community should be informed that within the general geological survey

in view of the issue of the GTCPs and OCTCPs areas that have an interest and could potentially be included in a geoparks' network could be proposed as ASPs and if they meet the characteristics of the law to be designated as protected Natural formations" and if they have a monumental character to "conservable monuments of nature".

3.5 The case of overlap of potential geoparks with existing protected areas.

The establishment of geoparks, in practice, is highly possible – if not certain – that will take place in areas that already enjoy protection either as National Parks, Forest Parks, Natura 2000 sites et.c. It is therefore worth examining the role of the provisions that govern the existing protected areas having elements of geoconservation. The designated protected area will be either (a) designated under the forestry legislation, or (b) environmental legislation (L. 1650/86) that includes Natura 2000 sites or both (i.e. Natura 2000 sites may also be Forest Parks). In addition, in relation to Natura 2000 sites' management, the Special Environmental Study will either be assigned, in the process of completion, or completed. Finally, the protected area will either have a Management Authority or not. The different options are examined below.

3.5.1 Operation of a Management Authority (Protected area & Geopark)

The presence, operation and activity of a Management Authority (the 25 protected areas that have a Management Authority are provided in article 13 of L. 3044/2002 (HOG A 197) while management authorities have also the National Park Schinias-Marathon and the National Park of Zakinthos, i.e. in total 27) may create conflicts as the Management Authority has as a mission the management of the area focusing on the conservation of biodiversity and habitats, while the Geopark's Management Authority' s mission is the conservation of geodiversity of the Geopark. It is therefore possible, if there is no coordination between those two bodies either to have conflicting decisions that will affect either biodiversity or geodiversity or repetition of the same activities (i.e. construction of footpaths) by both authorities. The assumption for the existence of two different management authorities responsible for the same area is not sustainable. Such a proposal is also in contradiction with the provisions of the European Geoparks Charter. Geoparks promote a holistic approach in nature conservation. The separation of responsibilities may raise danger and create conflicts.

The proposed solution is the participation in both authorities in decision-making.

- The management authority of the National Park/ Forest Park /Natura 2000 must have as a member in the Board one geologist that will observe the impacts of the authorities' decisions on the geopark and will intervene on issues relevant to geoconservation, and
- The decisions that involve active management of the geopark should have the **previous approval** of the management authority of the protected area.

Both proposals do not require any amendment to legislation, as members of the Board of the Management Authority are appointed by the Minister of Environment and the participation of a geoscientist is not excluded, and the condition of a previous approval may be put as a term in the Presidential Decree establishing the geosite.

3.5.2 Designated Area without management authority

In the absence of a management authority of the protected area there is no issue of coordination and the management authority of the potential geopark is limited only by provisions relevant to passive management (protection), if existent, until the management authority is in operation. That case is applicable in the case of the Forest Park of Sounion, the only Forest Park/Natura 2000 site, without a management authority. It is the case where a geopark is designated and has a management authority while for the (wider) protected area exists only a Presidential Decree or a Ministerial Decision providing designation and terms.

3.5.3 Special Environmental Study

If the protected area in at a stage of pre-designation, i.e. the Special Environmental Study has been assigned and it is being developed, or it has been completed but the necessary Presidential Decree of designation has not been issued, and in the meantime the Presidential Decree of the designation of the geopark is issued, the study group must be contacted in order for the elements of the study to be updated, include the geopark and the description of the elements of geological, geomorphological, mineral, extractive or metallurgical value that are met in the area. In case that the study is finished, then a relative annex must be issued. If the study has not yet been assigned, the future study group must be contacted and made aware that a geopark is in place, the relative Presidential Decree of designation and the elements to be conserved. It is without saying that during the compilation of the Special Environmental Study for the Geopark the elements of biodiversity that are worth conserving must be taken into account.

3.5.4 Geopark in a Natura 2000 site that has only been included in the network (no Special Environmental Study has been carried, does not have a management authority and no other special designation or terms)

In this quite probable scenario (Natura 2000 sites are about 18% of the country) then the management of the geopark is limited by articles 6, 11 and 12 of the Joint Ministerial Decision 33318/30281 (HOG B′ 1289) "Determination of measures and procedures for the conservation of Natural habitats and wild fauna and flora". Therefore (a) there is an obligation of carrying an Environmental Impact Assessment for every plan or activity not included in Category A of article 3 of L. 1650/86 (article 21 par. 2 line 2) and is not connected directly or is necessary for the management of the particular Natura site, provided it affects severely alone or in combination with other plans or activities the Natura site (b) the killing, collection, disturbance of the species and destruction of the habitats is forbidden (c) collection, uprooting destruction of flora protected under the above Decision and Directive 92/43 is forbidden. The plans that the management authority of the geopark are considered necessary for the promotion of the geopark, since they refer to the geodiversity of the site, that is not under protection by the above Decision nor the Directive 92/43 must be submitted to the above (a) procedure.

4. Conclusion - Proposals

4.1 At an international level

- Areas that fulfill the terms of inclusion on the European and International Geoparks Network to be proposed for inclusion in such networks.
- In view of the adoption of the EU Framework Directive on Soil, the issues of protection, conservation and management of geodiversity to be put anew, in accordance with the European Manifesto 2005, to the Parliament and the Council.

4.2 At a national level

- In accordance with the guidelines of the European Geoparks Network, a National Geoparks

Network to be established. Criteria to be established for local, regional and national significance of geoparks. Documentation is already available for the islands of the Aegean Sea (Ministry of Aegean, 2003).

- Greece to comply with Recommendation 2004(3) of the Council Of Europe and take advantage of the existing legal tools towards protecting, conserving and managing geodiversity.
- Greece to ratify the European Landscape Convention (Florence 2000).
- The existing environmental legislation to be used for the designation of geoparks or/and geosites within them as "protective Natural formations" or "conservable monuments of nature", with the issue of the relevant presidential decrees. The Ministry of the Environment to issue a circular for article 19 par. 4 of L. 1650/86 that will clarify that geosites can be designated, according to their importance as "protected Natural formations" or "conservable monuments of nature".
- Article 19 par. 3 of L. 1650/86 to be amended to include a provision on geodiversity and an explicit designation of «geopark».
- A special legal tool (a Ministerial Decision) to be issued to identify the specifications for the elaboration of studies for geoparks either by expert offices or agencies.
- All geoparks should have a management authority.
- Geoparks with interest only in caves do not need further designation, but approval by the competent regional Paleoathropology – Speleology Units of the Ministry of Culture.
- Geoparks to be designated as Areas of Special Protection in the GTCPs and OCTCPs.
- The geoscientific community to locate important geosites during the general geological survey.
- The Board of the Management Authorities of the protected areas where a geopark exists should have one member that is a geologist / geoscientist.
- Geoparks within protected areas that have a management authority should operate having the previous approval of the management authority for management actions within the park.
- Those elaborating the Special Environmental Studies should take into account the conservation of biodiversity and geodiversity accordingly.

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A NEW LATE PLEISTOCENE MAMMAL LOCALITY FROM WESTERN CRETE

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Abstract

During the last five years systematic explorations of the Natural History Museum of Crete have added more than 20 Pleistocene fossil localities around Crete to the catalogue of the over 70 already known on the Island. The new localities are distributed in all four prefectures of Crete. The most important of these is the newly discovered site of Koutalas at Cape Drepano in Western Crete. The fossil remains are found in two levels and in red cemented clays of a collapsed cave. In the upper level a rich assemblage of micromammal, bird and large mammal remains has been discovered. The large mammals consist of dwarf hippopotamus (Hippopotamus creutzburgi) and elephants (Elephas sp.). A partly articulated skeleton (vertebral column, mandible and few long bones) of a dwarf hippo has been found next to a deciduous molar of an elephantid, indicating that the two taxa probably coexisted. The micromammal remains belong to the giant Cretan mouse Kritimys catreus. Therefore, the age of the assemblage is dated to the Kritimys catreus zone and thus to the late Middle Pleistocene. In the lower level scattered remains of deers, birds and micromammals have been identified, and their age is most likely younger than that of the upper level.

Key words: *Endemic island fauna, Pleistocene, dwarf hippopotamus, fossil mammals, Kritimys, Crete, Greece.*

1. Introduction

1.1 General

In 1745, Pococke reported the first fossil bone findings from Crete Island, discovered in the Agios Georgios Cave (Akrotiri peninsula) in Western Crete. So, for more than 250 years the island has been widely acknowledged as an important and popular place for the study of endemic island faunas. All these years, several workers have surveyed the island, hunting out tens of Pleistocene fossiliferous localities (Fig. 1). In the mid nineteenth century Graves, Spratt and Raulin were those who discovered new fossiliferous sites, collected the first fossil remains from the island and handed them to well known palaeontologists of the time being for study (Owen, 1845; de Blainville, 1847; Lydekker, 1885). Based on their information almost half a century later, Simonelli (1907) and mainly Bate (1905), the latter has been proved fairly prolific, continued the surveys, discovering a significant number of new localities and most importantly they provided the first comprehensive accounts on the Pleistocene Cretan fauna. After the explorations of Simonelli and Bate the number of identified fossiliferous localities on the island was set to 16.

Again more than half a century passed before the scientific interest in the Cretan fossils was reheated.

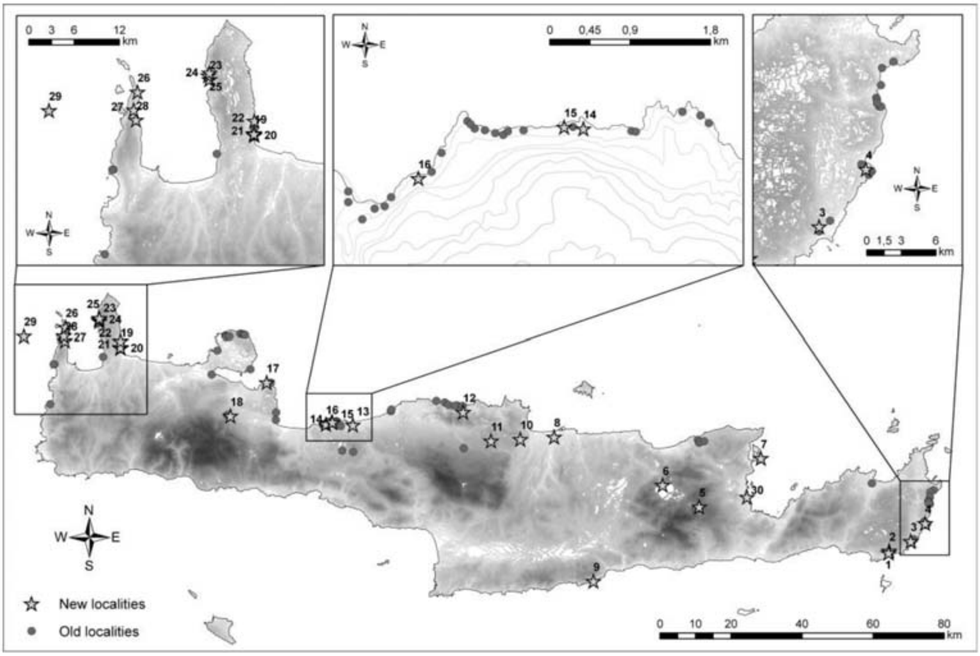

Fig. 1: Simplified map of Crete Island showing the Pleistocene localities on the Island. The names of the numbered new localities are provided in Table 1. The positions of the old localities are based on the maps of Kuss (1970), Dermitzakis (1977), Lax (1996) and position information from Poulakakis et al. (2002), Theodorou et al. (2000), Symeonides et al. (2000).

During the 1960's and 1970's three groups of palaeontologists were working on the island performing systematic surveys and excavations. The first group was headed by the German S. Kuss, the second by the Dutch P. Sondaar. The third one consisted of Italian palaeontologists. Evidently, the two eminent scientists and their colleagues with their long term systematic work discovered numerous new localities, some of which were extremely rich in material and provided new important information on the Pleistocene fauna of Crete. As a consequence most of this material, until recently, was housed in the collections of several Museums and Universities in Western Europe. Recently, a significant part of the Dutch collection was given to the Historical Geology and Palaeontology department of the University of Athens and the Kuss collection, previously housed in the State Natural History Museum of Karlsruhe, was allowed to the Natural History Museum of Crete. In 1970 Kuss presented a catalogue with 36 fossiliferous localities and seven years later Dermitzakis (1977) enhanced the catalogue incorporating the new localities discovered in the 70s, and hence their number was raised to 64.

In the following years the active surveying on the island was significantly reduced and consequently the number of discovered new localities dropped. So, Lax in his 1996 gazetteer, where he reviews the Cretan Pleistocene localities, reports 71 localities; only seven new ones were added. Until recently only four more localities have been discovered, raising the total number of Pleistocene localities to 75 (Fig. 1). The 75 localities are distributed among three out of the four prefectures of Crete Island; 21 localities are found in Chania Prefecture, 34 in Rethymno Prefecture and 20 in Lassithi Prefecture (Fig. 1). Its worth noting that all these years no localities had been reported from the Herakleio Prefecture. Another interesting fact comes from the geographic distribution of the localities. The vast majority of the discovered sites are confined to the north coast of Crete, some to the east coast and only seven (out of 75) in the interior of Crete (Fig. 1). Most localities are associated with caves or other karstic structures and only an insignificant number of sites are situated in other depositional settings. Among all researchers that have worked in Crete, Kuss can be regarded as the most prolific concerning the number of discovered localities (more than 25 localities).

1.2 The Pleistocene Fauna from Crete

All these sites have yielded a plethora of fossils that reveal a very interesting island fauna. The Pleistocene endemic fauna of Crete is characterised as unbalanced once there is almost a total lack of carnivore mammals, with the exception of the endemic otter (*Lutrogale cretensis*), and the presence of mammals with proven swimming abilities. This filtering process indicates that the animals reached the island either by swimming or drifting (Dermitzakis and Sondaar, 1978). The fauna consists of a small number of amphibians and reptiles, several birds, 12 species of micromammals, and as the number of cervid species has not been resolved yet, around 10 large mammal taxa are estimated. According to Dermitzakis and de Vos (1987) the fauna can be separated into two biostratigraphic groups. This distinction is based upon the phylogeny of the Cretan murids as determined by Mayhew in 1977, and the presence of a different genus in each group. The two groups correspond to the *Kritimys* zone and the *Mus* zone, which are split further into the *K. kiridus* and *K. catreus* and the *M. bateae* and *M. minotaurus* subzones respectively (Dermitzakis and de Vos, 1987). The *Kritimys* zone is associated with the Middle Pleistocene and the *Mus* zone with the Late Pleistocene. The first zone is characterized by the presence of the pygmy mammoth, *Mammuthus creticus* (Poulakakis et al., 2006), and the pigmy hippopotamus, *Hippopotamus creutzburgi*, whereas the second zone is associated with the small sized elephants (*Elephas* cf. *creutzburgi*) and an undefined, until now, number of deer species such as the *Candiacervus ropalophorus*. Todate, proboscidean material has never been found together with hippopotamuses in localities ascribed to the *Kritimys* zone, except from an uncertain and ambiguous report by Schlager (1996) from the Phangromouro I and II caves. The determinations of the elephants, as stated by the author, were performed by photographs and slides of the material *in situ*, thus making them questionable.

2. New Pleistocene localities

During the last five years, after more than two decades of surveying "drought", the Geodiversity department of the Natural History Museum of Crete of the University of Crete (NHMC) has conducted systematic palaeontological surveys all around Crete. The surveys focus among other tasks in the relocation of already known and published Pleistocene localities and particularly in the discovery of new ones that will provide more and novel data on the biostratigraphic and taxonomic affinities of the fauna and the distribution of the localities on the island. Obviously, by looking at Figure 1 one can easily notice that the distribution of the 75 recorded localities is biased. There are no localities in South Crete, as well as in the central part of the island (Herakleio Prefecture), and just a minor number in the interior of the island. In addition, there are some areas where Pleistocene localities are underrepresented for no evident reason.

In these five years 30 new Pleistocene localities have been found all over the island (Fig. 1 and Table 1), expanding their total number by 28% to 106. Most of these localities cover areas of Crete where no or few localities existed, and in addition they are situated in all four prefectures of Crete; 13 localities are found in Chania Prefecture, five in Rethymno Prefecture, eight in Lassithi Prefecture and four in Herakleio Prefecture (Fig. 1 and Table 1). So, for the first time Pleistocene localities are reported from Herakleio Prefecture. Similarly, the first three localities from the southern coast of the island are also cited here. Eight new localities found in the interior of the island double the recorded number of such sites and two more have been traced on small islets around Crete. Several localities have been discovered on the north-western side of Crete, which has been barely explored, and in the Chania Prefecture in general due to a funding provided by the Chania Chamber of Commerce and Industry. Apparently, the distribution of the new localities has shown that the reason for the lack of localities in certain parts of Crete can be attributed to the exclusion of these areas from expedition surveying in the past. The majority of the old localities are concentrated around well populated areas of the island, such as the north coast, and around areas with previously reported localities, indicating a humanly driven surveying bias.

Table 1. The thirty new localities discovered on Crete during the last five years.

No	*Locality name*	*Perfecture*	*Taxa*
1	Alogaras Cave	Lasithi	Hippopotamus, micromammals
2	Katharades	Lasithi	Hippopotamus
3	Xerokampos	Lasithi	Hippopotamus
4	Cave Kato Zakros	Lasithi	Hippopotamus
5	Katharo plateau (new)	Lasithi	Deer
6	Lasithi plateau	Lasithi	Deer
7	Kolokitha Island	Lasithi	Micromammals
8	Mastabas Herakleio	Herakleio	Hippopotamus
9	Choirospilios Cave	Herakleio	Deer
10	Kamilari Cave	Herakleio	Micromammals
11	Kolenias Pothole	Herakleio	Large mammals
12	Mougri Cave	Rethymno	
13	Kastelakia Cave	Rethymno	Micromammals, deer
14	Small cave east of Simonelli Cave	Rethymno	Deer
15	West of Simonelli Cave	Rethymno	Deer
16	West of Bate Cave	Rethymno	Deer
17	Koutalas Cave	Chania	Hippopotamus, proboscidean, micromammals, birds, deer
18	Lentakas hole Cave	Chania	Deer?
19	Kolimpari 1	Chania	Deer
20	Kolimpari 2	Chania	Deer
21	Kolimpari 3	Chania	
22	Paralia Afrata	Chania	Micromammals
23	Aspri Limni Cave	Chania	
24	Tripitos Troulos Cave 1	Chania	Deer
25	Tripitos Troulos Cave 2	Chania	Deer
26	Gramvousa 1	Chania	Micromammals
27	Gramvousa 2	Chania	Deer
28	Gramvousa 3	Chania	Deer
29	Pontikos Island	Chania	Micromammals
30	Amoudara	Lasithi	Elephant, deer

Hitherto, the identified taxa from these new localities consist mainly of hippopotamuses, deer and micromammals (Table 1). In one locality birds and in two proboscidean remains have been recognised. Based on the fossil findings, the most important of all these localities is considered to be Koutalas Cave.

3. The locality Koutalas Cave

3.1 General

The Koutalas Cave is situated at the rock cliffs just above sea level on the west coast of Cape Drepano, north-east of village Kokkino Chorio in Chania Prefecture. It was discovered after one of the authors (H.E.) visited the area and recognised the vertebrate remains. The locality consists of two levels, the upper and lower one, and thus of two fossiliferous outcrops. The upper level is found at the top of the cliff and constitutes part of a collapsed cave. The lower level is located underneath the upper level at sea level, at the entrance of a cave. The fossiliferous deposits in the upper level consist of well cemented red clays that contain significant numbers of limestone debris. In the lower level they are made of well cemented red and sometimes yellow clays. The former and most important ones contain skeletal remains of microvertebrates in remarkable abundance, as well as some sparse remains of macromammals. The latter yielded a small number of scattered remains of macromammals and birds. Clearly the deposits in the two levels correspond to two different depositional events.

3.2 The Koutalas Cave fauna

The upper level has yielded numerous remains of micromammals and birds. The most common of these are skeletal parts that belong to a giant murid. We were able to extract some mandible parts and determine them. The morphology and the large dimensions of the teeth (Table 2) indicate that they belong to the largest of the Cretan murids *Kritimys catreus*. The studied first lower molars (m1) (Fig. 2d) compared to the respective molars of the other Cretan murids, *K. kiridus*, *Mus bateae* and *Mus minotaurus* (Table 2) are proven significantly larger, but within the range of *K. catreus* (Table 2). At this stage bird bone material has not been recognised yet. The vast majority of the macro remains belong to a dwarf hippopotamus, and most likely to *Hippopotamus creutzburgi*. It consists of post cranial and some cranial remains, nevertheless the most important finding is an almost complete, articulated skeleton with the mandible in place (Fig. 2a and 2b). Unfortunately, the skull is missing and probably was destroyed by weathering processes. In close proximity to the skeleton another exciting finding, a part of a deciduous molar of a dwarf elephantid was found (Fig. 2c), evincing the co-existence of the two taxa. The molar consists of three lamellae and as shown in Figure 2c is particularly small in size. It is not clear whether it belongs to an elephant or a mammoth although its minute size seems to favour an affiliation with *Mammuthus creticus*. A more accurate determination is not possible with only this sole specimen, thus identification as Elephantidae indet seems reasonable. Bearing in mind the above mentioned uncertain report by Schlager (1996), it is almost a truism that this is the first certain report of the two taxa being found together in the same locality.

From the sparse fossil material in the lower level it has been possible to identify the presence of deer from postcranial and cranial elements. In addition some bird bones were recognised.

The presence of *K. catreus* in the upper level indicates that this layer was deposited during the *Kritimys* biozone and more specifically during the *K. catreus* subzone, and thus its age can be characterised as Middle Pleistocene. Conversely, the presence of deer clearly supports a younger age and consequently a Late Pleistocene age can be attributed for the lower level.

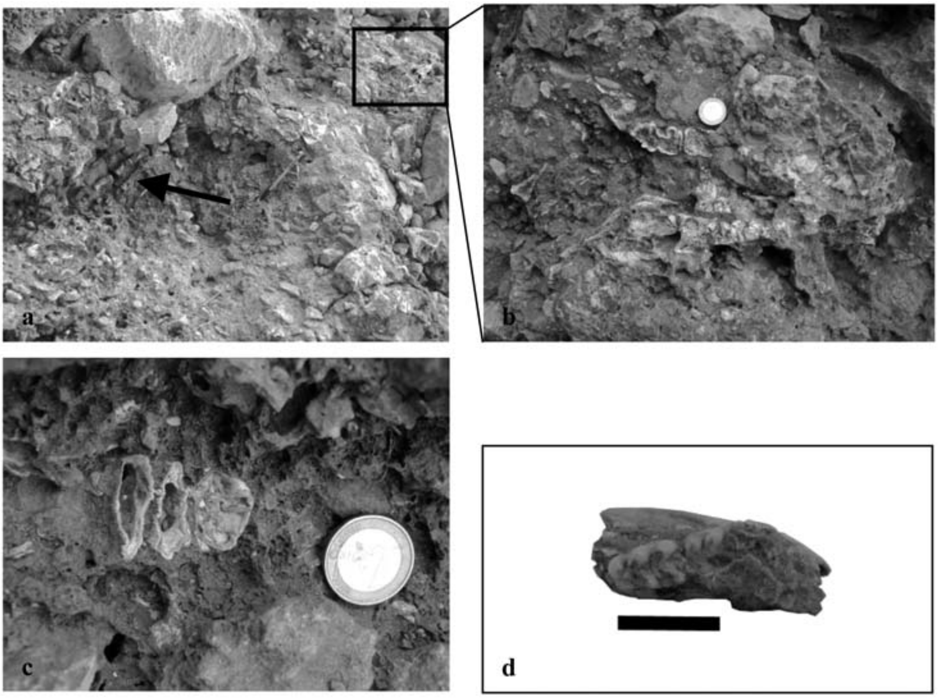

Fig. 2: (a): View of the upper fossiliferous level where the almost complete and articulated *H. creutzburgi* skeleton is lying. The arrow points to some of the articulated vertebrae. The square indicates the area where the lower mandible lies; (b): The lower mandible of *H. creutzburgi* in situ; (c): The deciduous molar of the dwarf elephantid; (d): Part of a lower mandible of *K. catreus* with m1 and m2.

Table 2. Measured length and width at crown level of the first lower molars of the studied murid material from Koutalas Cave and for comparison the respective size range of the three larger Cretan murid taxa.

Species	*Crown length*	*Crown width*
Kritimys kiridus*	2.89 - 3.30 mm	1.66 - 1.92 mm
Kritimys catreus*	3.55 - 4.72 mm	2.07 - 2.98 mm
Mus minotaurus*	1.96 - 2.30 mm	1.05 - 1.46 mm
Studied specimens	3.85 - 3.95 mm	2.32 mm

* Measurements from Mayhew, 1977

4. Conclusions

Systematic studies contacted by the Natural History Museum of Crete in the last years have identified many of the old, previously reported, and recognised 30 new Pleistocene mammal fossil sites located all around the island of Crete. Most importantly, these studies have proven that possibly the Pleistocene fauna of Crete was not only present near the north coast or in cluster areas (like Lassithi mountains) but also such localities can be found all over the island, presenting thus for first time new sites from the southern coast as well as from the Heraklion Prefecture. The total number of the Pleistocene sites has been risen up to 106.

The most profound among these new sites is the Koutalas Cave in Chania Prefecture, where for the first time the coexistence of hippopotamuses and Elephantidae can be undoubtedly documented. The fauna is distributed in two levels with the uppermost containing macro remains of dwarf hippopotamuses (*Hippopotamus creutzburgi),* a part of a deciduous molar of a dwarf elephantid, and numerous remains of micromammals and birds. The presence of the Cretan murid *K. catreus* dates the recovered faunal findings as Middle Pleistocene. The lower level which appears to be younger in age consists only of scattered bones of deers and birds.

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DESIGNATION OF GEOSITES- PROPOSALS FOR GEOPARKS IN GREECE

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Abstract

During the last three years, the research project: "Geosites, geoparks contribution to sustainable development" aiming at recording and designating geosites and potential geoparks, as a means to sustainable development, funded from the 3rd Community Support Framework (CSF) programme, is developing at the Institute of Geology and Mineral Exploration of Greece (IGME).

The project, according to its objectives, is divided in the following five sub-projects:

1: Identification, characterization, evaluation of geosites

2: Compilation of a DataBase and a Geographic Information System (GIS) for the geosites, geotrails and potential geoparks in the country.

3: Planning of walking and motoring geotrails around the geosites, in combination with other attractions of biotic, archaeological and cultural interest.

4: Specifications of the geoparks' studies and planning for interpretation, tourism, marketing, development, operation and management. Drafting of complete management proposals for selected areas, in view of their development into geoparks and of their participation in international networks.

5: Promotion of the project's objectives and benefits in international, national level and the local community, businesses and institutions. Compilation of interpretative, marketing material for tourism purposes, and for the community awareness on geological heritage conservation.

The whole project is based on the systematic inventory of the geosites and the compilation of a GIS-aided database for the geosites, geotrails and potential geoparks. The framework of the research materialization, the procedural steps, as well as the methodological approach for its accomplishment, will be presented in this paper, focussing mostly in the first sub-project methodology as Geosites registration is the base for the whole project.

The geosites, geotrails, potential geoparks Registry compiled with this project will function as a source of information for various uses: national and international level public or private sector projects regarding planning and conservation of nature, education and tourism.

Key words: *Geosites, geoparks, geotrails, sustainable development, IGME, geoconservation, geological heritage, geotourism, Greece.*

1. Introduction

Greece has an interesting geology-geomorphology, along with active processes, due to its geotectonic emplacement, in the collision zone of two tectonic plates. It is a country with richness and variety in areas for geological heritage conservation (Theodosiou et al, 2006) These areas contain appreciable geological-geomorphologic features and landscapes, some of which are of international importance, while at the same time some are very interesting for tourism development.

Awareness for geosites promotion and protection started systematically since 1995 in Greece. (Drandaki, 1995; Drandaki, Mettos, 1996). Thus, the year 1995 should be considered the starting point for the concept of geological heritage conservation in its entirety and complexity and the development of the relevant terminology (geological heritage conservation, geoconservation, geosites, geotopes, geodiversity, geoparks etc) (Theodosiou-Drandaki, 2000a). The year 2005 could be considered a turning point because IGME Board decided to allocate funds from the 3rd CSF for the "designation of geosites-geoparks".

The new orientation to register and promote geoconservation of the country and the plans to set out actions to conserve and enhance the geodiversity of particular areas (Dorset County Council, 2005), were a challenge to be achieved and to put some steps forward the geological heritage conservation in Greece. The 'Action Plan' process for two areas (Lavreotiki and Vikos-Aoos), builded upon an inventory to determine management requirements for the different geodiversity elements, it defined long-term objectives and short-term targets and identified human and financial resources necessary to achieve these (JNCC, 2004). It took ten years to develop the idea of geological heritage conservation into something concrete, a relatively justified period as new ideas need time to be accepted (Theodosiou, 2007).

But, "A mind once expanded with a new idea never regains its original proportion". All the more IGME in 2005 had already ten years experience in geological heritage promotion, education and training (Drandaki et al, 1999). It had as well the geoscientific information, the personnel and the infrastructure for the accomplishment of this new research project. It's obviously thus, the most appropriate organization for this infrastructure research, stimulating and harmonizing all efforts in the domain. IGME was also and still is, collaborator of UNESCO in geoscientific matters, the International Union of Geological Sciences (IUGS), and ProGEO National representative, as well as coordinator of the IUGS-UNESCO-ProGEO "Geosites" initiative, in Greece (Theodosiou-Drandaki, 2001; Theodosiou-Drandaki et al, 2001). The "Geosites" initiative set up by IUGS for the systematic inventory of the most important geological sites, active since 1996, it was undertaken by the Global Geosites Working Group. It aimed to involve the whole geological community in geoconservation, as well as to support any national or international initiative to protect geodiversity, a resource that is underestimated and completely unrenewable (ProGEO-Wimblendon et al, 1998). This inventory focuses mainly on the needs of the geological sciences research and education; there can be no science and education without site conservation, as it is well known (Theodossiou-Drandaki, 2000).

It's worth mentioning here the wider framework regarding geosites-geological heritage conservation and geoparks establishment (Drandaki, 1996; Theodossiou-Drandaki & Foundou, 1997):

On International Level

- **UNESCO:** a. Cultural and Natural Heritage Convention and attempt to include geological sites in the list (Cowie, 1993; Cowie & Wimbledon, 1994), b. Global Geoparks network (Patzak and Eder, 1996; Patzak and Eder, 1999).
- **IUGS** Geosites initiative.
- **ProGEO:** European Association for geological-geomorphologic heritage conservation.
- **European geoparks network.** (Zouros, 2004; Zouros ed., 2007).

- **Council of Europe:** recommendation on conservation of the geological heritage and areas of special geological interest (Adopted by the Committee of Ministers on 5 May 2004).

In National Level

- **Cultural and Natural Heritage Convention of UNESCO (1972)** ratified by Law 1126/30-1-1981, G. 32/A/10-2-81.
- **Environmental Legal Framework 1650/86.**
- **Lesvos petrified forest:** Founder European geopark in 2000, Global geopark in 2004.
- **Psiloritis Natural Park:** European geopark in 2001, Global geopark in 2004.
- **Chelmos-Vouraikos National park:** European and Global Geopark in 2009.
- **Geological-Geomorphologic Heritage Committee of the Greek Geological Society**, established in 2005.
- **Hellenic Ministry of Environment, General Town Planning and Open Town Organization Urban Plans, M.D. 27691/14-09-07** (G. 1902/B/07).

2. Methodology

The research project objectives have been the designation of Geosites and the compilation of proposals for Geoparks establishment, as well as relevant tasks. In order to accomplish these objectives it was divided in five sub-projects, running with a differentiation in time from one to another. Thus, needed acquisition and elaboration of data could be accomplished. Mentioned sub-projects are the following:

2.1: Identification, evaluation, classification and systematic registration of greek geosites.

2.2: Compilation of a database (DB) and a Geographic Information System (GIS) for the geosites, geotrails and potential geoparks in the country.

2.3: Planning of walking and motoring geotrails.

2.4: Specifications of the geoparks' operations, interpretation, tourism, marketing, development and management planning. Application dossiers for the European and Global UNESCO geoparks networks.

2.5: Production of appropriate material task either for scientific or awareness raising purposes.

This paper will focus mostly on the first sub-project methodology as Geosites registration is the source of information for the whole project.

Project research started in May 2006 with a budget of 600.000 E. Around 25 various professions geoscientists of IGME have been involved, either from the Central Services or from the regional Departments of the Institute.

2.1 Identification, evaluation, classification and systematic registration of greek geosites

The objective of this stage is primarily the inventory and recording of Geosites for the compilation of a dynamic Geosites Registry that will represent the geodiversity of the Greek territory. The preparation followed a number of steps, aiming at the mutual updating and feed backing in the project team, coordination of actions, exchanges of views and considerations, trying in that way to achieve the better grade of consensus and common outlook for the project running.

More detailed, the preparation steps have been:

— Quest of theoretical relevant research and good practices, or examples and experiences from other countries.
— Set up of research teams.
— Supporting actions: Two plenary and a number of partial technical meetings, as well as e- communication in a regular basis.
— Promotion actions (meetings, conferences), aiming at the information and sensitization of the geoscientific and the broader community for the project concept, the geological heritage conservation and interpretation.
— Training of the project research team in geological heritage interpretation theory and good practices. A workshop organization with Lavrion area as a case study (Veverka, 1998; Theodosiou, 2007a) took place.

For the higher possible standardization and normalization of collected information, the groups of scientists involved in the project were provided with:

- **1. An instructions sheet.** Detailed and elaborated instructions how this inventory should be done. These instructions revised periodically, with decisions taken from the project steering committee, as the project was advancing and theory become reality.
- **2. A geosite protocol form,** with a detailed series of attributes to be filled in. Criteria for selection (Gonggrijp, Boekschoten, 1981; Duff, 1994; Erikstad, 1994; Stevens et al, 1994; Rosengren, 1994; Wimbledon, 1996; Gonggrijp, 1997; Macadam, 1998; Theodosiou-Drandaki, 1999; Diakantoni et al 1999&2000; Drandaki et al, 2000; Gray, 2004; Theodosiou et al, 2006) classification and evaluation (Harley, 1994; Haaf, 1995; Junta de Andaluzia, 2001; Kasinski et al, 2004;) were set out according to following values: scientific, educational, and tourist-cultural.
- **3. A list with the Greek Frameworks for geosites.** Defined with IUGS/ProGEO Geosites initiative and published in Congresses (ProGEO-Wimbledon et al, 1998; Theodosiou-Drandaki, 2001; Theodosiou-Drandaki et al, 2001; Drandaki-Theodosiou, et al, 2003).
- **4. A list with potential geosites,** for specific area of each team, compiled previously from field experience, bibliographic references, maps etc (Theodosiou-Drandaki, 1997; Bornovas, 1999; Theodosiou-Drandaki, 1999a; Drandaki et al, 2000; Fassoulas 2001; Theodosiou-Drandaki et al, 2001; Theodosiou-Drandaki, Drandaki eds, 2001; Velitzelos et al, 2002).

The basic document for Geosites registration it's obviously the **Geosites inventory protocol form (•2)**, which will be described in more detail subsequently:

As already mentioned this sub-project aimed at a Geosites inventory. Data regarding each recorded geosite should fill in the specific geosite protocol form prepared for this purpose. The aim was to test this analytical tool, the geosite protocol form, which should be used by a big number of geoscientists with different specializations, in order to collect structured and the most possible standardized information for the DB and GIS compilation. Obviously it was the basic infrastructure for this sub-project and subsequently the whole project. Parameters taken into consideration during its preparation were:

- The previous international and national experience (Ellis (ed) et al, 1996; Zagorchev et al, 1996; Junta de Andaluzia, 2001). In Greece the first Geosites inventory protocol form appeared 3-lingual in the proceedings (Theodosiou ed, 1999a) of the 1st meeting on geological-geomorphological heritage conservation, which took place in Syros island, in the framework of Ermoupolis Seminars, on 13-15.7.06.

- The evolution of geosite concept (holistic considerations of nature, science social definition, sustainable development, environmental education, alternative tourism).

- The perspective to define areas as potential geoparks (experience acquired from close cooperation with UNESCO Earth Sciences Division, for the compilation of national geoparks establishement guidelines, as well as from cooperation with ProGEO) (Theodosiou-Drandaki, 2003).

The form asks for information of various nature either geographic, administrative, geoscientific, environmental, etc.

Such a form already has been prepared during previous years, in our effort to register geological sites in a voluntary basis. For the project specific purposes, it has been updated with new fields concerning suggestions for practical management, sustainable development principles, holistic approach, in fact with new concepts for the geosites and for the development of geoparks.

It is divided in **four parts**: a **first part** with fields asking for detailed information concerning the geosite itself, contains five blocks with 76 questions totally, while the **second part** searching for information for the area where the geosite is located, it contains one block with 22 questions. A small **third part** with five open questions follows for those interested to express opinions, ideas for some topics such as practical management of the geosite, avoidance of improper use in case of tourism, needed protection measures, etc. and a smaller **forth part** asking for accompanying documents (report, photos-sketches, bibliography).

Most questions are answered marking a v, e.g. for the question Significance of geosite, one of the following could be marked with a v as an answer: Universal, European, National, regional, local. Most of questions have one of 5 potential answers, in order to have comparative, concrete results to be elaborated with statistics afterwards.

As this information should be gathered once, funds are public and limited; attention was paid to obtain the proper quality and quantity, that is: The geosite protocol form duly completed, A geological map in appropriate scale, Photos of the site interests, A report as a free text for questions, suggestions, ideas, proposals not included in the forms.

A number of 1200 geosites have been registered; around 1000 have been entered in the data base and the GIS.

2.2 Compilation of a Database and a Geographical Information System for the geosites, geotrails and potential geoparks in the country

All spatial information together with the attributes have been used to create a multi-relational DB and a GIS with geosites symbols libraries, permitting various queries and relationships and serving for the production of multi-purposes, multi-users maps, as well as other selective either digital or printed products on demand.

Above mentioned project results will support a structured National Data Bank (NDB) of geosites and potential Geoparks and a GIS to emerge, which could be pumped to cover various requirements and users' needs in the country. It can be used for science, education and training, as well as for infrastructure works, rational land uses and conservation of local natural features, briefly, in the entire planning, development and conservation system. The Data Bank maintenance and expansion, with a new project including scientists of the whole geoscientific community, can justify author's expectations for IGME to operate as a **G**eosites and potential **G**eoparks **N**ational **D**ata **B**ank (**G_GNDB**) and **G**eosites-**G**eoparks **D**ocumentation **C**enter (**G_GDC**). (Copp, 1994; Ellis (ed) et al, 1996; www.lgt.lt; Miskiewicz, 2004; http://www.geology.cz/extranet-eng/geodata/databases/localities).

2.3 Planning of walking and motoring geotrails for potential geoparks

Applying certain criteria in the recorded geosites DB, a number of areas have been revealed. Information needed to respond to these criteria apparently was given from previously mentioned Geosites protocol forms.

Selection Criteria can be determined from the definition of the geoparks and the prerequites for a geopark establishment (Patzak, Eder, 1996; Zouros et al, (eds) 2003; UNESCO, 2003+2004; Jordan et al, 2004; Theodosiou-Drandaki, 2004; Theodosiou-Drandaki, 2004a). Thus, the following are the criteria applied:

- important geoscientific values: one-two geosite of international significance, with representativity, high scientific value, superb features, mosaics of geological features representative of the area, its geological history, events or processes.
- other values (cultural, natural, archeological etc).
- Certain extent.
- certain management, access.
- certain infrasructure, facilities.
- protection at least partial.
- interest and cooperation of local people and local authorities.

A geopark is an area with diversity and interest in Geosites but also with People, Other values, Infrastactures existing and/or "builded" gradually, Management structures, An information, reception center, Activities, accommodation places, points to eat, enjoy etc., in a way to have a positive effect in the local economy (Zouros et al, (eds) 2003). One or even more isolated geosites, an isolated walk, without opportunity for access, lack of variety, values, density of Geosites, lack of other interests in the area, without interest of the local community for tourism development is not a geopark. We cannot have a geopark from zero. Nevertheless Geosites should be designated and eventually protected in a physiocratic approach, Geoparks is a more antropocentric approach and includes economic and social values.

14 areas have been initially defined ((Patzak, Eder, 1996; Zouros et al, (eds) 2003; UNESCO, 2003+2004;) with geoparks potential for further study, in the framework of the project, the following:

1. Maronia area, 2. S. Thassos island, 3. N.W. Chalkidiki, 4. Olympos area, 5. Vourinos mountain, 6. Meteora, 7. Pindos mountain, 8. Aoos-Vikos area, 9. Kokkinopilos area, 10. Acheron, 11. N. Peloponnisos, 12. Lavreotiki, 13. W. Crete island, 14. Nisyros inland.

Availability of scientists, time, budget, and technical means gave priorities to the following areas for the pilot geotrails design and relevant publication geotrails cards.

1. Maronia area, 2. S. Thassos island, 3. Aoos-Vikos area, 4. Kokkinopilos area, 5. Acheron, 6. Lavreotiki, 7. W. Crete island, 8. Nisyros inland.

These areas constitute those with potential to evolve to geoparks according to the referred in the previous page criteria.

2.4 Preparation of specifications of the geoparks' operations, interpretation and management planning

For two of the above mentioned areas, Aoos-Vikos area and Lavreotiki, of outstanding values, but also with maturity grade of management plans, local authorities and people involvement, to serve for local sustainable development, occurred in higher degree. Geoparks studies were undertaken for those two areas, in the framework of the 4th sub-project.

Specifications for these two geoparks studies have been prepared following a model, as well as the requirements of European and Global Geoparks Networks (Patzak, Eder, 1996; Mattig, 2003; Zouros et al, (eds) 2003; UNESCO, 2003+2004, Theodosiou-Drandaki, 2004a). Later the geoparks studies have been compiled concerning operation, interpretation, tourism, management and development planning. Applications dossiers for those two areas to be included in the European and in the UNESCO Global Geoparks Networks have been also compiled and duly forwarded to appropriate Bureaus (Theodosiou et al 2009, Theodosiou et al 2009a). These candidature dossiers with all enclosures are to be found at www.igme.gr. Joining the European and the Global Geoparks Networks will give opportunities for science and conservation but also for the sustainable development of the area through geotourism.

2.4.1 Lavreotiki peninsula geopark, Attica region, Central Greece

The Geopark is located in Lavreotiki -a peninsula in the SE part of the Prefecture of Attica, within a distance of approximately 60 km from Athens, the capital of Greece. The territories of two Municipalities (Municipality of Lavreotiki and Municipality of Keratea) and of one Community (Community of Agios Konstantinos) constitute the total area of the candidate Geopark, where 49 geosites have been identified so far (Janikian, 2009; Theodosiou et al, 2009).

Marbles, mica schists, phyllites, is the geological setting in a complex composition and tectonic relation (Photiades et al, 2007).

Intensive activity started with silver exploitation since 3.500 b.C., culminated in 5th, 4th c. B.C., followed by welfare and prosperity of Athenian Democracy. After 3rd B.C. degradation started. Around 1860 started the new history of the exploitation. The area of Lavreotiki is famous worldwide for the exploitation of the mixed sulphide ore deposits and the abundance and variety of mineralogical specimens. Mineral names as Lavriotite, Kamarizite, Ktenasite, Thorikozite, Serpierite originated from the area of Lavrion; these minerals were discovered here, and are included in the collections of several well known mineralogical museums in a worldwide scale. During ancient times, the profit obtained from the exploitation of mines contributed greatly to Greek and European culture development. Nowadays, specialists in the domain of Economic Geology and Mining are impressed from the extremely advanced mining and metallurgical technology applied during antiquity as it is evident from archaeological findings. The significant extent of the ancient mining activity in the area is shown by the abundance of mining and metallurgical wastes. (Dimou, Perdikatsis, 2001).

All the above mentioned facts witness the special geological-mineralogical setting and geodiversity of the area under concern. In addition and intimately interconnected with it the archaeological and cultural setting is of great interest. The biotic environment as well, is of outstanding beauty and value as the area hosts a National Park (Sounio National Park) and two Natura 2000 sites with several types of important habitats. (Presidential Decree for the establishment of the national park -Gazette 80/A/26-3-1974 and Gazette 121/D/19 of February 2003,) (Philotis D.B.; Greek portal for Biodiversity).

The conclusion is that the area of Lavreotiki is considered as a geological, natural and cultural heritage of international significance that can be appreciated through conservation, education and geotourism. This precious heritage, highlighted, protected and managed properly, will be enjoyed by people all over the world, who wish to visit it and learn more about it.

2.4.2 Vikos-Aoos Geopark Epirus region, N.W. Greece

The Geopark area is mainly mountainous, and lies within the administrative boundaries of the following local authorities: Municipality of Konitsa, of Kentriko Zagori, of Tymfi and Community of Papigo, where 44 geosites have been identified so far (Paschos, Nikolaou, Papanikos, 2009).

There is a great variety of geosites in the area from a wide range of geological processes, which compose a picture of great aesthetics with high scientific and pedagogical interest. Geodynamic processes are very important and result to a very impressive landscape with canyons and huge faults (Astraka, Konitsa). Neogene and Quaternary quick ascending movements, combined with strong vertical erosion caused two of the most impressive and deep canyons in the world. Voidomatis (or Vikos) and Aoos rivers flow through them. The wealth of geological diversity resulted in numerous testimonies of the geological history of the area imprinted in a strongly dissected morphology and landscape: karstic springs, glacial age features (lakes), river terraces, caves, limestone lithostratigraphic changes, paleolithic remnants are very well combined with stone bridges, stone-paved walks, picturesque traditional stone-built villages with very rich vegetation. A great number of designated geologists of several countries dedicated a big part of their life studying the area fascinating geology. The relevant bibliography richness approves it. (Theodosiou et al, 2009a).

It is one of the most important areas at the national and European level, as it uniquely combines the natural (habitats, flora, fauna, landforms, hydrography and landscape) and long lasting human environments (traditional settlements, cultural and historic features), as well as unique cultural elements (folk music, popular – traditional arts, etc.) and architectural features (houses, bridges, etc.). Pindos Mountain is of particular ecological interest, because of the unique diversity of species and ecosystems, which are rare in Greece and Europe. The former National Park of Vikos and Aoos gorges (recently incorporated into the broad Northern Pindos National Park) and a number of sites included in the European Ecological Network NATURA 2000, is a clear evidence of its significance. (in Theodosiou et al, 2009a).

The area is already a well-organized tourist destination but the geological framework is evidently missing from interpretation means. Thus its promotion as a geopark will give an additive value and an alternative interest with scientific, pedagogical content to the tourist product.

2.5 Production of appropriate material either for scientific or awareness raising purposes

Promotion of the project’s objectives. Interpretative, marketing, awareness material production to sensitize the politicians, the stakeholders, the public, NGO’s, the tourist sector.

2.5.1 Cards of Geotrails in Greece

The series “Geotrails in Greece” (Theodosiou, ed. 2009) is a pilot publication for six Greek areas: Thassos, Maroneia, Epirus (Vikos, Acheron, and Kokkinopilos), Lavreotiki, Nissyros, W. Crete, Gavdos. It is accompanied with in situ **panels** and an **interactive application** at the Museum of IGME. Survey form of this publication and relevant in spot signs is to be found at http://www.igme.gr

2.5.2 Atlas of Geosites and potential geoparks in Greece, 1st edition

It contains several kinds of maps concerning geosites, geotrails and geoparks (Theodosiou, 2009).

2.5.3 Panorama of Geosites, 1st edition

It contains a brief description and photos of around 400 geosites (Theodosiou, 2009a).

2.5.4 Cards, Leaflets, Calendar 2010

3. Conclusions-Results

The Registry of geosites currently under construction will function as a source of information for every use: public or private sector projects in national and international level, for the development, planning and conservation of nature and heritage, environmental education, and for tourism.

Planning of geotrails around the geosites, in combination with other attractions of biotic, archaeological and cultural interest, as well as compilation of interpretative, awareness printed material is one of the objectives of the project. Same material in DB and GIS-aided digital form is used for applications, exploiting the potential of multimedia and interactive technologies, to attract the interest of the visitor on the geological history and at the time entertain him.

Development and management proposals for geoparks in selected sites, could be implemented by the local councils or other relevant entities, providing social and economic benefits to local communities.

Creating the right products will result in the designation of the geological heritage and the establishment of new forms of alternative tourism, a modern tourist trend for the social and economic development of each region.

Designating geosites will also have a positive impact on the awareness and knowledge of geological history at all levels of education, in our country and internationally.

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GEOTRAILS IN GREECE

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Abstract

Planning of walking and motoring geotrails around the geosites, in combination with other attractions of biotic, archaeological and cultural interest, as well as creation of interpretative, awareness printed material relevant to the geosites is one of the objectives of the project "Designation of geosites – geoparks, contribution to sustainable development". It is a project of the Institute of Geology and Mineral Exploration (IGME), funded from the 3rd community support framework program. Furthermore, this printed material which is also available in digital form aided by the project's data base and the geographic information system is used to develop an application for display at the IGME museum, exploiting the potential of multimedia and interactive technologies (e.g. touch screens), in a way that will attract the interest of the visitor on the geological history and at the time entertain him.

Making of the right interpretive products will result in the designation of the geological heritage and the establishment of new forms of alternative tourism, a modern tourist trend which will help in the social and economic development of each region. Designation of geosites will also have a positive impact on the awareness and knowledge of geological history at all levels of education, in our country as well as internationally.

Key words: *geotrails, geosites, geoparks, geotourism, sustainable development, Greece, Lavrion, Vikos-Aoos, Maroneia, Thassos, W. Crete and Gavdos island, Nissyros island.*

1. Introduction

The research project objectives have been the designation of Geosites and Geoparks and relevant tasks. In order to accomplish these objectives the project was divided in five sub-projects, running with a differentiation in time from one to another. Thus, needed acquisition and elaboration of data could be accomplished. Mentioned sub-projects are the following:

1.1 Identification, evaluation, classification and systematic registration of greek geosites.

1.2 Compilation of a database (DB) and a Geographic Information System (GIS) for the geosites, geotrails and potential geoparks in the country.

1.3 Planning of walking and motoring geotrails.

1.4 Specifications and studies regarding geoparks' operations, interpretation, tourism, marketing, development and management planning. Application dossiers for the European and Global UNESCO geoparks networks.

1.5 Production of appropriate material task either for scientific or awareness raising purposes.

Project research started in May 2006 with a budget of 600.000 E. coordinated by the Department of General Geology and Geological Mapping. Around 25 various professions geoscientists of IGME have been involved, either from the Central Services or from the regional Departments of the Institute. Cooperation with other specialists, eg. archeologists, civil engineers, environmentalists, interpreters, GIS specialists etc. has been also retained from the private domain.

2. Methodology

In another paper of this conference we have focussed mostly on the 1.1 sub-project methodology as Geosites registration is the source of information and the infrastructure for the whole research project.

This paper deals with the sub-projects 2.3, 2.3 and 2.5, that is planning of geotrails, the relevant database and GIS, the geotrails cards publication, as well as the informative and the interpretive relevant signs production. It's worth mentioning also that a survey form for geotrails and cards and signs is uploaded at igme site, www.igme.gr. (Theodosiou, 2009). An interactive application on geological heritage, geotrails, geoparks progresses for the Museum at IGME.

2.1 General

Applying certain criteria in the Geosites GIS-aided DB, a number of areas with geoparks potential have been revealed.

A geopark is an area with diversity and interest in geosites but also with people, other values, infrastactures existing and/or "builded" gradually, management structures, an information, reception center, activities, events, accommodation places, places to eat, enjoy etc. One or even more isolated geosites, an isolated walk, without opportunity for access, lack of variety, values, density of geosites, lack of other interests in the area, without interest of the local community for tourism development is not a geopark. We cannot have a geopark from zero. Nevertheless geosites should be designated and eventually protected in a physiocratic approach, Geoparks is a more anthropocentric approach and includes economic and social values.

Selection criteria applied in the Database to define areas with geoparks potential and relevant maturity status were:

- Important geoscientific, educational or tourist values representative of the area, its geological history, events or processes.
- Density of geosites.
- Diversity of geosites.
- Other values of the natural and cultural environment.
- Certain extent of the area under concern for tourism activities to take place.
- Existing or under preparation management structures, eg. an information, interpretation center, interpretation on site (informative, interpretive signs etc).
- Existing or under preparation infrastructure and facilities for staying, feeding, entertainment, access.
- Protection status at least partial.
- Interest and cooperation of local people and local authorities.

Information needed to respond to these criteria apparently was entered and elaborated in the Data

Base from Geosites protocol forms, with sub-project 1.1, filled in with data mostly from field work but also from bibliographic data.

14 areas have been that way defined with geoparks potential for further study, in the framework of the project, the following:

1. Maronia area, 2. S. Thassos island, 3. N.W. Chalkidiki, 4. Olympos area, 5. Vourinos mountain, 6. Meteora, 7. Pindos mountain, 8. Aoos-Vikos area, 9. Kokkinopilos area, 10. Acheron, 11. N. Peloponnisos, 12. Lavreotiki, 13. W. Crete & Gavdos island, 14. Nisyros inland.

Availability of scientists, time, budget, and technical means gave priority to the following areas for the pilot geotrails design and relevant publication geotrails cards, in order to promote the geoscientific values as well as other interests of these areas:

1. Maronia area, 2. S. Thassos island, 3. Aoos-Vikos area, 4. Kokkinopilos area, 5. Acheron, 6. Lavreotiki, 7. W. Crete & Gavdos island, 8. Nisyros island.

2.2 Interpretation

A number of IGME geoscientists involved in the project undertook the task to design the geotrails, to localize the points for signs to be placed. At the same time a question was the form to present these geotrails and sings in a way to be attractive and interpetive. The material should be attractive in order people to acquire the culture of this new outdoor activity, geotrails. All these new needs required updated knowledge of new concepts and means of communication and interpretation (Page, 1994). The critical point of interpretation revealed.

A first Interpretive Training Course for geoscientists of the Institute of Geology and Mineral Exploration of Greece was organized in December 2007 (Theodosiou, 2007).

2.2.1 Definitions, principles and concepts of interpretation (Veverka, 1998)

Within the interpretive profession there are several definitions of what interpretation is. One of the most commonly used definitions of interpretation is that:

Interpretation is a communication process designed to reveal meanings and relationships of our cultural and natural heritage, to visitors, through first hand involvement with objects, artifacts, objects or sites. (Interpretation Canada – 1976).

The American Association for Interpretation defines interpretation as: A communication process that forges emotional and intellectual connections between the interests of the audience and the inherent meanings of the resource.

The main difference between interpretation and information is not what the message or program contains – the information – but how the information is presented. The basics of interpretation principles are:

1. All interpretive efforts must relate to a visitor's personality, experience or interests. This includes tangibles, intangibles and universal concepts as well.
2. Information does not equal interpretation, but all interpretation contains information.
3. Interpretation is an art, which combines many arts regardless of subject material. Any art is to some degree teachable.
4. Interpretation does not equal instruction, but rather provocation.

5. Interpretation should aim to present a whole rather than a part.
6. Interpretation for children must be designed specifically for children, and not simply a dilution of programs and information for adults (Tilden, 1977).

The communication process used to «interpret» information is based on Interpretive Principles, expressed by Tilden in 1954. Tilden's basic communication principles are also the ones you will find in every first year marketing or advertising textbook on successful communication with your market (audience).
The main Tilden's principles are:

Provoke - attention, curiosity and interest.
Relate – to the everyday life of your visitors.
Reveal – the main concept or theme through some creative or unusual viewpoint.
Address the Whole – make sure your program relates to your main program theme.
Strive for message unity – use the correct supporting elements in your program to illustrate your theme or main concept.

Tilden's principles are based on Learning Concepts (in Veverka, 1998):

- We all bring our pasts to the present.
- Categories can blind us.
- First impressions are especially important.
- Unless helped, we often fail to find, see or comprehend.
- Meanings are in people, not in words.
- My perception is not your perception.
- Circuit overload causes distortion and fatigue.
- Feedback is essential.
- Simplicity and organization clarify messages.
- A picture can be worth than 1000 words (but can be the wrong 1000 words).

2.2.2 Hands on experience and practicum on interpretation

Agenda of the interpretive training course included at a first stage three successive workshops that took place in one day with the following issues:

Workshop 1-Concept map: approaching the concept of geological-geomorphological heritage.

Workshop 2- table mat: Geotourism and crucial issues, focused discussion in groups.

Workshop 3- card sort: Geoparks, priorities and scale of actions.

All three workshops attempted to answer the question: *why a course on geological heritage interpretation*. Discussion at the end of the day was a stimulus for the main course on interpretation in the following days.

The course included theory and practice in the room, as well as at the spot (case study Lavreotiki) training on interpretation issues.

Started with Introduction to heritage interpretation, passed to Planning and design of interpretive media and to Interpretive master planning for heritage/geological sites, parks and facilities.

Armed with first experiences on interpretation concepts, a Field Trip in Lavreotiki and its ancient mines and other geosites in the area for hands-on experience took place. Sites assessment has been preceded in the framework of 1.1.sub-project of the reasrch project. The area is under study for a geopark establishment. Famous since ancient times for its substratum, rich in metals and minerals, the region of Laurium became a major metallurgical centre as early as 3000 B.C. approximately, when the first galleries were dug. Laurium provided all the great civilisations of the Aegean with silver, lead and bronze. The importance of the Laurium mines for the city of Athens grew rapidly after the 6th century B.C.

Practicum on site experience to begin an analysis and interpretive planning considerations, started with the depiction of interpretive on the spot signs.

Back in room Interpretive planning practicum for the site visited, to develop the interpretive plan draft for Laurium to include: Specific objectives, Specific theme and storyline flow, Potential visitors and marketing considerations, Begin filling out interpretive planning form sets for inventoried sites, Develop an implementation and operations matrix for putting the plan into action, Discussion for next steps to take (Veverka, 2007). These considerations helped in preparing the specifications and studies of sub-project 1.4.

The interpretive workshop was evaluated by a critical friend (Demertzi, 2007).

While seminar was open only to IGME geoscientists and research project special objectives, an open session on “An interpretation general overview” took also place that gave the opportunity to invite interested people from relevant domains (universities, NGOS, private domain, ministries etc) and have an interesting and feed backing discussion.

2.3 “Series Geotrails in Greece” Publication

The series “Geotrails in Greece” (Athanassouli et al, 2009; Epitropou, 2009; Janikian, 2009; Kossiaris, Michail, 2009; Paschos et al; Vougioukalakis, 2009) is a pilot publication (ed. Theodosiou) of IGME, provided in Greek and in English version, for six greek areas: Thassos, Maroneia, Epirus (Vikos, Acheron, Kokkinopilos), Lavreotiki, Nisyros, W. Crete, Gavdos. Supported by GIS-aided DB, it is completed with in situ panels and an interactive application at the Museum of IGME. A survey (evaluation) of the geotrails, the cards and the signs is uploaded currently on www.igme.gr

Each folder of the series contains a number of 12-15 numbered waterproof cards. The 12cmx28cm rainproof folder can be hanged in order to let the hands of the hiker free. First cards deal with general issues like: **Background on the area**, **How to use the cards**, **Useful information (and credits), Code of conduct of the responsible hiker**, **Warnings**. Follow cards briefing the natural, cultural heritage of the area, as well as its geological history, a card present the group of the suggested geotrails in a map, while in the successive cards the suggested geotrails are described severally on a map, a text and photos. In the following paragraphs the general cards, more or less the same in all folders are described, as the rest cards are specific for its area. Photos, sketches, geological maps and sections are included interpreting and decorating the geosites in the cards.

2.3.1 Background on the area

The area under concern is presentes briefly focussing on its geological heritage interests, as well as on specific nterests which ourlines its specific character, its physiognomy.

2.3.2 How to use the cards

The trails described in the cards have been designed to let us know some key points in the geological history of the area, all intimately connected with its cultural history. The introductory cards briefly outline the natural, cultural and geological heritage of the area, while the rest of the cards describe the respective trails.

Some of the routes are designed to be covered by car, whereas others are meant to be completed on foot. Each card describes one route except a few cards which describe more than one shorter routes. The paragraphs that begin with a letter (A, B...) contain instructions on how to reach a site, whereas the numbered paragraphs (1, 2...) provide mainly information on the geological interest of a location (geosite). The same letters and numbers can be seen on the map.

The maps on the cards are indicative and the information they provide is not exhaustive. The 1:50,000 topographic map is an essential tool for your hike, and you could also use the corresponding geological maps.

Some of the geotrails concentrate on one particular topic, while others cover more than one topics. Several geotrails run along designated trails of the international, national or local network.

The coloured geotrails that are traced on the map (one colour for each trail) are not currently marked on the spot. The geotrails will eventually be marked with signs (initially, with the name of the geosite and, later, with further interpretative information) at the points of interest described in these cards. That is why it is a good idea to observe carefully the route you are covering, for relevant signs. Before you set off, it is also a good idea to read all the commentary in the cards regarding your route. The trails are all relatively easy; when a trail presents a certain difficulty, this is mentioned in the corresponding card. What you need is a car in good condition, appropriate clothing, hiking boots, some equipment (e.g. walking stick, torch...), water, food and good company.

2.3.3 Useful information. Credits

This first attempt at tracing geotrails focused on the geotrails running along existing roads or open paths with a minimum of marking. In a few cases, the trails cross private or archaeological sites. Geohikers should behave accordingly in each case, respect the rights of the landowners or the rules of the sites and try to maintain them in the best condition possible.

During the planning of the series, several similar attempts have been used as reference (Flowerdew, Smyth, ed. Mc Keever, 2001; ProGEO Croatia, 2008; Fassoulas et al, 2008; Zouros et al, 2008; Sperrins Tourism limited, 2002).

Credits for the entire work regarding field research, texts, photographs, project coordination, editing, design, coordinating department, copyright, publisher are referred as well.

2.3.4 Code of conduct of the responsible hiker

When we hike along a trail, it is a good idea to keep in mind that this is a, public or private, protected area. The environment is a source of health, fitness, pleasure and recreation on condition that we treat it with care. It is, therefore, desirable to follow some basic rules.

- Use a car in good condition, preferably an off-road vehicle.
- Wear clothing that is appropriately warm or cool, depending on the time of the year. Use walking footwear (preferably hiking boots).
- Park carefully so that you do not obstruct entry to or exit from a place.
- Do not damage fences or walls.
- Be careful when lighting fires! If you see fire burning, call the Fire Brigade immediately.
- Do not leave any waste material behind.

- Avoid aimlessly collecting minerals or fossils. Mineral and fossils are more valuable when encountered in their natural context.
- Use the geologist's hammer wisely.
- If an accident occurs, notify emergency services immediately.

2.3.5 Warning

Hikers who wish to cover the trails we propose should know that they are doing so at their own risk. IGME will bear no responsibility for any incident that might occur.

2.3.6 Where to ask for material provision

For information, publications, studies and maps on the geology of Greece or of specific Greek regions, contact the Greek Institute of Geology and Mineral Exploration Greek Institute of Geology and Mineral Exploration.

The cards that follow in the folder are specific for its area, thus they are referred by their name but are not described here:

2.3.7 map of the area of interest with the suggested geotrails

2.3.8 Natural and cultural heritage of the area

2.3.9 Geology

2.3.10 Geotrail 1, 2, etc.

2.4 Signs small, big, informative, interpretive

Geotrails cards are combined with in situ sings (Page, 1994; http://scottishgeology.com/outandabout/geotourism.html). Large informative-interpretive bilingual aluminium signs of 60cmX70cm have been designed 3-5 for each geotrails area, to be put in central places of the area. Each one contains a topographic map, with the geotrails in the same colours as in the cards and a small general bilingual text promoting the values and the specific interests of the place. A small text in red colour warns for attention. The title of the project, the logos of IGME, project, the programme are also depicted on the sign. Signs are fixwd on a 2m long staff.

Informative small 18cmX21cm signs have been produces, one for its geosite at least to be placed along each geotrail and at the very place of the geosite. Each geotrail's small signs are in the same colour with the geotrail on the map of cards and narg signs. In that way one can realize always in which geotrail one is.

Interpretive signs on geosites are to be prepared with the circumstance of a new project.

2.5 Survey

Survey-evaluation form of this publication and relevant in spot signs are to be found at IGME website (http://www.igme.gr). There, it is to be found a briefing on the project and the sub-projects. The opinion of those who used the cards as well as suggestions will be very helpful for their improvement.

2.6 Interactive application

Supportive to geotrails, geoparks idea but also to geological heritage conservation concept is an application for display at the IGME museum. Exploiting the potential of multimedia and interactive technologies (e.g. touch screens), in a way that will attract the interest of the visitor on the geological history and at the time entertain him, involves in promotion of the idea.

3. Conclusions-Results

Planning of geotrails around the geosites, in combination with other attractions of biotic, archaeological and cultural interest, as well as compilation of interpretative, awareness printed material is one of the objectives of the project. Same material in DB and GIS-aided digital form is used for applications, exploiting the potential of multimedia and interactive technologies, to attract the interest of the visitor on the geological history and at the time entertain him.

Creating the right products will result in the designation of the geological heritage and the establishment of new forms of alternative tourism, a modern tourist trend for the social and economic development of each region.

Designating geosites will also have a positive impact on the awareness and knowledge of geological history at all levels of education, in our country and internationally.

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HYPOGENIC FEATURES IN MARONIA CAVE, THRACE, GREECE. EVIDENCE FROM MORPHOLOGIES AND FLUID INCLUSIONS.

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Abstract

The evolution of caves is usually controlled by meteoric water seepage into karst systems (epigenic process). In some cases, caves are formed by ascending fluids the aggressiveness of which is gained in depth. Such cavities are defined as hypogenic. Many caves considered previously as epigenic are now reinterpreted as hypogenic. Most Greek hypogenic caves are related with confined speleogenesis in karstic rocks near to impermeable rock exposures. At the present study the hypogenic features of the Maronia cave in Thrace of Greece, are described. The cave system is developed in a relatively thin layer of eroded Nummulitic limestones with a Middle Eocene age. Medium scale morphological characteristics such as cupolas and feeders indicate rising flow of solutions. In addition, fluid inclusion studies in selected calcite spars from the cave show elevated temperatures of formation (93 to 164ºC with two peaks at 100 and 140 ºC) from circulating hydrothermal fluids.

Key words: *hypogenic caves, hydrothermal karst, Maronia cave, rising flow morphologies, fluid inclusions, Thrace, Greece.*

1. Introduction

Most speleological studies were concerned with unconfined geologic settings and related to meteoric water recharge. Some explored cave systems in Greece display patterns, morphologies, sediments and minerals that do not correspond to established epigenic karst development and speleogenetic procedures. Hypogenism has different origin and characteristics comparing to epigenic processes. In most cases, this is totally climate independent (Klimchouk, 2007). Hypogenic caves are formed by water that recharges the soluble formation from below, driven by hydrostatic pressure or other sources of energy, independent of recharge from the overlying or immediately adjacent surface (Ford, 2006). They are often referred to as "thermal caves" or "sulphuric acid caves" due to their relation with thermal dissolutions containing sulphuric acid. Hypogenic caves are formed as well in seacoast mixing zones because the aggressiveness that forms them is generated below the surface by diffuse water that infiltrates directly into soluble rocks (Palmer, 2007).

Hypogenism is closely related with thermal waters and hydrothermal karst. The term hydrothermal karst refers to processes of dissolution of cavities and mineral precipitation therein by thermal waters (Dublyansky, 2005). The water must be several degrees warmer than the normal groundwater temperature of the surrounding region (at least 4°C) in order to be classified as thermal (Scoeller, 1962). Conventionally, the temperature of 20°C is considered to be the lower limit of the thermal environment (Hölting and Coldewey, 2005).

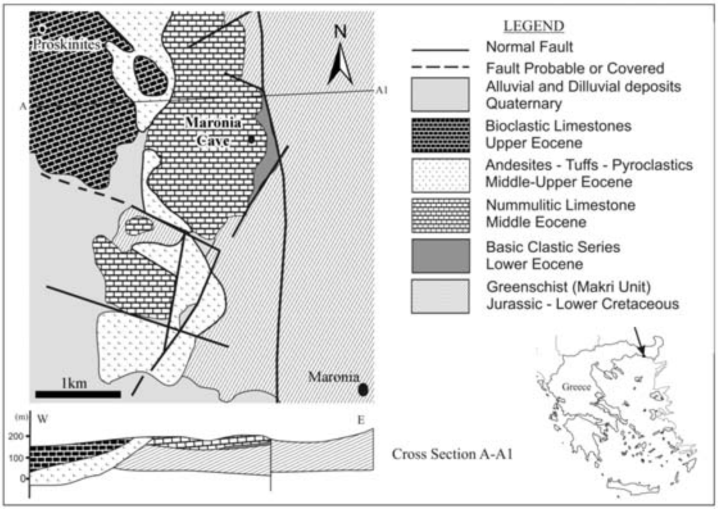

Fig. 1: Geologic map and cross section of Maronia Cave surrounding area (based on maps by Papadopoulos, 1982; Kouris, 1980; Melfos et al., 2005).

At the present study, morphological data from the Maronia cave are being described and genetically interpreted. Rising flow morphologies and fluid inclusions data imply thermal ascending solutions. Preliminary results of the fluid inclusion study are presented here in order to confirm this idea of the thermal environment during the speleogenesis. The purpose of this research is to demonstrate the mechanism for the deposition of calcite, forming the speleothems, and its physicochemical conditions in the context of the fluid inclusions data.

2. Geological setting

Maronia cave is located at the Koufoplati hill (3 km NW of the Maronia village) and developed in a relatively thin layer of eroded Nummulitic limestones of Middle Eocene age (Kouris, 1980; Papadopoulos, 1982; Melfos et al., 2005; Pavlides et al., 2008). These Nummulitic limestones have been unconformably deposited on top of the underlying Mesozoic greenschists of Makri and Drymos-Melia Units (Circum Rhodope geotectonic belt), and are spread over a wide area, covering today the top of the region hills (Fig. 1). The limestones are strongly fissured and fractured, slightly inclined towards the west and contain several species of fossilized foraminifera, algae, corals, sea urchins, bivalves and bryozoa. A basal clastic series partly defines the contact between limestones and the underlying greenschists. It comprises mainly conglomerates and sandstones and is considered to be the regression series marking the beginning of limestone deposition.

The greenschists of the Makri Unit are a complex of Jurassic-Lower Cretaceous metavolcanic rocks (lavas and tuffs) of low metamorphic grade. The Mesozoic metamorphic rocks and the Eocene limestones are intruded by Oligocene volcanic rocks, which, in the area of Maronia cave, are represented mainly by altered andesites alternating with bedded and partly unbedded tuffs. The andesites and the nummulitic limestones are overlain by up to 60 m thick bioclastic limestones of Upper Eocene age. The superficial microtectonic analysis has shown two main sets of joints: the primary one (D1) is striking S20°E to S30°E and comprises of long (>10 m) and quite sparsely (*ca.* 0.5 m) developed joints, while the secondary one (D2) is striking N60°E and comprises shorter joints (Pavlides et al., 2008).

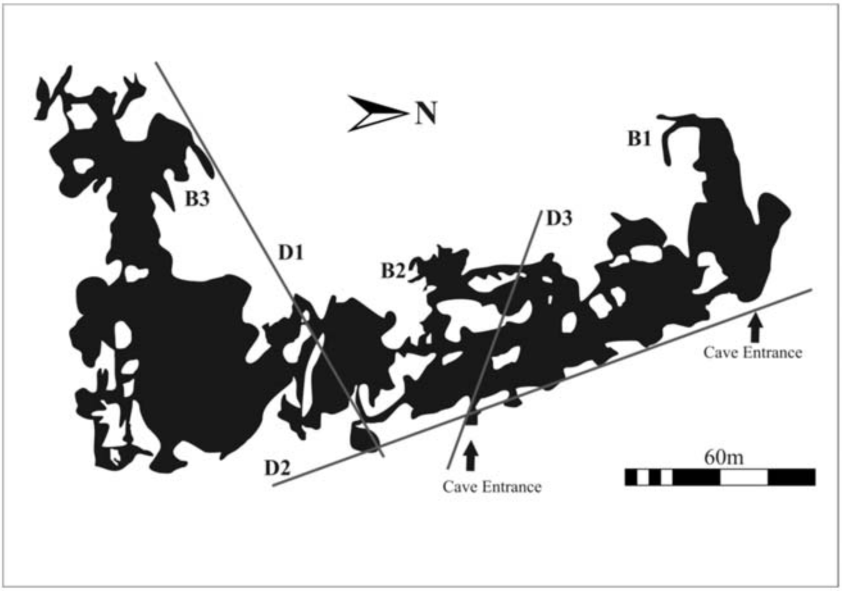

Fig. 2: Simplified plan of the Maronia cave (based on Petrochilou, 1984). The main tectonic lines depicted in map with D1, D2 and D3. A lot of blind terminations are also distinguished (B1, B2, B3).

3. The Maronia Cave

The Maronia cave presents a total passage length of approximately 2,000 meters and expands 10,000 square meters. There are two natural entrances to the cave, both on the eastern slope of the Koufoplati hill. The cave development is apparently controlled by the two main tectonic lines (D1 and D2). The primary one (D1) is trending NW-SE and forms the main axis of the cave chambers, while the other one (D2) is trending ENE-WSW and forms the secondary cave walls (Fig. 2). These lines are in good agreement with surface microtectonic analysis. A third tectonic line (D3), incising the older two, is striking N110°E and constitutes the main cause of the south-eastern cave entrance development. The coincidence in strike between the two main joint systems, the cave chamber orientation and the tectonic lines of the near area, lead to the conclusion that the speleogenesis was controlled by these three main tectonic zones. These breaks seem to be the recharging ways of the hypogenic ascending waters. These tectonic lines are now being controlled by the vadose corrosion phenomena. Most of the cave ceiling is defined by the limestone low inclined strata.

Most of the floor surface is covered with calc-crust flowstone and sediment accumulations. The southern part of the cave comprises the largest chambers characterized by breakdown morphology. It has a great biological interest due to the presence of 11 different species of bats and 31 species of invertebrates. 1/3 of this fauna consists of endemic species (Paragamian, 2004). The northern part of the cave has rather smaller champers with speleothems which have been affected by strongly corrosion processes. The stalactites of the ceiling of some chambers have collapsed.

Extensive calcite secondary deposits occur throughout the cave as common speleothems, such as stalactites, stalagmites, cave shields, draperies, flowstone, rimstone and coralloids, as well as less common such as helictites and mammilaries. The development of speleothems follows the main tectonic lines of the cave and is affected by the contemporary epigenic conditions.

4. Methods of analyses

At the present research, several morphological characteristics of the Maronia cave were observed and analyzed. The macro-morphological analysis was based on the cave survey. In addition, medium scale features were observed in the cave interior and determined water flow directions.

Microthermometric data on four calcite speleothems were obtained using a LINKAM THM-600/TMS 90 heating-freezing stage coupled to a LEITZ SM-LUX-POL microscope, housed at the Department of Mineralogy, Petrology, Economic Geology of the Aristotle University of Thessaloniki. Calibration of the stage was achieved using organic standards with known melting points (chloroform –63.5°C, naphthalene 80.35°C, Merck 135 135°C, saccharine 228°C, Merck 247 247°C) and ice (H_2O). The precision of the heating and freezing measurements were ±1°C and ±0.2°C, respectively. Fluid inclusion shapes and sizes, spatial relationships among inclusions and minerals and phases within inclusions were observed in five doubly-polished thin sections prepared at the University of Hamburg, Germany. Routine heating-freezing runs were performed on a total of 121 fluid inclusions. The FLINCOR program (Brown, 1989) was used to process the fluid inclusion data for calculating salinities and densities.

4.1 Morphological criteria

The macro-morphological analysis, based on the cave survey, indicates a relevant spongework maze pattern, with highly irregular passages interconnected with champers. This pattern is used in combination with the medium scale features in order to interpret the speleogenetical function. The meso-morphological features, including cupolas, roof pendants, partitions, dead ends and calcite spar geods situated in two different levels, display morphologic suite of uprising flow.

Cupolas are abundant in most parts of the cave (Fig. 3A). They are located mostly at the ceilings composing ceiling channels. They are rounded solution pockets indicating slow moving thermal water. They rarely indicate corrosion by condensation in convecting air. Some cupolas are hosted at inclined cave walls.

Pendants are residual pillars of rock between channels cut into ceiling and interpreted as bedding plane anastomoses or as pillars between closely-spaced paragenetic ceiling channels (Fig. 3A). The latter fits well to epigenetic processes as well. However, the hypogenic explanation best fits to the model of buoyancy currents rising from multiple feeders (Klimchouk, 2007). They have widespread occurrence at the southwestern part of Maronia cave. In many cases, they are covered by epigenetic speleothems (stalactites, coralloids). Feeders (inlets) are scattered found on the floor of the cave (Fig. 3B). Most of them are covered with clastic sediments. They represent basal input points of hypogenic solutions.

Calcite spar geodes are found at the central part of the cave (Fig. 3C). The crystals (dogtooth spars) have dimensions from 2 to 9cm (main axis) and comprise fluid inclusions. Since 1930's, calcite spars, found in voids in carbonate rocks, were considered to be the product of descending meteoric karst waters, but detailed fluid inclusion studies by Ermakov (1945) on several cave deposits revealed the hydrothermal nature of this kind of calcite (Hill and Forti, 1997). Mammilaries are also phreatic speleothems usually formed by thermal waters. They comprise calcite coating at bedrock projections and they are often rimmed by coralloids or stalactites at the Maronia cave (Fig 3D).

Partitions and blind terminations are indicative of hypogenism (Fig. 3E). They are thin separations

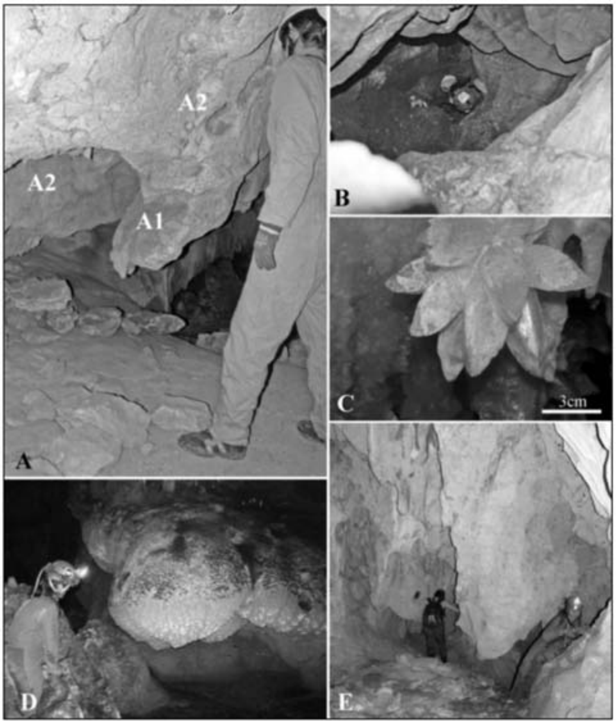

Fig. 3: Hypogenic features in Maronia Cave: A) View of the northern part of the cave, A1) Pendants, A2) Cupolas in cave walls, B) Caver inside a feeder, C) Calcite Spars, D) Mammilaries, E) Two separate partitions leading to dead-end with cupolas at the ceilings.

between adjacent passages or chambers formed by intense dissolution of the bedrock. Several blind passages are separated by partition walls. Blind terminations of passages in the Maronia cave can be clearly distinguished at the plan view of the figure 2. They are widespread and formed by the enlargement of a single, isolated fracture.

4.2 The fluid inclusions

The fluid inclusion data were obtained from calcite spars which comprise the speleothems in the Maronia cave. Fluid inclusions were evaluated using fluid inclusion types and fluid inclusion assemblages (FIAs). FIAs are groups of inclusions of similar habit, having similar degree of filling (gas to liquid ratio) and showing similar, within 10°C to 20°C, homogenization temperatures. This evaluation ensures that the results were not influenced by different sizes and shapes of fluid inclusions and it helps to eliminate variable data caused by changes after entrapment (Goldstein and Reynolds, 1994).

Fluid inclusions in the calcites of the Maronia cave have regular or irregular shapes (Fig. 4), and are isolated or are arranged in clusters and planes. Inclusions with negative crystal or rounded to elongated isometric shapes, which are mostly isolated, often occur along crystal faces of calcite. They are assumed to be primary in origin with only a few considered as secondary, according to the criteria of Roedder (1984) and Bodnar (2003). Microthermometric measurements were conducted mainly on primary fluid inclusions; inclusions that had been necked down or were secondary in origin were avoided.

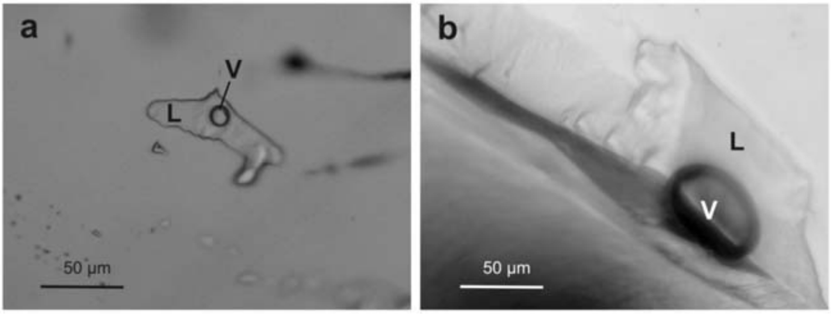

Fig. 4: Two-phase aqueous fluid inclusions (a,b) in calcite from the Maronia hypogenic cave. L: Liquid, v: vapour.

Microthermometric results and compositional data from 121 fluid inclusions are depicted in Figs. 5 and 6. At room temperature, only two phase liquid-vapor inclusions were identified. Inclusions that were analyzed ranged in diameter between 9 and 105 µm and in some cases they reached up to 500 µm. They all homogenized into the liquid state. The primary fluid inclusions have relatively consistent liquid to vapor ratios (5–10 vol % vapor). The variability in homogenization temperature data is due to real variability in the FIAs (Goldstein 2003).

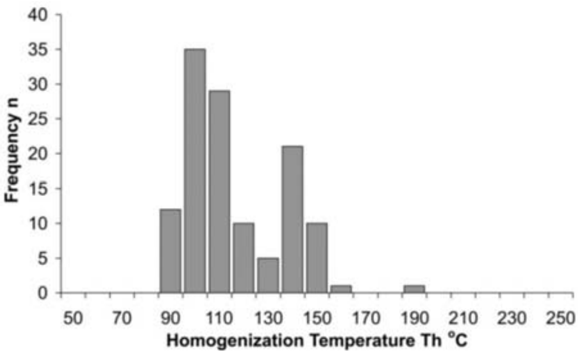

Fig. 5: Homogenization temperatures of two-phase liquid-rich aqueous fluid inclusions from the Maronia cave.

Homogenization temperatures of the fluid inclusions range mainly from 93°C to 164°C, and show a bimodal peak at 100°C and 140°C (Fig. 5). Eutectic temperatures (T_e) around -21.4°C suggest that salts in the fluids are dominated by NaCl (Crawford 1981, Shepherd et al. 1985). The final ice melting temperatures range from -0.1°C to -0.6 °C, corresponding to very low salinities between 0.2 and 1.0 wt% NaCl equiv. Many inclusions in calcite can be grouped into FIAs which have a constant liquid to vapor ratios (~10%) and variable shapes, clustering along linear trends that do not cross cleavage or growth boundaries. FIAs showed restricted temperature ranges such as 93°C to 102°C, 99°C to 124°C, 104°C to 114°C and 141°C to 156°C, showing that the assemblages are true FIAs and, therefore, these ranges probably represent primary T_h.

5. Discussion - Conclusions

The majority of the hydrothermal karsts are attributed to CO_2 from deep seated sources such as magmas or decarbonation reactions during rock metamorphism (Spötl et al., 2009). According to

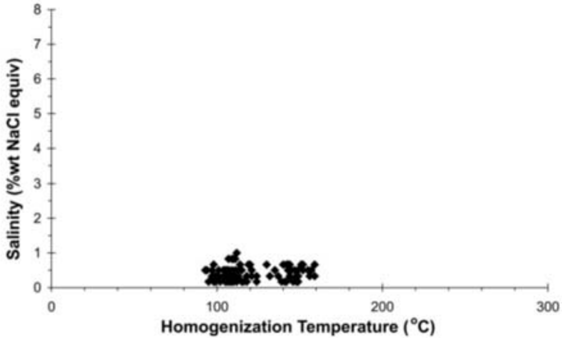

Fig. 6: Homogenization temperatures versus salinity plot for the fluid inclusions from the Maronia cave. Salinity was calculated using the equation of Potter et al. (1978) and Bodnar (1993).

Dublyansky (1995) thermal waters ascending from depth are saturated with respect to CO_2 and become a potential factor in dissolution of carbonate rocks near the land surface or the ground water table. The upwelling warm waters are deeply circulating meteoric, and most rarely karst waters, which are connected with the precipitation of large calcite crystals in the karst systems, usually below the water table (Ford and Williams, 1989; Forti, 1996; Martini and Marais, 1996).

Based on the morphological features and the microthermometric studies the Maronia cave has been developed under hypogenic processes. Thermal ascending water is the main cause of morphological features such as cupolas, roof pendants, partitions, dead ends and calcite spar geods. Epigenic morphologies and sediment accumulation has masked these hypogenic elements.

The fluid inclusions in calcite from the Maronia hypogenic cave and the thermometric conditions derived from these inclusions, resemble those associated with hydrothermal karsts elsewhere (Bosák, 1998; Immenhauser et al., 2007; Spötl et al., 2009). It is therefore most reliable that the studied speleothems were formed at relatively high temperatures from 93°C to 164°C, with two peaks at 100°C and 140°C, supporting the assumption that the Maronia cave was formed under confined conditions in a geothermal convection system.

A hydrothermal derivation of the fluids is the most possible process for the calcites formation. The low salinities (0.2 and 1.0 wt% NaCl equiv.) are possibly attributed to the circulation of downward migrating dilute meteoric water. Such a process is very likely in a hydrothermal environment of shallow depth, with fault-controlled vein structure. We estimated the pressure of the fluids, applying the Brown and Lamb (1989) equation of state to the microthermometric data of the H_2O-NaCl system. It is around 5 bars, indicating that the Maronia cave's last speleogenetical stages are located in a very shallow depth, very close to the surface. In this case pressure correction is not necessary and the homogenization temperatures correspond to actual trapping temperatures. Figure 6 shows a plot of the salinity data versus the homogenization temperatures for the liquid-rich aqueous fluid inclusions. From this diagram it is evident that the temperature decreases while the salinity remains constant. This implies that the temperature of the ascending fluids dropped from 164°C to 93°C without any change in their salinity. This episode was followed by cooling of the system due to the mixing of the warm with cold waters in shallow depths.

The andesite intrusion during the Upper Eocene forced the karstic aquifer to confined conditions. The thin carbonate unit was overlain by andesites and underlain by the impermeable strata of Makri unit's greenschists (Fig. 7). The early speleogenesis could be connected with the intrusion of the volcanic rocks in the area of the Maronia during Miocene. Small magmatic chambers generated the hydrothermal circulation and the convection of the meteoric waters in a geothermal system. Tectonism and uplift imposed fracture permeability which permitted thermal fluids to migrate upwards.

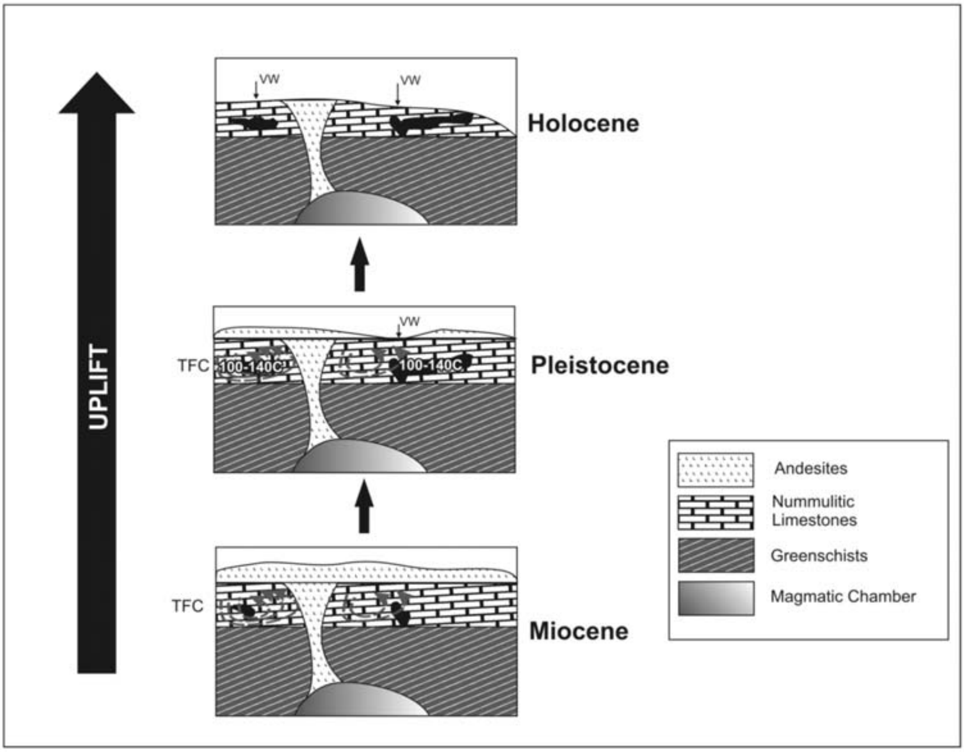

Fig. 7: Hypothesis on speleogenetical evolution of Maronia area. During Miocene the intrusion of andesites generates thermal fluid circulation (TFC) in the Nummulitic limestones that forms hypogenetic voids (confined karstic aquifer). In Pleistocene, meteoric water (VW) directly affects the phreatic conditions (unconfined karstic aquifer), while in Holocene is main cause for corrosion in vadose zone.

This function of thermal circulation formed small scale hypogenetic voids with integrated karstic conduits in phreatic conditions. The cavities were interconnected inside the confined karstic aquifer. Ascending thermal water was recharging the cave system through feeders and developed rapidly partitions, blind corridors and cupolas. The calcite spars were formed not until the phreatic conditions became swallower under the proccess of the area's uplift. This tectonic uplift led to vadose processes that mask the hypogenic features. The protective caprock has been entirely stripped under the Nummulitic limestones so vadose phenomena became more intense.Vadose corrosion is the only contemporary speleogenetical process in the Maronia cave. Moreover, breakdown morphology is taking place and develops the big cave chambers. The cave ceilings become thinner and consequently a new vertical entrance will be formed.

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PALAEOCLIMATIC EVOLUTION IN LOUTRA ARIDEAS CAVE (ALMOPIA SPELEOPARK, MACEDONIA, N. GREECE) BY STABLE ISOTOPIC ANALYSIS OF FOSSIL BEAR BONES AND TEETH

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Abstract

Carbon and oxygen stable isotope values ($\delta^{13}C$, $\delta^{18}O$) were obtained from structural carbonate in the bioapatite of bear bones (Ursus ingressus) from Loutra Arideas cave, Almopia Speleopark, Macedonia, N. Greece. Samples of Late Pleistocene bear bones were studied for palaeoclimatic reconstruction of the area. The age range of the fossil layers is from 32ka BP to a maximum of 38ka BP. Generally, the palaeoclimatic proxy is correlated with literature data for climatic variations in the area during Late Pleistocene, whereas dietary behavior was investigated taking into account possible diagenetic processes that may have affected the carbonate matrix of the bones.

Key words: *Cave bears, stable isotopes, bioapatite, palaeoclimate, Almopia, Greece.*

1. Introduction

Recent palaeoclimatic studies include several different proxies for reconstruction of the Late Pleistocene unstable climatic and environmental conditions. This frame of research gets even more complicated in the transition climatic zone of Eastern Mediterranean region, which experienced several alterations during the last 40ka. Fossil bones offer a suitable material for such study and their isotopic composition has been widely used. In this study, fossil bones of cave bear from N. Greece have been used. However, in order to render fossil materials as reliable for palaeoclimatic and palaeodiet interpretation, diagenetic effects should be investigated.

Cave bears are considered to be endemic in Europe (Kurten, 1976). The diet and the physiology of this species are not well known. However, the morphology of teeth, skull and mandible indicate a basically herbivorous regime (Kurten, 1976; Mattson, 1998; Rabeder et al., 2000; Grandal-d'Anglade et al., 2005). The metabolism of this species is usually considered similar to this of the American black bear (*Ursus americanus*) or of the brown bear (*Ursus arctos*), according to Fernández-Mosquera et al. (2001). The fact that the cave bears are thought to have been up to 3 times larger than modern brown bears led Hilderbrand et al. (1996) to hypothesize that they were omnivores like most other temperate zone bears,

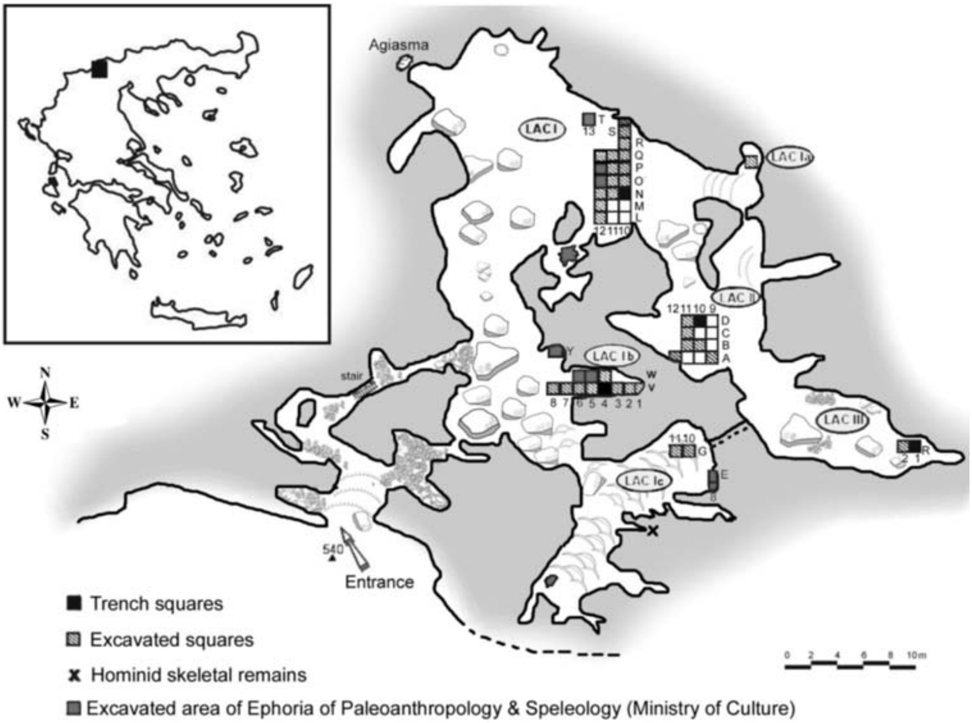

Fig. 1: Ground plan of the Loutra Arideas bear cave with the excavated block of squares of the various chambers [based on the topographic plan (Kambouroglou and Chatzitheodorou, 1999; Kambouroglou et al., 2006) modified in Tsoukala et al. (2006)].

but because of their size were specialized for feeding on megafauna, including carrion. The shortage of data in literature concerning cave bears isotopic analyses in combination with the burden of the difficulties in spotting and sampling such rare materials makes difficult to compare the results of a study.

Bones consist of an inorganic and an organic part. The inorganic part of the bone is mainly crystalline minerals in the form of bioapatite ($Ca_{4.5}[(PO_4)^{2.7}(HPO_4)^{0.2}(CO_3)]^{0.3}(OH)_{0.5}$, Hoppe, 2006), which is composed of both -CO_3 and -PO_4. The organic part of matrix is mainly composed of collagen; however, in this study just the inorganic part of bioapatite was analyzed. Oxygen stable isotope ($\delta^{18}O$) composition of both -CO_3 and -PO_4 is used for palaeoclimatic reconstruction while carbon stable isotope ($\delta^{13}C$) of bioapatite (-CO_3) provides information for both palaeoclimatic conditions in the habitat of the animals and their palaeodiet habits. Furthermore, diagenetic effects of the fossil bones can be identified by $\delta^{13}C$ variations.

2. Setting of the area

The material was excavated from Loutra Arideas cave in Northern Greece (Macedonia) (Fig. 1). The cave is located on the slopes of the Voras Mountain, at an altitude of 540m. The abundance of the milk teeth shows clearly that bears used the cave as a den. The fossils originate from other places or cavities, but they were moved by floodwater to their present sites, somewhere between 34 ka and 32 ka B.P. while according to radiocarbon dating these cave bears lived at least 37 ka BP (Rabeder et al., 2006). According to Rabeder and Hofreiter (2004), the bear findings belong to the species *Ursus ingressus*.

3. Materials and Methods

Fossil bone samples were collected during excavations from B11 square (Fig. 1). The material went under a chemical procedure to isolate the inorganic phase of the bone. In many cases, the protocol used for the isolation of the inorganic material has some variations between the published studies. Each researcher adapts the method in accordance to the samples' particularity, after performing a number of tests and analyses (Bocherens, 1992; Koch et al., 1989; Fricke et al., 1998; Iacumin et al., 2004, Hoppe, 2006). Studies have been done on the effects of these adaptations (Garvie-Lok et al, 2004).

The cleaned material was manually powdered by agate mortar. 20 mg of the material was soaked in 30% H_2O_2 to eliminate the organic material and afterwards in 1M acetic acid buffered solution to remove as much as possible the labile carbonate present in the sample. Finally the samples have been dried in an oven at 60°C, before the analyses.

The isotopic analyses of the bones took place in the Stable Isotope Unit of Institute of Materials Science (NCSR Demokritos, Athens) on a ThermoScientific Delta V Plus mass spectrometer, after reacted with ortho-phosphoric acid (99%) at 72°C, to produce CO_2 (GasBench II device). Results are reported in standard delta (δ) notation and units are reported per mil (‰).The standards used for comparison were NBS 19 and NBS 18 carbonates and an internal Carrara marble standard (VPDB).

4. Data and Results

4.1 Oxygen isotopic analysis

The period between Upper Pleistocene until the Holocene is characterized by a general climatic instability (Dansgaard et al., 1993). According to Iacumin et al. (1996) the difference between oxygen isotopic values from PO_4 ($\delta^{18}O_P$) and from CO_3 ($\delta^{18}O_C$) of bioapatite is about 9.2‰, conclusion given through research on bone and tooth samples of modern mammals. Similar value is given by Longinelli et al. (1973), in a study on modern carbonate shells, a completely different material by a biological point of view. Other more recent studies (Bryant et al., 1996, Zazzo, 2001) confirm these equations. The $\delta^{18}O_C$ VSMOW values of B11 square were used to estimate approximate values of $\delta^{18}O_P$ by using the value of Iacumin et al. (1996). Then, the equation $\delta^{18}O_P=0.64* \delta^{18}O_W+22.37$ after Longinelli (1984) was used, in order to calculate an estimation value of the $\delta^{18}O_W$ of the time of bears living (table 1).

Table 1.

Depth (cm)	*$\delta^{18}O_C$ vs SMOW (‰)*	*$\delta^{18}O_P$ vs SMOW (‰)*	*$\delta^{18}O_W$ vs SMOW (‰)*
88-103	22.21	13.22	-14.29
103-113	20.59	11.62	-16.79
113-123	22.63	13.63	-13.65
123-128	23.24	14.23	-12.71
128-133	22.88	13.88	-13.26
133-138	23.53	14.52	-12.26
138-143	22.07	13.08	-14.51

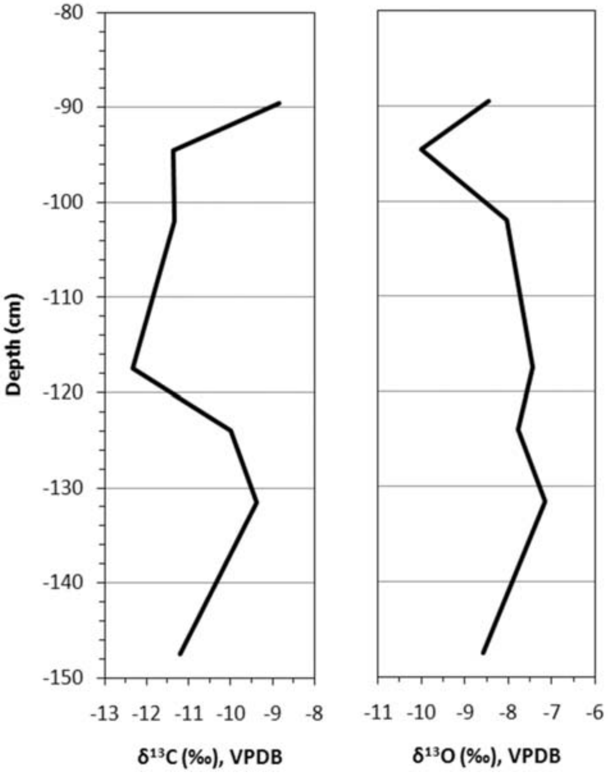

Fig. 2: Isotopic composition ($\delta^{13}C$ and $\delta^{18}O$ vs. VPDB) of cave bear bones from square B11 (Loutra Arideas cave, Almopia Speleopark) versus depth from cave floor surface.

4.2 Carbon isotopic analysis

The study of extinct species lead in most cases to approaches that eliminate at least one parameter. For instance, the results of an extinct species study are compared either to current ones, underrating the climatic conditions and accepting the similarity of metabolisms or to different species that lived under the same climatological conditions rejecting physiological conditioning (Fernández-Mosquera et al., 2001). This intriguing fact led this study to the path of elimination of as many concessions as possible. Fernández-Mosquera et al. (2001) collected isotopic data of cave bear bone collagen from literature, from the same period (Late Pleistocene), by nearby areas in the Eastern Alps, covering a wide range of altitudes (878 – 2800 m). This material is closer to the one of the present study. Both materials belong to the same species and lived in relatively close geographical areas. To achieve this comparison, it is necessary an established relationship between collagen and apatite isotope values provided by Krueger and Sullivan (1984):

$$\delta^{13}C_{apatite} = \delta^{13}C_{collagen} + 7(‰) \text{ for herbivores} \quad (1)$$

$$\delta^{13}C_{apatite} = \delta^{13}C_{collagen} + 3(‰) \text{ for carnivores} \quad (2)$$

The study of Fernández-Mosquera et al. (2001) showed that altitude is not a parameter that affects the carbon isotopic values in a large and incomparable scale. Using (1), carbon isotopic composition of bioapatite was converted to $\delta^{13}C$ of collagen and the values ranged from -19.3 to -15.8‰. An average deviation between them and the data from Fernández-Mosquera et al. (2001) is approximately 4‰ higher. The isotopic composition of the samples ($\delta^{13}C$ and $\delta^{18}O$ vs PDB) is shown in figure 2.

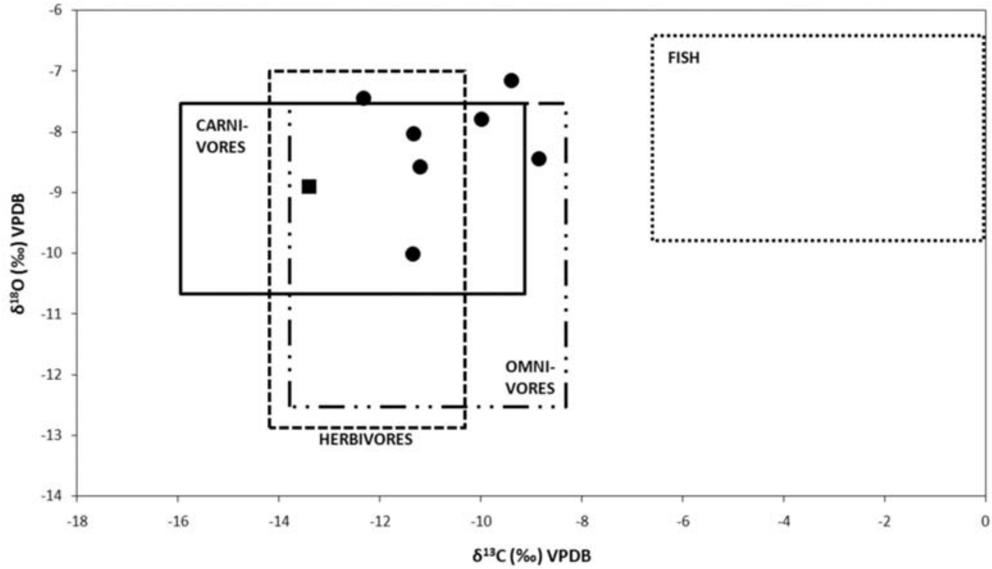

Fig. 3: Plot of $\delta^{13}C$ and $\delta^{18}O$ values (vs. VPDB) from bone structural carbonate of cave bear from Loutra Arideas cave (black circles). Also, bivariate plot of median isotopic composition of brown bear (omnivore) bone structural carbonate (black square). Frames facilitate the identification of the position of each dietary behavior/habitat preference in the plot (modified from Bösl et al., 2006).

5. Conclusions

Based on present isotopic data from local precipitation (Dotsika and Lykoudis, in press), the oxygen isotopic composition of precipitation in the area of Voras mountain (Almopia Speleopark area) is between -8 and -9.5‰. The depleted $\delta^{18}O_W$ estimated in this study by the fossil samples (average -13.92‰) in comparison to the modern oxygen isotopic composition of local meteoric waters (-8 and -9.5‰) indicate probably colder climatic conditions in relation to modern climate in the area. The radiocarbon dating of the samples (ca. 38 ka BP) set their respective populations living during the middle of Marine Isotope Stage 3 (MIS 3, 60-24 ka BP) (Dansgaard et al., 1993). MIS 3, although is considered a relatively warm period of the Würm glaciation, it is still characterized by much more cold and arid conditions in relation to MIS 1 (modern climate). Based on palaeoclimatic data for the region (Digerfeldt et al., 2000; Karkanas, 2001; Tzedakis et al., 2002), the relative colder climatic conditions indicated by the results of this study at 38 ka BP may be correlated with the cold and arid H4 event, assenting wider time limits of that phase due to dating uncertainties.

Studies have shown that depending on the unstable climatic conditions during the living time of the cave bears, they could be either herbivores, omnivores or even carnivores (Richards et al., 2008). These climatic variations probably pushed the cave bear to move southwards to the northern parts of the modern Greek territory. Bösl et al. (2006) distinguished the nutritional habits of different Late Neolithic vertebrates from Bavaria, Germany, including brown bear, using $\delta^{13}C$ and $\delta^{18}O$ of the bone structure carbonate (Fig. 3). Plotting Loutra Arideas cave bear samples' isotopic composition on figure 3, it can be noted that there is a general good correlation between the data and the plotted areas. However, the brown bear isotopic fingerprint seems to fall in different location in the diagram, indicating either distinguished nutritional habits in relation to cave bear or minor diagenetic effects of Loutra Arideas cave findings which may influence their isotopic composition. In fact, carbon stable isotope is possible to be enriched during diagenetic processes due to interaction with "dead" carbon from carbonate rocks and sediments ($\delta^{13}C \approx 0$). Other than that, it is difficult to differentiate the specific nutritional habits of the cave bears, as the overlapping plotted areas do not offer high precision. The estimated $\delta^{13}C_{collagen}$ of the cave bear from Loutra Arideas shows enriched values in relation to other studies (Fernández-Mosquera et al., 2001). This could indicate different nutritional habits (less herbivore), different vegetation in the area (C4 plants, arid conditions) or effects from minor diagenetic processes. From the above, the most likely combination seems to be some differentiation in cave bear diet and some diagenetic effects that influenced the carbonate matrix of the bones. This speculation should be further examined by collagen isotopic analyses and for diagenesis examination (e.g. C/N ratio, mineralogical identification).

6. Acknowledgments

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GEOPARKS MANAGEMENT AND ASSESSMENT

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Abstract

Established in 2000, the European Geoparks Network (EGN), comprising 35 members (November 2009), aims to protect geodiversity, to promote geological heritage to the general public as well as to support sustainable economic development of geopark territories primarily through the development of geological tourism. All requests for recognition as a "European Geopark" must be submitted by the organisation in charge of managing the area. The application dossier includes precise information dealing with identification of the zone, scientific description of the existing geoheritage, management body, management plan, infrastructure, educational and promotional activities, sustainable development policy instituted and geo-tourism. Membership of the EGN is for a period of four years after which membership is reviewed and assessed. The first revalidation procedure occurred during 2004 and since then has helped to keep all Geopark operations, infrastructure and services at a high quality level. The revalidation process involves a field visit by two independent evaluators nominated by the EGN and UNESCO. Assessment methodology examines the progress in geological heritage protection and promotion as well as the development of sustainable economic activity within each territory. However it also takes into account the Geopark's degree of active participation in international collaboration and networking.

Key words: *Geoparks management, evaluation assessment methodology, European Geoparks Network.*

1. Introduction

Following the 1972 Convention on the Protection of the World Cultural and Natural Heritage and the 1991 Declaration on the rights of the memory of the Earth (Martini 1993), a new initiative was developed in Europe by the active collaboration between territories (through local management bodies), aiming at Earth heritage protection and conservation through a sustainable local development strategy, with the support of the EU. According to the proposed new "concept", a European Geopark is a territory with a geological heritage of European significance, a sustainable development strategy, a strong management structure and is often supported by a European funding programme to aid further development (Zouros et al. 2003).

Established in 2000, the European Geoparks Network (EGN) aims to protect geodiversity, to promote geological heritage to the general public, as well as to support sustainable economic development of Geopark territories, primarily through the development of geological tourism. The network has drawn together territories from across Europe that share these aims and now work together in an active and dynamic way in order to achieve them. Originally consisting of four territories, the network has grown to include, as of November 2009, 35 territories across 13 European countries (fig 1). Greece is represented by three Geoparks in the European Geoparks Network, the Lesvos Petrified Forest (2000), founding member of EGN, the Psiloritis Geopark in Crete (2001) and the Helmos – Vouraikos

Geopark (2009), which is the youngest member of the EGN (www.europeangeoparks.org).

In 2001 the European Geoparks Network signed a formal agreement with UNESCO's Division of Earth Sciences, whereby UNESCO gave the network its endorsement. A further agreement was signed with UNESCO in 2004 whereby the EGN was given the responsibility for regulating membership of European Geoparks in the UNESCO Global Geoparks Network (GGN). As a result the EGN acts as the European sector of the GGN. The European Geoparks Network operates through continuous electronic communication, biannual coordination meetings and the establishment of common projects through which territories can exchange ideas, experience and best practices, thereby supporting each other on geotourism development.

UNESCO recommends the creation of similar regional networks, reflecting local conditions, elsewhere in the world. (UNESCO 2008) Today, in addition to the European Geoparks Network, the Asia-Pacific Geoparks Network (A.P.G.G.N.) formed in 2007 is also active and several other regional networks are under consideration in Latin America, North America and Africa (McKeever et al 2009).

The structure of the European Geoparks Network is relatively simple and comprises of an Advisory Committee (11 members including representatives of UNESCO, the International Union of Geological Sciences - IUGS and the World Conservation Union - IUCN) and a Coordination Committee (comprising two representatives from each member). Decisions concerning the network are made only by the Coordination Committee. As part of the Coordination Committee, there is an elected EGN Coordinator and Vice Coordinator to represent the whole Network. They coordinate contacts with other international bodies (E.U., UNESCO, IUGS, IUCN, Council of Europe etc.) and prepare the agenda of the meetings in cooperation with the meeting hosts.

The European Geoparks Network has adopted a common logo which is registered in all European countries. An EGN member has the right to use the European Geopark logo in its communications thereby contributing over time to the creation of a common image of quality, linking the enhancement of European Earth heritage with sustainable development.

Membership in the EGN entitles a Geopark to call itself a European Geopark and to use the logo of the EGN in its promotional material. These logos must only be used on products produced directly by the Geopark management (Zouros 2004, McKeever and Zouros 2005).

2. Geopark management

A European Geopark integrates the range of resources found within its broader region, including geological attractions and geosites, landscapes, wetlands, sites of natural beauty and ecological value, as well as cultural monuments and sites. A Geopark can also include intangible heritage and traditions including gastronomy, crafts and local agricultural products. No distraction or sale of original, ornamental geological material is permitted within a European geopark (Zouros et al 2003).

A broad range of activities combines the main components for the operation of each Geopark, including scientific research, the creation of an inventory and map of geological sites, protection of the geological heritage, the operation of thematic museums and interpretation centers, interpretation and promotion of geological sites, the conservation of fossils, the creation of parks for visitors, the establishment of a network of walking trails linking geological sites to ecotourism infrastructures, the development of environmental education programmes on geological sites, the organization of scientific and cultural events, and the promotion of monumental geological sites. Geoparks also promote themselves as ideal destinations for educational activities (Zouros 2004, McKeever and Zouros 2005, EGN 2009).

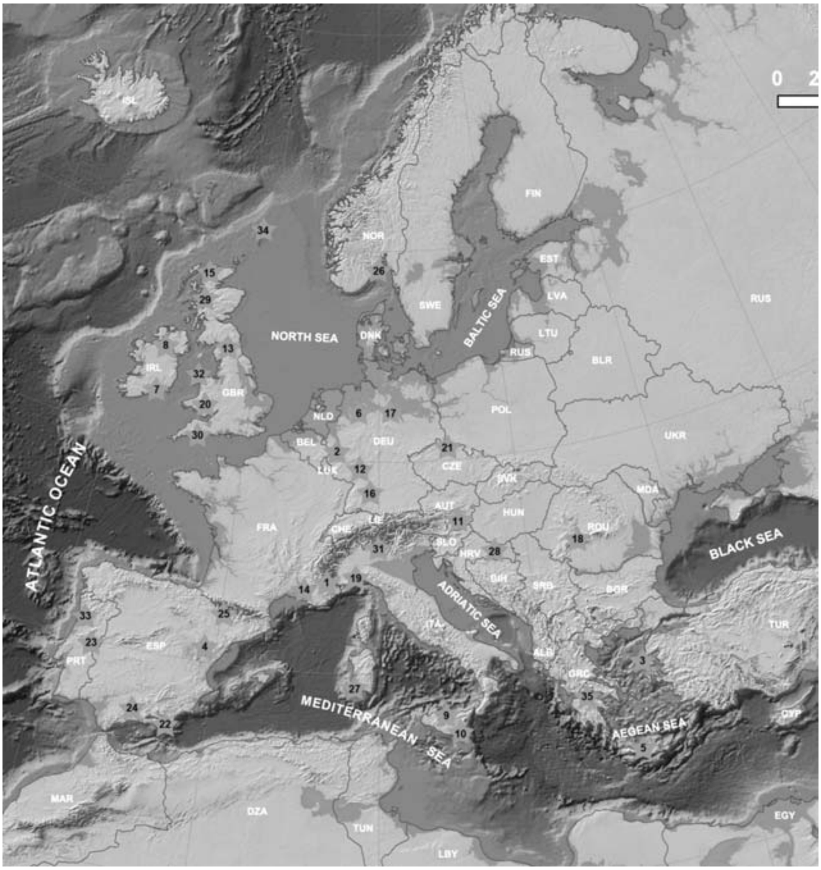

Fig. 1: Map showing the location of the 35 members of the European Geoparks Network as of September 2009. 1. Réserve Géologique de Haute - Provence–FRANCE, 2. Vulkaneifel European Geopark – GERMANY, 3. Petrified Forest of Lesvos – GREECE, 4. Maestrazgo Cultural Park – SPAIN, 5. Psiloritis Natural Park – GREECE, 6. Terra.Vita Naturpark – GERMANY, 7. Copper Coast Geopark – IRELAND, 8. Marble Arch Caves Geopark IRELAND & N. IRELAND 9. Madonie Geopark –ITALY, 10. Rocca di Cerere Geopark – ITALY, 11. Naturpark Steirische Eisenwurzen – AUSTRIA, 12. Naturpark Bergstrasse Odenwald – GERMANY, 13. North Pennines AONB – UK, 14. Park Naturel Régional du Luberon – FRANCE, 15. North West Highlands – UK, 16. Geopark Swabian Albs – GERMANY, 17.Harz Braunschweiger Land Ostfalen– GERMANY, 18. Hateg Country Dinosaurs Geopark – ROMANIA, 19 Beigua Geopark – ITALY, 20. Fforest Fawr Geopark – UK, 21. Bohemian Paradise Geopark – CZECH REPUBLIC, 22. Cabo de Gata – Nijar Natural Park – SPAIN, 23. Naturtejo Geopark – PORTUGAL, 24. Sierras Subbeticas Natural Park – SPAIN, 25. Sobrarbe Geopark – SPAIN, 26. Gea Norvegica Geopark – NORWAY, 27. Sardenia Geominerario Park – ITALY, 28. Papuk Geopark – CROATIA, 29. Lochaber Geopark – UK, 30. English Riviera Geopark - UK, 31. Adamello-Brenda Geopark – ITALY, 32. Geo Mon Geopark - UK, 33. Arouca Geopark - PORTUGAL, 34. Shetland Geopark –UK 35. Helmos Vouraikos Geopark – GREECE.

Geopark educational activities focus on young people, aiming at the promotion of a common European geological heritage as a key factor for environmental understanding and sensitisation on nature protection. The main target group for Geoparks are schoolchildren and university students. Ages range from 4 years upwards to university level and the interpretation and information material produced is tailored to the needs of each age group.

To achieve all of the above a European Geopark must be managed by a clearly defined structure, organised according to the national legislation of each country and with the ability to enforce the protection, enhancement and sustainable development policies within its territory. Through this management body, a European Geopark can play an active role in the economic development of its region. To achieve this active role, the Geopark needs to reinforce the local identity through enhancement of a strong image linked to the geological heritage and the development of geotourism. The Geopark must work with local enterprises to promote and support the creation of new by-products linked to the geological heritage.

One of the main goals for all European Geoparks is to improve and increase the recognition, protection, conservation and promotion of the geological and geomorphological features they contain. To achieve this, Geoparks are continuously developing, experimenting and enhancing methods for preserving our geological heritage and supporting the development of scientific research in the various disciplines of Earth Sciences (Zouros 2005, 2007 Zouros and Mc Keever 2008).

3. Evaluation procedure

In order to achieve high quality standards in Geoparks operations and the services provided to visitors, the EGN has established an evaluation procedure for all new applicants for membership in the EGN. EGN membership is limited to a period of 4-years after which a revalidation procedure determines the renewal of the membership. The revalidation procedure is similar to the evaluation procedure.

The application dossier must include precise information on the following points:

- Identification of the Geopark.
- Scientific description.
- Arguments justifying nomination as a European Geopark.
- Overall economic situation of the zone.
- Sustainable development policy instituted and importance of geotourism in this context.
- Official application for nomination signed by the competent authority.

All applicants need to provide evidence that their operation respects the provisions of the EGN Charter. According to the EGN Charter "the sites in European Geopark must be linked in a network and benefit from protection and management measures. The European Geopark must be managed by a clearly defined structure able to enforce protection, enhancement and sustainable development policies within its territory. No loss or destruction, directly or via sale, of the geological values of a European Geopark may be tolerated." (EGN 2009).

The application is followed by the assessment document in the form of a questionnaire which refers to the main elements of Geopark operation. Submitted nominations need to be checked to ensure that all information as per EGN guidelines has been included and reviewed. Then IUGS carries out a desk top evaluation on the value of the geological heritage. Nominations are discussed at the spring meeting of the EGN and calls for evaluation missions are issued at this stage.

Evaluation missions are undertaken by two Geopark experts who are sent to the applicant territory to evaluate the application and to discuss the application with the relevant national and local authorities as well as stakeholders and local communities. Furthermore, the evaluators are also requested to make comments on the integrity and future management of the proposed Geopark. These recommendations have been, in many cases, critical to strengthening the success of applications in the long run. Evaluation missions reports are discussed and decisions made at the autumn meeting of the EGN.

Every four years the EGN membership review takes the form of a revalidation process involving the submission of a revalidation dossier and progress assessment document. An inspection visit is carried out by two evaluators from two different countries from the revalidating Geopark, nominated by the EGN CC and UNESCO.

The revalidation process involves an examination of progress in geological heritage protection and promotion within the Geopark as well as the development of sustainable economic activity within the territory. However it also takes into account the Geopark's degree of active participation in common activities with the network members (Zouros and Mc Keever 2008).

Once the revalidation process is completed, the results are discussed by the CC in the absence of the Geopark under discussion. One of three results are awarded. A "Green Card" renews the membership in the network for a further 4 years period and reflects the fact that the Geopark has been an active member of the network and has made a significant degree of progress in the areas aforementioned. A "Yellow Card" is issued if the CC determines that the results achieved by the Geopark during its four years of membership in the EGN have not been satisfactory or an issue has risen that does not permit the allocation of the green card. The CC will give the Geopark continued membership for a period of time at the discretion of the CC (e.g. up to a maximum of two years) after which a further revalidation process will be undertaken. If sufficient progress has not been made by that time, that Geopark is issued a red card. A "Red Card" is issued if the EGN CC determines that the Geopark has been inactive over the 4 year period and has done little to advance the work and philosophy of the network. A red card means that the Geopark's membership in the EGN has been revoked. Any Geopark that loses its membership in the EGN automatically loses its membership in the UNESCO Global Geoparks Network. Any Geopark that loses its membership in the EGN has the right to re-apply for membership in the normal manner.

4. Assessment Methodology

4.1 General

A quantitative assessment methodology is performed to assign a numerical value to the main elements in the operation of a Geopark. This evaluation process includes the assessment of five criteria with different weighting. Each criterion includes a series of indicators. The incorporation of each of the above elements in the evaluation process was performed by assigning a numerical value for each indicator.

	Criteria	*DWeighting (%)*
I.	Geology and Landscape	
	I.1.Territory	5
	I.2. Geoconservation	20
	I.3. Natural and Cultural Heritage	10
II.	Management Structure	25
III.	Interpretation and Environmental Education	15
IV.	Geotourism	15
V.	Sustainable Regional Economic Development	10
Total		100

Criterion 1: Besides the description of the geology and landscape, the description of the natural resources and the cultural heritage of the area is also required, thereby introducing a holistic approach to the Geopark's territorial management. It is divided into three sub-criteria:

- I.1. Description of territorial geological resources, which is based on the following indicators a. the number of geosites, b. geodiversity, c. public interpretation of the Geopark's sites of interest, d. comparison to the geology of existing Geoparks.
- I.2. Protection and conservation of earth heritage sites, which is based on the following indicators: a. inventory and significance of geosites, b. strategy and legislation to protect geological sites and features, c. geosite protection against misuse and damage, d. measures to protect geosites and infrastructure against damage and natural degradation.
- I.3. Recognition of the territorial natural and cultural heritage, which is based on the following indicators: a natural value (aesthetic, biodiversity), b. cultural heritage, c. relation between natural resources and cultural heritage.

Criterion 2: The management structure describes the potential of the managing body to apply its strategy in the territory. The assessment of the management body is based on the following indicators: a. effective organization and budget, b. Management plan, c. Action plan, d. marketing strategy, e. adequate staff, f. monitoring of earth heritage protection and geotourism development, g. scientific support, h. interpretation infrastructure.

Criterion 3: Interpretation and Environmental Education describe the activities related to the presentation of the natural and cultural characteristics of each Geopark to the general public and raising public awareness, and especially among young students, of the need for the protection and preservation of Europe's natural heritage through guided tours and educational activities in Geoparks. The assessment of the third criterion is based on the following indicators: a. research, information and education scientific activity within the territory, b. environmental education programmes, c. educational materials, d. published information, e. professional marketing, f. material in different languages, g. guided tours, h. vocational training of guides – rangers, i. marketing educational activities, j. media - press – internet.

Criterion 4: Geotourism refers to the existing infrastructure and activities dedicated to public access and interpretation of the Earth heritage for the general public. The assessment of the fourth criterion is based on the following indicators: a. geotourism attractions and visitors centers, b. quality of interpretation for the public, c. public access and facilities, d. guided tours, e. visitor information, f. infrastructure for adventure sports, g. trails, h. visitors' evaluation.

Criterion 5: Sustainable Regional Economic Development refers to the existing links with local enterprises and the contribution of the Geopark to employment and local development. The assessment of the fifth criterion is based on the following indicators: a. regional food and craft product promotion, b. creation and promotion of regional geotourism products, c. promotion of links between the Geopark and local businesses, d. contracts offered to local business, e. networking with local enterprises.

4.2 The Lesvos Petrified Forest Geopark assessment analysis

The above mentioned assessment methodology has been used to evaluate the operation of the Lesvos Petrified Forest Geopark. The self-evaluation of the management structure and its functionality measured the response of the Lesvos Geopark operation, activities and services to the proposed criteria. A detailed analysis of the scientific, economic and social data was used to examine thoroughly and diachronically all aspects of the management of the Lesvos Geoparkas a means for further improvement. There was a complete documentation of the points given, which led to an objective as

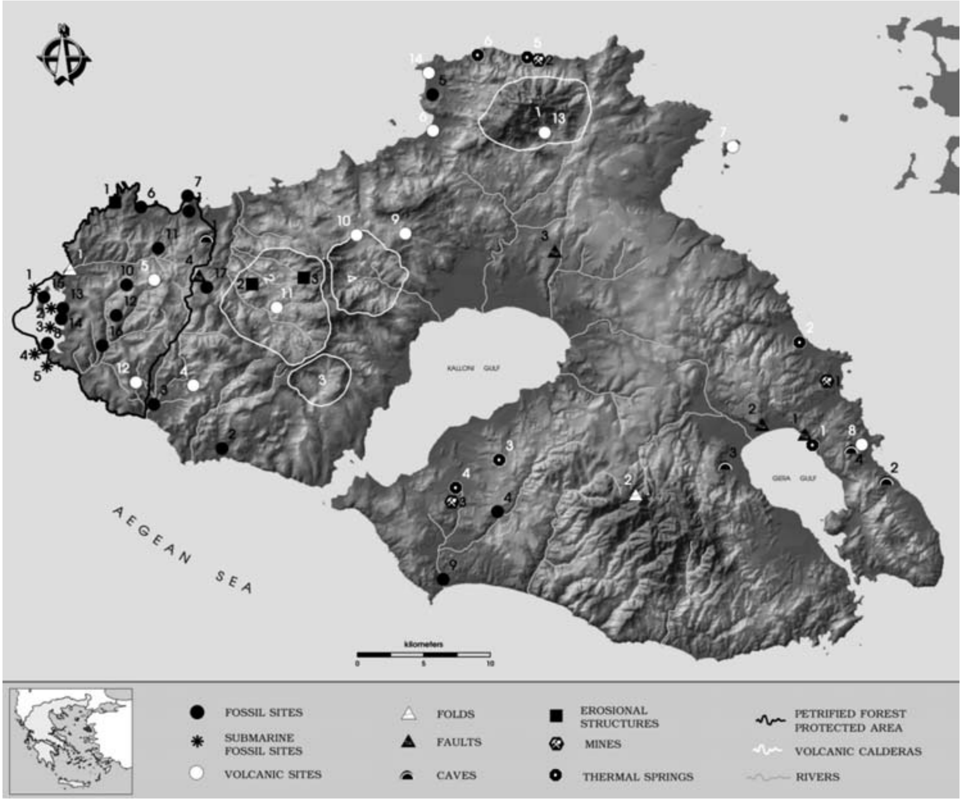

Fig. 2: Geosites on Lesvos Island.
FOSSIL SITES : 1:Koukla fs ; 2 :Tavari fs ; 3 :Eressos fs ; 4 Rougada f.s.; 5 : Molyvos-Petra f.s.; 6 : Lapsarna f.s.; 7 : Gavathas f.s.; 8 : Sarakina f.s ; 9 : Vatera f.s.; 10 : Akrohiras f.s.; 11 : Mavros Lofos f.s.; 12 :Petrified Forest park; 13: Sigri park; 14: Plaka park; 15: Nissiopi park; 16 : Chamandroula f.s.; 17 :Skaminiouda f.s. SUBMARINE FOSSIL SITES : 1. Nissiopi f.s. ; 2. Ag Georgios f.s. ; 3. Fanes f.s. ; 4. Sarakina west f.s. 5. Sarakina east f.s. VOLCANIC : 1: Lepetymnos Caldera; 2: Vatoussa Caldera; 3: Agra Caldera; 4.Anemotia Caldera ; 5. Ipsilou Dome; 6. Petra Volcanic Neck ; 7: Panagia Columnar Lavas; 8: Alifada Vein; 9: Filia Vein; 10: Anemotia Columnar Lavas; 11:Hidira domes ; 12:Eressos Dome; 13: Pelopi Columnar Lavas; 14: Molyvos Columnar Lavas; FOLDS: 1: Faneromeni Folds; 2: Olympos Tectonic Window; FAULTS: 1: Gera Gulf Fault; 2: Larsos Fault; 3: Agia Paraskevi Fault; 4. Antissa fault. CAVES: 1Antissa Cave; 2: Taxiarhon Cave; 3: Mihos Cave; 4: Alifada Cave. EROSIONAL STRUCTURES: 1: Lapsarna Cliffs; 2: Vatoussa Spheroidal Erosional landforms; 3: Voulgaris Gorge. MINES: 1: Moria Ancient Quarry; 2: N.LesvosMines; 3: Magnesite Mines. THERMAL SPRINGS : 1: Gera hot springs; 2: Thermi hot springs; 3: Lisvori hot springs; 4: Polichnitos hot springs; 5: Argenos hot springs; 6: Eftalou hot springs;

possible assessment. The criteria on which the assessment was based were the following.

I. Geology and Landscape: The Lesvos Petrified Forest Geopark includes a core zone (15,000 hectares of the Petrified Forest protected area) and a broad buffer zone (more than 20,000 hectares of the central volcanic terrain). The Petrified Forest, which includes large accumulations of exposed fossilised tree trunks, is a protected natural monument (Presidential Decree 433/1985). The area of the Petrified Forest also belongs to the NATURA 2000 network of protected sites due to its exceptional natural characteristics (fossils, flora and fauna). Based on the results of scientific research, a large number of geosites were identified, assessed, and mapped and a new geosite map of Lesvos was published.

Geosites within the Lesvos Petrified Forest Geopark, apart from the fossil sites, include volcanic geosites, stratigraphic geosites, tectonic geosites - active fault scarps, geothermal fields, karstic geosites and caves, erosional geosites (tafoni) and coastal and fluvial landforms (Zouros 2005). Important cultural monuments lying within the Geopark such as the ancient acropolis of Eressos, the Ipsilou monastery and the Sigri castle are directly related to volcanic geosites. The Lesvos Petrified Forest Geopark applies certain measures for the protection and conservation of the inventory of geosites present in the territory.

II. The management structure: The Lesvos Petrified Forest Geopark is managed by the Natural History Museum of the Lesvos Petrified Forest. The Museum is a legal non-profit entity that belongs to the Greek state and is supervised by the Minister of Culture (N. 2260/1994). The aims of the Museum are the study, research, promotion, exhibition, maintenance, protection and any suitable usage of the Petrified Forest of Lesvos.

The Natural History Museum of the Lesvos Petrified Forest as management body is responsible for the operation and the development of the Geopark. It is well staffed; besides the director, the staff consists of 15 permanent and 25 temporary scientific and technical staff and rangers. Major decisions are allocated to the Board. Its members represent organisations and institutions which are important for the Geopark (such as the different levels of government and different scientific disciplines). Chaired by a president, the Board decides on main strategic issues and projects which are proposed by the Director of the Geopark.

III. Information and Education activities: The Geopark has produced a series of informative scientific and popular publications for visitors such as coffee-table books, field guides, magazines, conference proceedings, brochures, leaflets, posters etc.

Educational activities in the Lesvos Geopark support the development of educational geo-tourism. Environmental education programmes organized for elementary and high school students at the Petrified Forest cover a broad range of activities such as geosite recognition, fossil excavation and conservation, nature observation, bird-watching etc. School visits are organized during spring and autumn, outside the main tourist period, thus contributing to the local economy.

IV. Geotourism: The Lesvos Petrified Forest Geopark has developed a range of tourist infrastructures to serve its visitors. The Natural History Museum of the Lesvos Petrified Forest in Sigri village is at the core of these infrastructures. This state-of-the-art museum has become a key factor in attracting visitors to this part of the island. Within the Petrified Forest's protected area, the main fossil sites are fenced and safeguarded, and five visiting parks have been established, attracting thousands of visitors each year. These include the Petrified Forest Park, the Sigri Park, the Plaka Park, the Nisiopi Park and the Skamiouda Park. Several other areas will become visiting parks during the next years, as the Museum has already begun the necessary procedures. Another main infrastructure is the "Lava Paths" that lead visitors down the ancient paths of the pyroclastic flows from the main volcanoes to the Petrified Forest, equipped with information panels that explain the various geosites. A broad range of activities accomplish the task of attracting and informing visitors. Lectures and multimedia presentations at the Museum, guided tours in the Petrified Forest parks, thematic guided walks, guided trekking and various recreation activities in the vicinity of geosites help raise public awareness about the value of geosites.

V. Sustainable development: The Geopark has created links with local tourist enterprises, restaurants and small hotels in order to provide the necessary infrastructure to meet the needs of the increasing number of park visitors. In the Geopark, the number of "Bed and Breakfast" accommodations has doubled over the last few years in order to meet the increasing demand. More importantly, visitors have increased the duration of their visit to the Geopark area. As a result the majority of the new enterprises established in western Lesvos are connected with the activities of the Lesvos Geopark. The Geopark also supports the making of local handicrafts such as the production of fossil casts and souvenirs by local enterprises. These items are on sale in the Museum shop along with a variety of other locally made products. Lesvos has a long tradition in pottery and wood carving and the Geopark promotes these products to its visitors. The Lesvos Geopark also collaborates closely with women's agrotouristic cooperatives and local organic food producers to offer its visitors the opportunity to taste and buy local food products (pasta, organic olive oil, wine, ouzo, liquors, traditional sweets and marmalades etc). The catering for all Geopark events (conferences, meetings etc.) is supplied by the women's cooperatives which use local traditional recipes. Their products are also sold in the Museum snack-bar. Every summer the Geopark organizes an Agrotouristic festival (attended by 29.000 visitors in 2009), which promotes quality local products, food and drinks prepared by the women's cooperatives.

Geopark activities are being monitored by an internal evaluation procedure based on the EGN assessment methodology. The results in the different sections of activities of the Lesvos Petrified Forest Geopark are being reported on a regular basis by their supervisors to the director whoreports them to the Board. All of the above has led to the conclusion that the continuous monitoring and assessment of the Lesvos Petrified Forest Geopark has led to its effective operation and activities.

The external evaluation conducted in 2007 by two Geopark experts nominated by UNESCO and EGN concluded that the management of the Geopark has a clear and transparent structure and functions very efficiently towards achieving the aims of the Geopark. The high score and the excellent comments by the evaluators that accompanied the report, as well the tangible results of continuous improvements during the last 15 years, are indicators that the management structure of the Lesvos Petrified Forest could work as an example also for other Geoparks in Greece or abroad.

4.3 The Lesvos Geopark results

Apart from the EGN assessment methodology, the Lesvos Petrified Forest Geopark has been evaluated by two independent assessment procedures that tested the quality of the Geopark's operation in the fields of nature protection, conservation and sustainable development.

The Lesvos Geopark operation results in the field of sustainable tourism were recognized by SKAL International, the largest organization of travel and tourism professionals in the world. To encourage the conservation of the environment and to help promote the development of responsible and sustainable tourism, Skål International initiated an awards program in 2002. While the purpose of these awards was to highlight best practices in ecotourism around the world, they were also created with the aim of acquainting the world with this new concept that puts emphasis on the importance of the interaction of the physical, cultural and social environment, the traveler's responsibility and the need for active community participation for ecotourism. In 2008 53 entries were received. The applications were evaluated by three independent judges and the scores, given by each separately, were added up to find the winners. The primary criteria for the evaluation was based on points such as contribution to the conservation of nature and cultural heritage, community involvement, educational features, business viability and innovation. The Lesvos Geopark won the SKAL International Ecotourism Award 2008 in the category "general countryside" as the best ecotourism destination.

Due to the quality of its operations and services, Lesvos and the Petrified Forest were awarded by the European Commission as European Tourist Destination of Excellence.2009. The theme of the EDEN competition for 2009 was ‘’Tourism and Protected Areas’’. The participating European countries had to choose a destination that respects several general award criteria such as being “non traditional”, being based on an area that is part of the Natura 2000 Network or otherwise designated as a “protected area” by national or regional legislation and managing its own tourism offer in such a way as to ensure its social, cultural and environmental sustainability, with the management being a partnership between the authorities responsible for the protected area and all those involved in tourism in and around the area (e.g. tourist service providers, local communities). Both awards guarantee the quality of the Lesvos Geopark’s operation and services, thus providing an independent confirmation of the EGN assessment methodology.

5. Conclusions

Geopark management requires a solid, efficient, flexible and as autonomous as possible management structure that will be able to decide on the protection, promotion, economic development and progress of the Geopark. Careful long term planning, continuous monitoring and regular evaluation are essential factors for successful results.

Among the 35 members of the European Geoparks Network, several different models of management can be found, depending on the country, the area, the organization in charge etc. Most of those models are very effective and demonstrate excellent results.

The assessment methodology adapted by the European Geoparks Network members provides an excellent tool for setting the general guidelines for successful management. The assessment review of Geoparks is now well underway, and represents a mechanism for encouraging the continuing assessment and upgrading of individual Geoparks. It is notable than many Geoparks are taking advantage of the periodic assessment to try to improve their weak points indicated by the review process. More important perhaps is the fact that some of the delisted Geoparks have returned some years later to present extremely powerful new membership applications.

With the Natural History Museum of the Lesvos Petrified Forest as its management body, the Lesvos Petrified Forest European and Global Geopark can provide a excellent example of how to successfully manage a Geopark and could function as a model for the management structures of potential Geoparks. The assessment methodology developed within the European Geoparks Network has proven to be a useful and excellent tool for monitoring the progress of the Geopark.

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ΔΙΔΑΚΤΙΚΗ ΤΩΝ ΓΕΩΕΠΙΣΤΗΜΩΝ / TEACHING EARTH SCIENCES

Δελτίο της Ελληνικής Γεωλογικής Εταιρίας, 2010
Πρακτικά 12ου Διεθνούς Συνεδρίου
Πάτρα, Μάιος 2010

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THE CONTRIBUTION OF MUSEUMS' DIGITALIZED PALAEONTOLOGICAL COLLECTIONS TO THE SCIENTIFIC LITERACY OF COMPULSORY EDUCATION STUDENTS: THE CASE OF AN INTERACTIVE MULTIMEDIA PRODUCTION OF THE PALAEONTOLOGICAL AND GEOLOGICAL MUSEUM OF THE UNIVERSITY OF ATHENS

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Abstract

The aim of the current paper is to present an interactive trilingual multimedia production, which designed in order to support school students' scientific literacy; as well as to enhance them the awareness, provision of information and education mainly in matters of palaeontology. In order to achieve scientific literacy, school students, must interact with scientific objects and data and must experience the role of interpretation and analysis in problem solving activities. The current production, based on a part of the digitized collections of the Palaeontological and Geological Museum of the University of Athens, offers this opportunity to the school students.

The application is a stand-alone learning environment and is divided into two parts. In the first part, there are presented the key geological concepts and the second part comprises interactive educational activities. Through an environment that promoted the development of observation skills, quest for information, decision-making procedures, critical thinking and systematization and following the spiral development of the material, there have been designed two sets of activities: one - for Primary and one - for Secondary education.

Key words: *geosciences literacy, scientific literacy, museums, digitalized palaeontological collections, education, virtual environment, Greece.*

1. Introduction

The Museum of Palaeontology and Geology of the University of Athens was created in 1835. Nowadays, it still maintains its primary objectives -collection, maintenance and research- while at the same time further developing its newer objectives, namely - exhibition, interpretation and education.

The university museum offers its visitors the possibility of training, study and entertainment on the grounds that the evolution of life on our planet has been imprinted in the geological strata, through different categories of plant and animal fossils.

In the museum, a special emphasis is placed on developing experiential educational activities through which visitors can understand various geological upheavals, climatic as well as environmental changes over the millions years. Based on the project digitization of a part of the Museum's collections, there has been also created a trilingual interactive multimedia production designed in order to enhance the awareness, provision of information and education to the pupils mainly in matters of geosciences.

Within the digitization programme of the museum, there have been digitalized numerous palaeontological samples for scientific and resource purposes. At the same time, one of the aims of the programme is to support the scientific literacy of the school students. For this purpose a production of a digital interactive educational application (DVD) under the title «A journey in time and space», was implemented within the framework of the programme Digitization of the Museums of National and Kapodistrian University of Athens (Fermeli & Dermitzakis, 2008).

2. Theoretical background

2.1 Scientific literacy

The term "scientific literacy" was coined in the late 1950s, and most probably appeared in print for the first time when Paul Hurd (Hurd, 1958) used it in a publication entitled *Science Literacy: Its Meaning for American Schools* (Laugksch, 2000).

In recent years, the term "scientific literacy" has become increasingly prominent in discussions of the aims and purposes of school science education. In the UK, the Beyond 2000 report argued that the purpose of science education, as a component of young people's whole educational experience, is to prepare them for a full and satisfying life in the world of the 21st century. The same report refers to the fact that 'the science curriculum from 5 to 16 should be seen primarily as a course to enhance scientific literacy' and continues saying that the compulsory science curriculum should be designed to develop the scientific literacy of future citizens. It also recommends that from about the age of 14 a separate, parallel course is needed to prepare those young people who opt for it for more advanced study in science (Millar & Osborne, 1998).

However, the term 'scientific literacy" has been used in different contents by many authors. For example, the International Forum on Scientific and Technological Literacy for All offered a variety of views, such as: «The capability to function with understanding and confidence, and at appropriate levels, in ways that bring about empowerment in the made world and in the world of scientific and technological ideas» (UNESCO, 1993).

The US National Science Education Standards defined scientific literacy as, «the knowledge and understanding of scientific concepts and processes required for personal decision making, participation in civic and cultural affairs, and economic productivity» (National Research Council-NRC, 1996).

Bybee (1997) has proposed four levels of scientific literacy, from the lowest to the highest as follows: «nominal scientific literacy», «functional literacy» «conceptual and procedural scientific literacy» and «multidimensional scientific literacy».

The third level is the most appropriate for the purposes of the OECD/PISA science framework instead of the forth, which includes understanding of the nature of science and of its history and role in culture, at a level most appropriate for "some students-the scientists of tomorrow" rather than for all citizens.

According to OECD/PISA (2003), scientific literacy is the capacity to use scientific knowledge, to identify questions and to draw evidence-based conclusions in order to understand and help make decisions about the natural world and the changes made to it through human activity.

The OECD/PISA (2003) definition of scientific literacy comprises three aspects: a) Scientific knowledge or concepts, which will be assessed by application to specific subject matter; b) Scientific processes which, because they are scientific, will involve knowledge of science, although in the assessment this knowledge must not form the major barrier to success; and c) Situations or context in which the knowledge and processes are assessed and which take the form of science-based issues.

These should be the products of science education for all students. For some students, the minority of whim will become the scientists of tomorrow; this will be extended to in-depth study of scientific ideas and to the development of the ability to «do science».

Although these aspects of scientific literacy are discussed separately, it must be recognised that, in the assessment of scientific literacy, there will always be a combination of all three.

International Student Assessment (PISA) programme of Organization for Economic Co-operation and Development (OECD) has assessed the domain of science literacy (as well as reading and mathematical literacy) of 15-year-old students. Surveys conducted worldwide reveal that even adults, who express strong interest and support for science, do not have a firm grasp of basic scientific facts and concepts, nor do they have an understanding of the scientific process. Usually, adults pick up information about Science media (from watching television or print media), however media can be faulted for miscommunicating science to the public by sometimes failing to distinguish between fantasy and reality and by failing to cite scientific evidence when it is needed (NSF, 2004).

2.2 Geosciences literacy

Geosciences literacy constitutes part of scientific literacy. An Earth-science-literate public, informed on current and accurate scientific understanding of Earth, is critical to the promotion of good stewardship, sound policy, and international cooperation. Earth science education is important for individuals of all ages, backgrounds, and nationalities. (ESLI, 2009).

In recent years, several geological communities have been developing "Geosciences literacy frameworks" as enhancements to the National Curriculums. Like curriculum, these new geosciences literacy frameworks have focused on K-12 education, although they are also intended for informal education and general public audiences. These geosciences literacy frameworks potentially provide a more integrated and less abstract approach to science literacy that may be more suitable for non-science major students that are not pursuing careers in science research or education (Fig.1). They provide a natural link to contemporary environmental issues - e.g., climate change, resource depletion, species and habitat loss, natural hazards, pollution, development of renewable energy, material recycling (ESLI, 2009).

2.3 Geosciences Education in Greece

In Greece, as from 1997, geology has not existed as an independent discipline in higher secondary education (Lyceum). Some geological issues are included in two optional subjects ("Issues of Environmental studies" and "Natural resources management") in the 2nd Grade of Lyceum, however a short percentage of students select these optional subjects. In respect of compulsory education, geology has a better perspective. In lower High School (Gymnasium), there exists a subject "Geology-Geography" in the 1st and 2nd grades, taught for 2 hours per week. In primary school, Geology (as well as Physics, Chemistry, Biology and Geography) is included in the subject "Environment's Study" for 1^{st}, 2^{nd}, 3^{rd} and 4^{th} Grades and "Study the natural world" in the 5^{th} and 6^{th} Grades (Fermeli & Marcopoulou-Diacantoni, 2004).

Following the analysis of the above mentioned text books, it arises that the presence of geology is limited. However, if we agree that geosciences literacy is necessary/important then we have to design specific programmes to foster the interest in geosciences among young people, by developing students' interests outside the classroom.

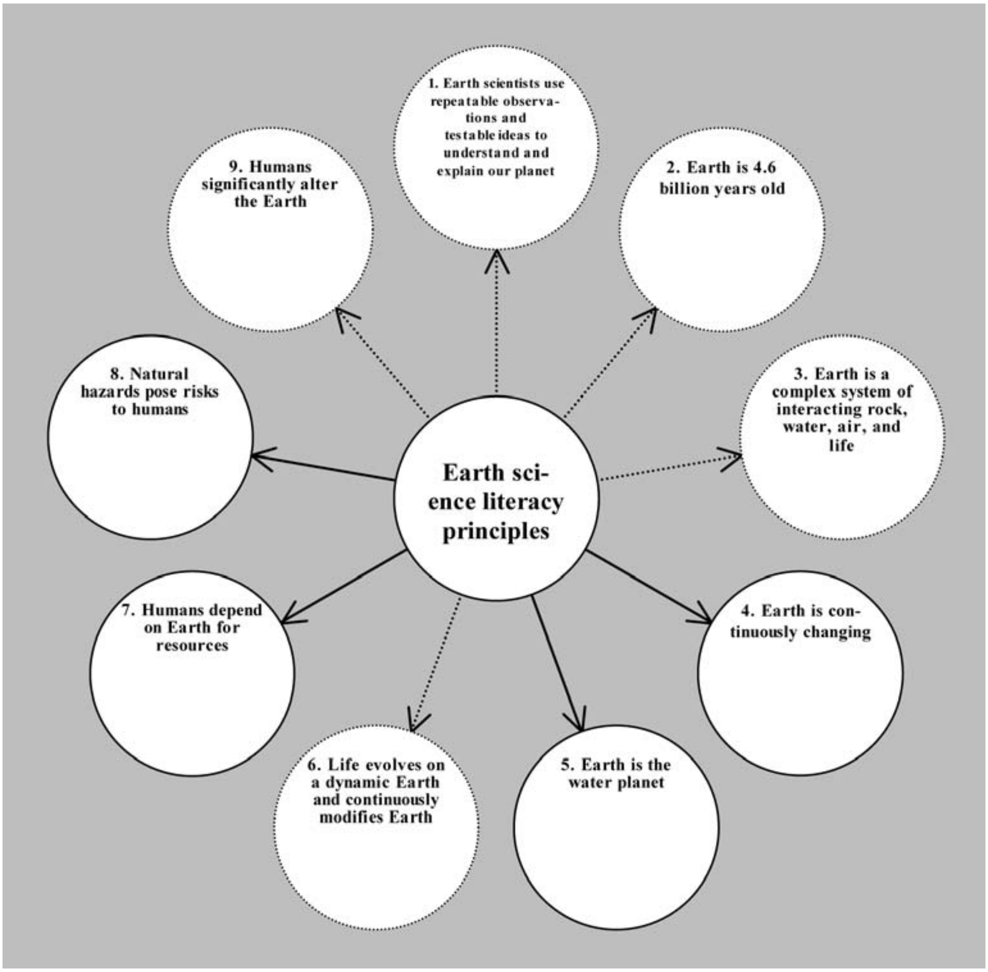


Fig. 1: Overview diagram of Earth Sciences Literacy principles (ESLI, 2009).

Students' geoscientific literacy is not an exclusive target of school education; therefore museums can play an important role in this process - both in formal and informal education. Griffin (1998) mentions that museums provide to us the opportunity to explore using our hands and our minds in numerous and varied ways. They also provide unique opportunities to closely examine specimens (or objects), to understand detail and also allow appreciation of the big picture by providing a wide range of specimens or objects to allow comparisons. In museums, students can develop perceptual skills that teach them how to gather information from "objects" and experiences. Henriksen & Froyland (2000) referred to the possible contribution of museums to scientific literacy and argue that in the present situation, it is no longer enough for museums to contribute to the cultural and professional/economic aspects of scientific literacy. Innovative ways of using the museums' collections and expertise need to be conceived to realize museums' potential to contribute also to the civic and practical aspects of scientific literacy.

MacDonald & Alsford (1997) point out that digital technologies offer a large scale of possibilities for the dissemination of knowledge, thus transforming museums: “In addition to the physical dimension of material objects, this transformation will give the museum another dimension, a digital one. This digital dimension will lead to a new form of museum that enriches the objects with information: the meta-museum which consists of a physical museum and a digital dimension”.

University museums, even small local geological and palaeontological museums or collections of natural history which display a limited number of objects in exhibits could foster the interest in local societies particularly among the young people. On the other hand, digitalized palaeontological museums collections offer opportunities to use new media that appeal to the senses, stimulate the imagination, relate science to everyday life, and allow visitors to discover geosciences in ways that are both accessible and interesting to many different categories of visitors. Such digital educational applications are most effective when they draw on the expertise of both researchers and educators and implicate both continual and mutual process of education.

Geosciences community has the objects (real and/or digital) and a clear aim (contribution to the scientific literacy of school students); it has to find attractive ways to express in words learning opportunities that can be understood by all. The objects, like fossils, are an effective means of helping to dissipate misconceptions of geosciences as boring, irrelevant or too difficult.

3. Digital application: "Journey in Time and Space"

3.1 Design and development of the application

The Geological and Palaeontological museum of the University of Athens, based on the project digitization of a part of the Museum’s collections, has created a trilingual interactive multimedia production designed in order to enhance the awareness, provision of information and education to the school students mainly in matters of palaeontology.

The aim for this production under the title: “Journey in Time and Space” was to use a number of the digitalized palaeontological samples of the palaeontological museum of the University of Athens in order to support: a) the scientific literacy of students (of compulsory education) and b) encourage cross thematic educational procedure in schools.

In order to achieve the above mentioned aim, there has been a prototype compulsory school geosciences curriculum unit, based on the national curriculum (YPEPTH, 2003a & YPEPTH 2003b) as well as mainly on geosciences literacy framework (ESLI, 2009). Two cross thematic concepts (“Time” and “Space”) have been chosen and finally, there have been designed and developed in both of them (curriculum unit and cross thematic concepts) a number of digital interactive educational activities under the general title “Journey in time and space” (Table 1). Each activity consists of a multi-user virtual environment with virtual contexts and digital fossil samples that directly and implicitly guide learner investigations. All materials, within the virtual environment, are presented in three languages (Greek, English and French).

Digital interactive educational applications based on museums digitalized collections offers school students, as well as informal education and general public audiences, opportunities to “drill down” to greater levels of detail, according to their interests or information needs. Introducing digital (or on line) resources – including visualizations of data sets, simulations and interactive games –helps school students develop skills in assessing the kinds of science-oriented material they will see after they leave high school – hence maintaining and enhancing their science literacy.

Table 1.

Part of Geosciences literacy framework on which the application "Journey in time and space" (ESLI, 2009) is based	Units of the application "Journey in time and space"
Earth scientists use repeatable observations and testable ideas to understand and explain our planet ***Earth science investigations take many different forms***. *Earth scientists do reproducible experiments and collect multiple lines of evidence. This evidence is taken from field, analytical, theoretical, experimental, and modelling studies.* ***Earth scientists use their understanding of the past to forecast Earth's future***. *Earth science research tells us how Earth functioned in the past under conditions not seen today and how conditions are likely to change in the future.*	– What is palaeontology – The work of a palaeontologist – A day of a palaeontologist in the field – Palaeontological excavation – The history of the museum
Earth is 4.6 billion years old ***Life on Earth*** *began more than 3.5 billion years ago (Fossils indicate that life began with single –celled organisma, which were the only life forms for billions of years. Humans (Homo sapiens) have existed for only a very small fraction (about 0.004%) of earth's history.*	– Geological Time-Virtual visit in the museum – The age of the Earth – Put the time of the Earth in the geological time table – Geographical distribution of fossils- Virtual visit in the museum – A different treasure
Earth is a complex system of interacting rock, water, air, and life ***Earth's climate*** *is an example of how complex interactions among systems can result in relatively sudden and significant changes. The geologic records show that interactions among tectonic events, solar inputs, planetary orbits, ocean circulation, volcanic activity, glaciers, vegetation, and human activities can cause appreciable, and in some cases rapid, changes to global and regional patterns of temperature and precipitation.*	– The climate is changing in Attica region
Life evolves on a dynamic Earth and continuously modifies Earth ***Fossils are the preserved evidence of ancient life***. *Fossils document the presence of life early in Earth's history and the subsequent evolution of life over billions of years.* ***Evolution, including the origination and extinction of species, is a natural and ongoing process***. *Changes to Earth and its ecosystems determine which individuals, populations, and species survive. As an outcome of dynamic Earth processes, life has adapted through evolution to new, diverse, and ever-changing niches.* ***Biological diversity, both past and present, is vast and largely undiscovered***. *New species of living and fossil organisms are continually found and identified. All of this diversity is interrelated through evolution.*	– Fossils -Fossilization – My own palaeontological diary – Who is who – Palaeo- puzzle – The climate is changing in Attica region (2) – Group of fossils – Characteristic exhibits – The museum collections – An interview of the Maastricht monster

(continued)

Table 1 (continued)

Part of Geosciences literacy framework on which the application "Journey in time and space" (ESLI, 2009) is based	Units of the application "Journey in time and space"
More complex life forms and ecosystems have arisen over the course of Earth's history. *This complexity has emerged in association with adaptations to new and constantly changing habitats. But not all evolution causes greater complexity; organisms adapting to changing local environments may also become simpler.* ***Mass extinctions occur when global conditions change faster than species in large numbers can adapt****. Mass extinctions are often followed by the origination of many new species over millions of years as surviving species evolve and fill vacated niches.* ***The particular life forms that exist today, including humans, are a unique result of the history of Earth's systems****. Had this history been even slightly different, modern life forms might be entirely different and humans might never have evolved.* ***Life changes the physical and chemical properties of Earth's geosphere, hydrosphere, and atmosphere.*** *Living organisms produced most of the oxygen in the atmosphere through photosynthesis and provided the substance of fossil fuels and many sedimentary rocks. The fossil record provides a means for understanding the history of these changes.*	– A geological scale – The history of the earth through fossils – Paint your own palaeontological stamp – Palaeo-quiz 1, 2

3.2 Description of the application

The application is divided into two "microcosmos" -The museum of Palaeontology and Geology and the Museum of Archaeology and History of Art- which are connected and interact mainly through the cross thematic significances "Time" and "Space".

This application is a stand-alone learning environment which drives students to learn following their personal interest and curiosity. This way, school students are gaining more than simple knowledge; they are practising scientific investigative processes. The application is also designed for use in a classroom context, supplemented by conventional classroom activities such as textbooks and teacher-led discussions.

In this paper, only the "microcosmos" of the Museum of Palaeontology and Geology is presented. This "microcosmos" is divided into two main parts. In the first part, there are presented the key geological concepts, such as geological time, types of rocks, the process of fossilization, fossils etc as well as a part of the exhibits and digitized collections of the museum. The aforementioned part can constitute: i) Educational support materials for teachers in order to: i) teach the concepts presented by the DVD and included in the school curriculum (Geology, Environmental Studies, etc.), ii) support educational activities in the context of the Environmental Education or iii) prepare students for a visit to the Museum. ii) Material for the pupils' self-study.

The second part comprises interactive educational activities that rely on basic general concepts and the museum's collections that have been presented in the first part of the application. Through an environment that promoted the development of observation skills, quest for information, decision-making procedures, critical thinking and systematization and following the spiral development of the material, there have been designed two sets of activities: one - for Primary and one - for Secondary education.

Fig. 2: "Journey in Time and Space": Virtual visit to the Museum of Geology and Palaeontology.

Every activity leads to a form of assessment of the user. There is also an evaluation activity as concerning the total of the educational activities for every level of education.

More analytically, the application is divided into four units: a) Virtual museum's visit, b) Time, c) Play area and d) Museum's identity.

a) Virtual museum's visit: This unit includes 5 subunits (Geological time, geographical distribution, fossils' category, impressive fossils, and Fossils' collections). The visitor can choose the way in which he/she would like to make a virtual visit to the museum (through time, geographical distribution, fossils' categories or to select to see the most representative and impressive fossil samples of the museum) (Fig. 2).

The most interesting part in this unit is the one, comprising the activity based on digitalized palaeontological fossil collections (Fig. 3). This activity is like a "Virtual museum", in which visitors can choose to see fossils from three main collections (vertebrates, invertebrates, plants) or to see fossils according to their age or geographical distribution. For each fossil, there is presented a detailed identity card with all information about it.

b) Time: Geology is the science with the clear focus on deep time and on the procedures of retro diction. It is proposed that collective and individual grasp of deep time influences the quality of engagement with a host of broader matters, ranging from current environmental issues (e.g. sea-level change and coastal retreat) to longer-term matters (e.g. mass extinctions, asteroid impacts, periods of enhanced volcanic activity, evolution of the Universe). It is suggested that, if we have an insecure deep time framework, we will be less able to accommodate new learning of geosciences concepts with a strong (deep) temporal component. As both teachers and learners we will, therefore, tend to avoid such new knowl-

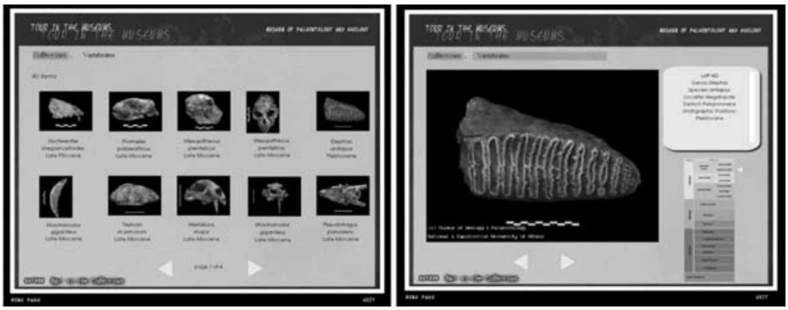
a  b

Fig. 3: (a): Activity based on digitalized palaeontological collections (vertebrates, invertebrates, plants); (b): Fossil's identity card.

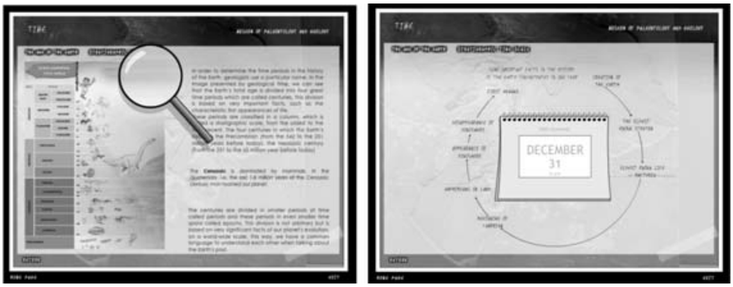


Fig. 4: Time's activities.

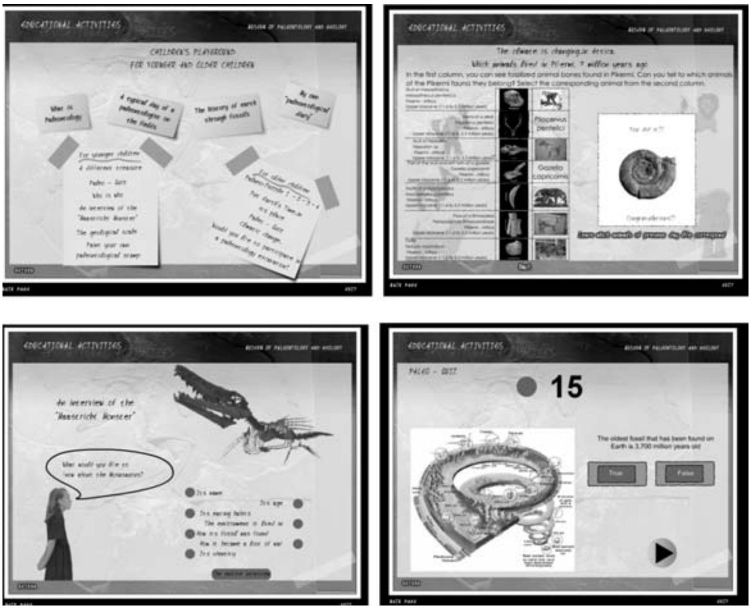
edge and understanding (Roger, 2000).

In this unit, there is discussed the concept of geological time. Except the introductory text about geological time, there is also presented information about the age of the Earth and the subsequent evolution of life over billions of years. In addition, there is an interactive activity, following which the school students face the task to order time intervals in the geological time table (Fig. 4).

c) Play area: This unit includes educational activities (General activities, activities for primary school students and activities for secondary school students). Students are familiarized with the proposed activities in experimental work. They cultivate scientific dexterities and problem solving abilities. They can also test their ideas. School students participate in teamwork, develop positive attitudes toward the educational material and are actively involved in the educational process (Fig. 5).

d) Museum's identity: This unit presents the history of the museum of palaeontology and geology of the University of Athens from its creation in 1835 till currently through video, texts and pictures.

a



b

c

d

Fig. 5: (a): Characteristic examples of school students' activities from the Play area unit; (b): Climatic change in Attica region; (c): Interviewing the Maastricht "monster"; (d): Overall evaluation activity.

4. Conclusions

People of all ages better absorb information on any topic, even a very complex one, when they are directly and personally involved. There is no doubt that motivation is the primary factor in increasing interest in geosciences. In seeking to help improve scientific/geosciences literacy, it is therefore necessary to address not only the intelligence but also the imagination and the emotions, in order to make geosciences understandable, as it is only when one has understood that he/she can make a valid contribution to discussions of geosciences.

To achieve scientific literacy, adolescents as well as adults, must interact with scientific objects (real and/or digital) and data and must experience the role of interpretation and analysis in problem solving activities. Through their exhibits and digitalized collections, museums can offer this opportunity to the school students and general public too. However, museums offer a large range of information, which may seem overwhelming to students. Helping students to recognize the way in which this information is classified or displayed will, in turn, help them learn how to select, sort, classify, code, synthesize and analyse information and, finally, how to communicate it. Tasks involving these skills will teach school students that classification and recording of data can be based on clear and stated criteria, and that the methods will be influenced by the purpose for which it will be used, such as to show relationships between fossils and evolution of life on Earth.

The "Journey in time and space" is an interactive educational multimedia application for students of compulsory education which supports scientific/geosciences literacy. Observations and data gathered by the "Journey in Time and Space" can lead to further questions for investigation. In some instances, these questions may be answered through further examination of the "real" objects and information available at the museum of geology and palaeontology of University of Athens. Alternatively, some questions may be answered through experimental processes carried out at school.

This multimedia production is encouraging as a learning medium for geosciences. Through describing such activities and analyzing design processes, we hope to provide inspiration to other researchers to "open" scientific collections to school students and general public, as well as to develop computer-supported collaborative learning environments in order to support geosciences literacy.

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THE USE OF EDUCATIONAL SEISMOGRAPHS IN THE SEISMOLOGY SCHOOL NETWORK "EGELADOS"

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Abstract

In this paper we attempt to describe the experience we gained, working with a specially designed seismograph as an educational device. It is a modern instrument with short period response, GPS timing and digital recording on personal computer. The installation was done in the frame of the local seismology school network, called "Egelados".

The knowledge of basic concepts of geology, physics and mathematics (Lower High School level - Gymnasium) is a prerequisite for the use of the instrument. Further research of the earthquake phenomenon and the analysis of the recorded data leads to didactic objectives in sciences and mathematics which are included in the Lyceum curriculum. The reliability test of the results obtained using the seismograph has, from the analysis students made, shown up to now declinations of the events magnitude of 0,2 - 0,4 when compared to magnitudes published by National Observatory of Athens-Institute of Geodynamics. Students' constructions to overcome the calculation difficulties to find the exact location of epicentre are often proposed activating in this way their research mood.

Up to now the use of the tool, in the framework of network "Egelados", not only connects the participating schools but also gives the opportunity for further collaboration among teachers and students that have installed a similar instrument. Finally, everyday use of the seismograph reveals its drawbacks and provides ideas of enhancements.

Key words: *sciences education, earthquakes, educational seismograph, environmental education, Egelados network.*

1. Introduction

1.1 The International experience

At an international level, during the last three decades educational institutes suggest and attempt the introduction, to the school's curriculum, of programs - activities related to geosciences. Such projects are currently, at least in United Stated of America (USA), connected under the umbrella of larger collaborations between institutions such as the U.S. Educational Seismology Network (USESN 2001). The goal of USESN is to provide a mechanism for coordination of individual efforts, to provide common technical and educational resources that will enhance all of the educational seismology programs, and provide a mechanism for advocacy for educational seismology (USESN 2001). The Princeton Earth Physics Project (PEPP http://www.indiana.edu/~pepp/) is a network of seismic recording stations in high schools across the United States for educational purposes. Students use the PEPP network to study earthquakes and develop scientific and mathematical skills in the classroom using real seismic data. PEPP's aim is to engage students in the process of hands-on science and inquiry-based learning by operating their own seismological observatory and gathering and analyzing research quality data.

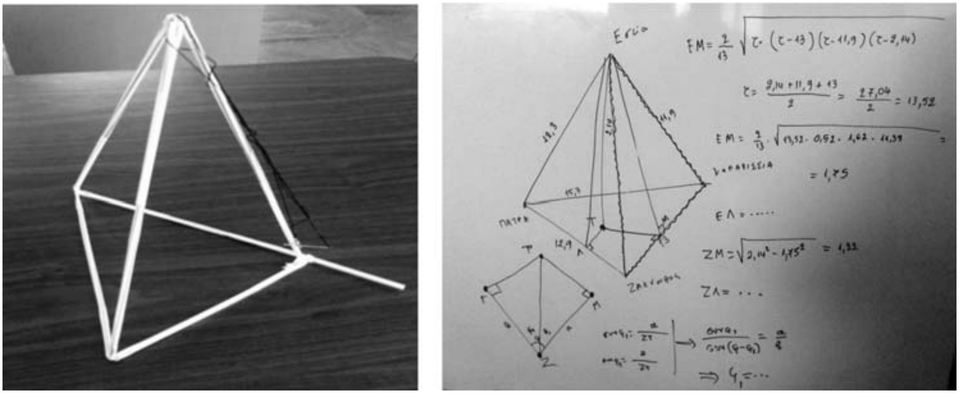
EDUcational SEIsmological (EDUSEIS) project in Europe makes also an attempt to connect schools with science museums and research institutions through the earthquake phenomenon (EDUSEIS http://www.eduseis.net/; Virieux 1999; Bobbio and Zollo 2000). For the time being few schools in Europe are directly connected with EDUSEIS. Liceo Scientifico "Nicolo Copernico" of Naples, Odivelas Secondary School in Portugal and Copernicus Gymnasium Philippsburg in Germany are such schools that have also acquired seismographs. But there are also other European schools and other European projects that are running their own projects using seismographs of different construction. Such schools are "Monschau School", "Faust Gymnasium", "Staufen and St. Michael Gymnasium" in Germany, while the Projet "Sismo des Écoles" in France (Berenguer & Virieux 2006) and the "SeisSchool" Norway project (Federenko et al. 2000; Husebye et al. 2003) are projects aiming to create interest in geosciences and seismology among high school students using seismographs.

1.2 The Hellenic School Educational Seismology Network "Egelados"

The thematic network Egelados was established in 2004, on a volunteer basis, as a collaboration between educators (geologists), researchers (seismologists) and engineers from schools, universities, research institutions and the Bureau of Environmental Education in Messinia prefecture.

The aim of the network is to improve scientific literacy, spark student interest in scientific research, increase their understanding of natural hazards, and to actively engage them in real-world scientific research. In order to achieve this aim the network promoted at secondary school level the use of "educational seismographs" and processing of recorded seismic data. The objectives of the network are to give to the students the basic information about the earthquake generation and the ways this phenomenon affects our life. To make students understand that earthquakes are natural phenomena, connected with the landscape formation; are frequent in Greece and thus essential for us to understand and face by constructing appropriate houses and acting in a certain way when an earthquake occurs (Fermeli et al. 2006).

Each school from the network was working at the first two years on its own project concerning the study of either volcanic or seismic activity in Greece. During those two years students attended lectures from scientists from universities and research institutions about natural disasters, volcanic activity and especially about seismic phenomena. They have also attended lectures about First Aid and participated in Earthquake related activities in their schools. Students also visited areas of great earthquake hazard and volcanoes like Santorini, Corinth (Sousaki), Naples (Vesuvius) and Sicily (Etna).



(a) (b)

Fig. 1: Example of educational activity (a): Construction made out of straws for the estimation of an earthquake's epicentre; the edges of the tetrahedron drawn from its vertex represent the distances of the loci of the earthquake from three seismographs placed in different locations. The epicentre is empirically estimated using the plumb. (b): Geometric solution of epicentre (distances from earthquake loci been known). The epicentre is placed at the trace of the height of the tetrahedron. Its position is estimated using formulas and theorems from geometry and trigonometry of A and B Grades of lyceum.

A more intense effort to bring schools in collaboration has been made during the last two years when a network between schools has started to work, spreading the information to the partners through a web page (http://www.egelados.gr).

2. Instruments and materials in use

Exploring web pages of universities and schools on seismic networks, we can find a variety of instruments, didactic modules and activities, proposed for a better comprehension of the earthquake phenomenon (IRIS http://www.iris.edu/hq/; EDUSEIS http://www.eduseis.net/).

So far the steering committee of Egelados network has drawn a specific curriculum for the needs of the network. The curriculum is carried out through 20 educational activities (modules), an independent project for each school, as well as by the recording of the seismic activity through the educational seismographs. The educational activities give students the opportunity to apply their knowledge from geology, physics, mathematics, geography, and other disciplines when, for example, they try to estimate parameters of an earthquake from the data recorded by a seismograph. As well as, students use a number of instruments from school sciences laboratory, in order to explore the way waves are transmitted and affect human constructions.

All these activities not only call them to apply their knowledge in order to solve problems but also ask them to find solutions in mathematics and sciences and even more to design their own devices to estimate empirically the earthquake's depth or epicenter (Fig. 1a, 1b).

The subjects of the activities have been chosen in a way that helps students proceed in the study of an earthquake. They include a variety of activities like the following:

a) Maps and scales: Students learn how to convert distances on the map to real distances and vice versa, using a map's scale. Worksheets are used for this purpose. Real seismic data taken from school's seismograph or from seismological institutes are used in the worksheets in order for students to com-

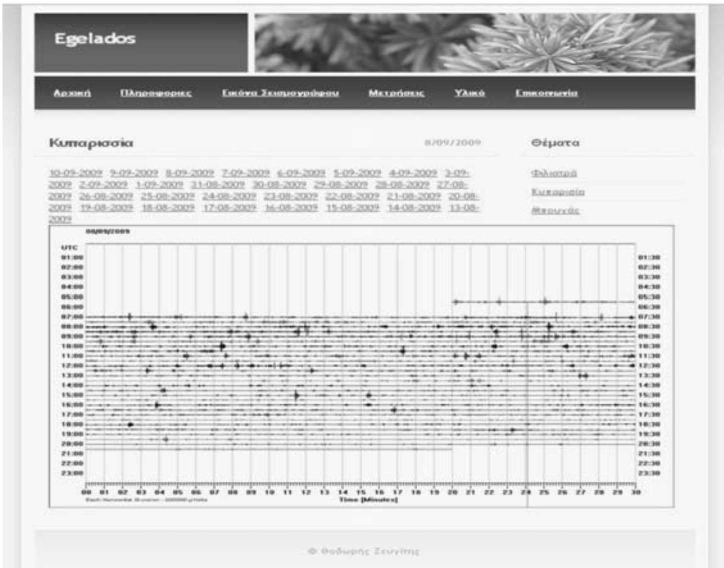


Fig. 2: Egelados' website informs the public about the aims and activities of the network. Interested visitors can see the recorded and stored data from student measurements and their works produced within the frame of the project. National and international links related to Egelados network are also presented on the site.

pare their estimations to the published results. This activity can be realized by students of A Grade f gymnasium up to C Grade of lyceum.

b) Propagation of waves: Wave types and their propagation is analyzed through presentations by teachers, experimental devices of sciences laboratory and discussion in working groups. Using worksheets students attempt to measure the distance of the loci of the earthquake from the seismograph based on, a) the different speed that transverse and longitudinal waves have, b) the subsurface structure that determines the speed of the waves and c) the distance formula for smooth linear motion. Required skills: first degree equations, laws of smooth linear motion, propagation of a wave in different materials.

c) Estimation of earthquakes loci using distances on a map under scale: Students empirically estimate the epicenter of an earthquake using the distances of the loci from three seismographs and the map scale without taking into account the depth of the loci.

d) Empirical estimation of earthquake epicentre: A more precise estimation of the epicenter (when the area estimated from the distances from the loci is large enough) is attempted through techniques that students are called to discover. Constructions like the one in figure (1a) proposed by the students not only solve the epicenters problem but also highlight their ingenuity as a result of their cooperation. Students often have to work on the surface of the map like if they live on it trying to find solutions of the epicenters problem.

e) Geometrical estimation of earthquake epicentre: Students have to use all the knowledge they have acquired in mathematics in order to solve the epicenters problem using the distances from the loci to the seismographs and the distances between the seismographs on the map. Theorems of geometry that are not yet taught to them are often necessary to be discovered so that students will give a more precise explanation on the epicenters problem.

Guesses or even conjectures and interpretations proposed by the students strengthen even more in their eyes the relation between mathematics, physics and geology while at the same time they realize their applications in real words problems.

Students usually work in groups, using information taken from: a)school's seismograph, b)university sites, and c)research institutions like National Observatory of Athens-Institute of Geodynamics (GI, http://www.gein.noa.gr/index-en.htm) and European Mediterranean Seismological Centre (EMSC, http://www.emsc-csem.org/index.php?page=home). Network's pedagogical activities can also be used in conjunction with the material found on the web produced by national or international organizations in Europe and USA (SSN http://www.seismosoc.org/society/education/; Eduseis http://www.eduseis.net/) which include, beyond working sheets, scientific information and real time simulations.

As well as, a webpage (http://egelados.sch.gr; Fig. 2) has established which supports schools to collaborate and spread information. Schools participating to the Egelados network have their own access code for the webpage. In this way schools can record their measurements from the school's seismograph. The measurements can help students complete their research giving them the necessary support in educational data. With the appropriate software schools can have a visual representation of the seismic activity of their region. Further development of the website could include uploading of the seismic data directly from other schools' computers so that students can have the opportunity to process and compare it with that coming from their own seismograph.

2.1 The educational seismograph

The most interesting tool for educational activities in the framework of Egelados network is the seismograph. This is a pedagogical tool designed specifically, by the University of Patras, Seismology Laboratory and the Industrial Systems Institute, for educational purposes (Foundas, P., and Germenis, N., 2007). The educational seismograph is a low power and low cost digital acquisition system. It was designed for monitoring of seismic events or other geophysical parameters. The device consists of two parts, a sensor and a digitizer. The sensor converts earth movement to a current (analogue signal) and is an inexpensive geophone. Both three component and one component designs are available in order to reduce the systems cost even further. The digitizer converts analogue to digital signals with a dynamic range of up to 132 dB. It is based on a powerful, wide dynamic range delta-sigma analog–to-digital converter (ADC), with very low noise characteristics and excellent power supply rejection. The sampling rate was set to 100 samples per second. Each digitizer can support up to three analogue channels. Therefore, three ADCs can be used which operate simultaneously and independently. Each converter operates from a single power supply and utilizes fully differential inputs. The differential inputs provide common-mode rejection eliminating much of the system noise imposed on the input signal.

The digitizer also includes a complete on-board calibration circuit to correct internal offsets and gain errors or limit external system errors. Internal calibration procedures run automatically on power up. The device ensures high stability and reliable continuous operation. In order to prevent unpredictable malfunctions, a watch-dog timer function for auto self-reset on failures is also provided. Data synchronization is the process of establishing consistency among data from a source to target data storage and vice versa and the continuous harmonization of the data over time. It is fundamental to a wide variety of applications, including file synchronization and data comparison. The data synchronization is achieved using a real time clock and a phase locked loop circuit, which generates a pulse per second (PPS) signal. The first sample of data is aligned to the PPS signal. The time reference for both circuits is provided by a 12 channels GPS receiver. Connection of the digitizer to a PC is via RS232 port, which establishes a two way communication between them. Data and status information are transmitted from the digitizer to the PC and there the information is organized into packets and stored.

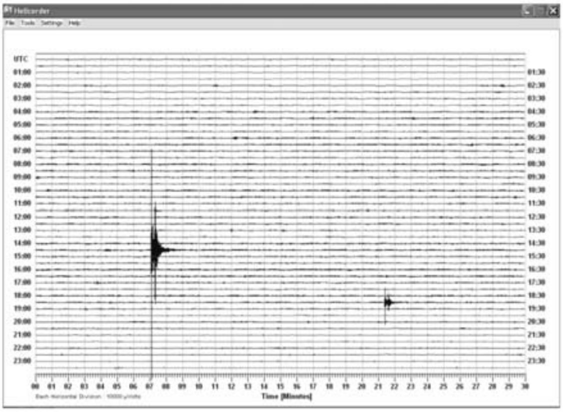


Fig. 3: Helicorder display

Various processing software is available for seismic data analysis, namely: a) DataMonitor b) DataViewer and c) Helicorder.

DataMonitor controls the serial communication and organizes the packets in data files; a new file is created every 10 minutes, absolutely synchronized to the world time.

DataViewer allows the user to work with files that were created by DataMonitor. Using the DataViewer, the user can zoom in and out in a graph, find specific features, select features that meet certain criteria, estimate the distance from the seismic event, its magnitude, and more.

The Helicorder shows 24-hour period graph of the data. The graph is «read» like a book, from left to right and top to bottom (this is the direction that time increases). As with a book, the right end of any horizontal line «connects» with the left end of the line below it (Fig. 3).

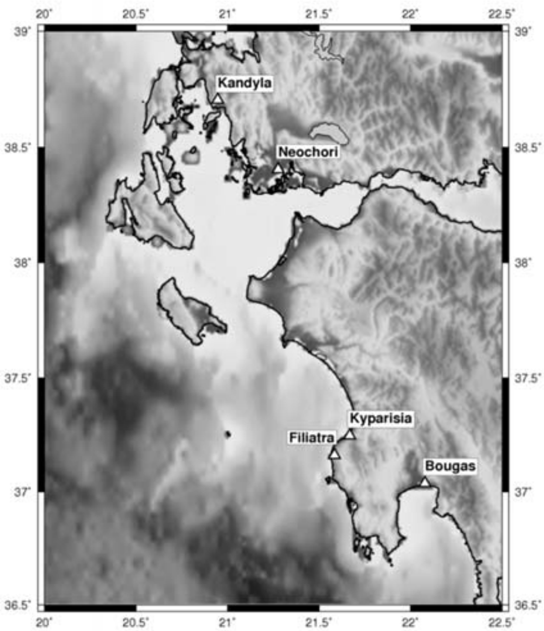


Fig. 4: Labels show network's schools in which operate educational seismographs.

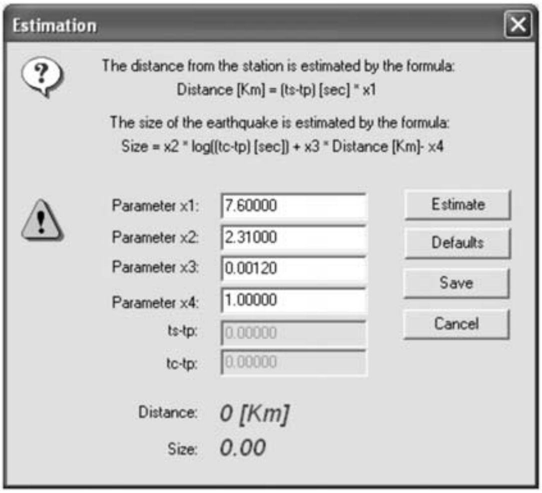


Fig. 5: Distance-magnitude estimation and parameters.

Five seismographs were installed in the first two years of this collaboration: 1) Bouga's School in Kalamata, 2) Lyceum of Filiatra 3) High School and Lyceum of Kyparissia 4) High School and Lyceum of Kandyla and 5) High School and Lyceum of Neochori (Fig. 4).

The seismographs were installed at schools under the supervision of the members of the steering committee. The network had no financial support and the seismograph's cost was provided by the schools.

2.2 Distance-magnitude estimation and parameters

The estimation process provided by DataViewer software gives a rough method to estimate the magnitude and the distance from the station of a seismic event (Fig. 5). The following formulas are used:

$$\text{Distance [Km]} = \text{ts-tp [sec]} * \text{x1}$$

$$\text{Size} = \text{x2}*\log(\text{tc-tp [sec]}) + \text{x3}*\text{Distance [Km]} - \text{x4}$$

The parameters x1, x2, x3 and x4 have been provided with default values, so the user does not have to generate the information from scratch. However, teachers and students have to adjust the parameters in order to fit in to their area's geological structure by testing them and comparing their results to those of a national or an international seismological laboratory. Since precision is a necessary factor in scientific research, they have an opportunity in this way to practice in it. Of course precision is not the ultimate aim for the students working on seismic data. A seismic event should be an opportunity for them to comprehend the procedure of the generation of an earthquake creating at the same time questions in other fields of science e.g. geology, physics, mathematics.

2.3 Instrument calibration

Thirty three earthquakes have been used to evaluate the instrument. Most of them took place in 2009. Students estimated the magnitude of the earthquake and epicentral distance from the reference station and compared them to the data that European Mediterranean Seismological Centre or the Geodynamic Institute of Athens provides. The mean magnitude difference between school stations and EMSCs' magnitude was 0.36. The standard deviation in these differences was 0.03 to 1.09. The students observed that the difference was dependent on the distance from the station and the seis-

Table 1.

Absolute Magnitude difference versus distance					
Bouga's School			Kyparissia's School		
N	Valid	14	N	Valid	19
	Missing	0		Missing	0
Mean		,2579	Mean		,4305
Median		,2650	Median		,3900
Std. Deviation		,13268	Std. Deviation		,33294
(3 channel configuration)			(1 channel configuration)		

mograph's configuration (one or three components). In particular, the mean magnitude difference was smaller (0.24) when the earthquakes took place in areas near the stations (distance <60km). It was also smaller if the source data have been recorded by a three channel seismograph. Therefore, the mean magnitude difference was smaller for Bouga's School seismograph measurements (0.26) than that of Kyparissia's School (0.43) (Table 1).

The difference was attributed to increased noise in the records, due to large epicentral distance, which resulted in erroneous picking of P, S and coda times. This is also the reason why teachers and students measured different magnitudes on the same graph (Table 2).

Table 2.

Magnitude estimations of Kyparissia's School (earthquakes from the region of Megalopoli)					
DATE	HOUR	DISTANCE from Kyparissia's station	MAGNITUDE1 student	MAGNITUDE2 teacher	EMSC's MAG
6/8/2009	02:49	22km	2,34	2,55	3,3
6/8/2009	04:58	50km	3,61	3,89	4,6
6/8/2009	05:42	27km	2,47	2,61	3,1

This is probably the major problem in estimating the earthquake's magnitude correctly. Students' estimations are better when they define the endpoint of an earthquake as the point where all perturbations on the graph have ceased. The problem becomes larger if there is also "noise" coming from school activities that take place close to the sensor. It's almost impossible in these cases (especially for the schools using one coordinate sensors) to estimate properly the duration of an earthquake.

In any case, the difference in magnitude from EMSC or other scientific institutes' data is completely acceptable for the educational purposes. The difference can be minimized through a calibration procedure. The seismograph provides a very useful educational tool and a three coordinate sensor gives better data as it helps students to define more accurately the S wave picks and the duration of an earthquake.

2.4 Advances from the use of educational seismograph

The use of the educational seismograph improve scientific literacy, spark student interest in scientific research, increase their understanding of natural hazards, and to actively engage them in real-world scientific research. Up to now the use of the tool, in the framework of network "Egelados", not only connects the participating schools but also gives the opportunity for further collaboration among teachers and students that have installed a similar instrument. More specifically the use of the educational seismograph, promotes:

a) Experimental science in schools: The measurements and follow-up of Earthquakes request to students to develop scientific knowledge, dexterities and skills in experimental science (measure, observe, gather and organize data, test hypothesis, present results and draw conclusions).

b) New technologies use: the implementations of seismic data from the schools' seismograph demand data processing and a special software use, so that students can have a visual representation of the seismic activity of their region. This procedure requests to students to develop new technology skills.

As well as, educational seismograph use supports:

c) Inter disciplinary approach: The recording of the seismic activity through the educational seismograph is a complex procedure. Students need to implement knowledge from different disciplines like geology, physics, mathematics, as well as other disciplines like arts, history and languages. A specific curriculum unit is designed by the steering committee which addresses the national curriculum (YPEPTH 2003a; YPEPTH 2003b) in geology, physics, mathematics, geography, environmental education etc. and offers opportunities to involve students in interdisciplinary approaches.

d) Team work and collaboration: Collaboration nowadays seems to be a major task in education. Students need to collaborate and to work in teams in order to interpret scientific data and draw conclusions, as well as, they have to work with other schools (minimum three) in order to specify Earthquakes epicenter.

3. Conclusions

The use of the educational seismograph within the frame of geosciences subjects or environmental education projects creates new opportunities for students and teachers to gain knowledge and apply teaching methods appropriate also for the interdisciplinary curriculum. Students have opportunities through the seismograph to explore an earthquake at the time it occurs collecting data from scientific institutes and universities and processing them with their schoolmates from other schools.

Evaluation of the seismograph and data processing gives them opportunities to get used to scientific methods. Student estimations produced from the processing of the seismograph's data showed declinations of 0,25-0,35 M.

More modules for students are necessary for project completeness while network continuity and evolution demands even more cooperation between network's steering committee, research institutions and universities. The network is still working on a volunteer basis however financing of the network is necessary in order to attract schools that could participate in it, using their own seismographs. Achieving a long life for such projects requires, besides pedagogical and scientific support of the network's steering committee and ethical support from the educational authorities, financing and a periodical revision of the teaching modules so that schools continue to be interested in participating to the network.

In the school environment, the study of earthquake phenomenon demands knowledge from various disciplines like geology, physics, mathematics, history, geography and technology. As such, it can be a successful example of a model, based on techniques that interdisciplinary approach uses. However, such an approach requires knowledge and instruments that schools of secondary education don't usually have and of course lack of knowledge and instruments discourages teachers and students from participate in such initiatives.

A system of students and even teachers evaluation participating in the project through certification and a program for post-graduate studies (for example a Master degree on Geodidactics) for teachers working on such projects could help motivate students and teachers who get involved. Publication of student work in local newspapers and magazines could help as a public acknowledgment of their work, encouraging them to keep working in spite of the difficulties in finding time and study conditions that they might face working on such a project.

Finally teachers' persistence in applying new teaching methods trying to infuse in their students the spirit of research and excite their interest in science is a major factor in networks continuity and success.

4. Acknowledgments

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PERCEPTION OF FIRST-YEAR GEOLOGY STUDENTS ON THE TECTONIC PLATES THEORY

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Abstract

This paper examines alternative ideas and perceptions of first-year students of the Department of Geology at the Aristotle University of Thessaloniki, on the theory of tectonic plates, prior to completion of relevant courses. There is partial confusion both in terms of the conceptual background, as well as on the causal links between geological phenomena associated with the movement of tectonic plates. One out of two questioned students has systematic and consistent knowledge on the principles of the theory of tectonic plates, both at a conceptual and at a deterministic level, as well as in terms of geometric, kinematic and dynamic analysis.

***Keywords**: alternative ideas, misconceptions, conceptual confusion, causal relationships, lithosphere structure, convergence, divergence, tectonic plates.*

1. Introduction

The effort to detect, record and analyze the alternative ideas of children on Natural Sciences starts from the extensive research activity of Piaget (1929). In doing so, various data collection methods have been used worldwide, such as written statements, posters, business cards, mental tests, interviews, questionnaires, experiments, projects, etc. (Driver et al., 2000 & Javeau C., 2000). At the present paper, a closed multiple choice questionnaire was selected as the preffered method for obtaining the data (Paraskevopoulos, 1993). The performance of students in objective-type questions, such as multiple choice questions, depends on their reading ability (Alexopoulos, 1998). Due to the age of the respondents, it is assumed that the reading ability is adequate.

The subject of the questionnaire was selected on the basis that the theory of tectonic plates is a single theory for the interpretation of geological phenomena, processes and mechanisms, relevant to the theory of "Big Bang" in Physics, or the Darwinian evolution theory in Biology, or the atomic theory in Chemistry. Moreover, the theory of tectonic plates allows a holistic approach to the teaching of Natural Sciences.

It is important to clarify that the surveyed students had not been taught anything relevant to the theory of tectonic plates before completing the questionnaire. The aim of the present work is to point out questions rather than to solve them.

The key questions that this paper deals with are:

- Do first-year geology students know that plate-related events are dynamic rather than static?
- Does the perception about the constant movement and change belong to their cognitive system in a consistent and systematic way?
- Do the students know what causes the movement of tectonic plates and what the consequences are?

The objective of the present work is to detect the perceptions, correct or incorrect, of the students, both at the conceptual and the deterministic level. It is also clear that this effort was a part of a holistic vision of our planet as a dynamic system, a sum of interactions and continuous changes.

2. Methodology

The research took place in Thessaloniki, Greece, on the 30th of November 2009, during class hours of the first semester. A close-end multiple choice questionnaire on the theory of tectonic plates was distributed to first-year students of Geology (N = 49). The questionnaire comprised of five (5) questions; each of them had five (5) possible answers. Attempt was made in order to include a list of all essential elements of the theory of tectonic plates in the above mentioned small number of questions, in order to point out the key words of the above theory. The questions are related to the movements of the plates; more specifically, which is the rate of movement (question 1), which is the cause of plate movement (question 2), what is the effect of the movement on convergent boundary (question 3), how the lithosphere is structured (question 4), and what is the effect of the movement on divergent boundary (question 5). This way, it is studied whether the students can only understand the purely geometric structure of the lithosphere, or furthermore its kinematic level and ultimately percept the dynamic causes of tectonic plate movement. The two questions on the converging and diverging margins, link the theory of tectonic plates to the widely known geological phenomena, such as earthquakes and volcanoes. Through these questions, the level of perception of students in geological terms and concepts, such as convergent-divergent tectonic plates, convection currents of the mantle, core-mantle-crust, mid-ocean ridges, earthquakes, volcanoes, subduction zones etc. are studied, since geological structures as well as geological processes and mechanisms are included. The level of perceptions of the outcome of tectonic plates movement, as well as the causal links between various geological phenomena is also investigated. The order of questions in the questionnaire was designed so as to avoid the definition of a way of thinking, *i.e.* not to lead the students to specific answers and to avoid the effect of luck in the responses. So, two questions about the rate and the causes of tectonic plate movement were selected for the beginning of the questionnaire, since one possible answer was that the plates do not move an option that is associated with one of the main objectives of this research.

3. Results – Conclusions

From the analysis of responses using Microsoft Excel formulae, the following results were obtained. In the 1st question about the rate of movement of the tectonic plates (Table 1), half of the students (53.1%) responded correctly (cm/yr). From the remaining responses, the response rate that the move is given better in (cm/Myr) was assigned at the questionnaire to check the level of internal consistency and stability of students' knowledge. The higher proportion (32.7%) in this response reveals the internal inconsistency and uncertainty of the students. The remaining 14.3% who chose to answer (km/yr), or (m/yr) probably indicates lack of any relationship to the geological science (Fig. 1).

Table 1.

1st Question: Tectonic plates move at an average rate that is best described by:	Answers
a. km per year (km/yr)	5
b. cm per year (cm/yr)	26
c. m per year (m/yr)	2
d. cm per million years (cm/Myr)	16
e. none of them, since the tectonic plates do not move	0
total	49

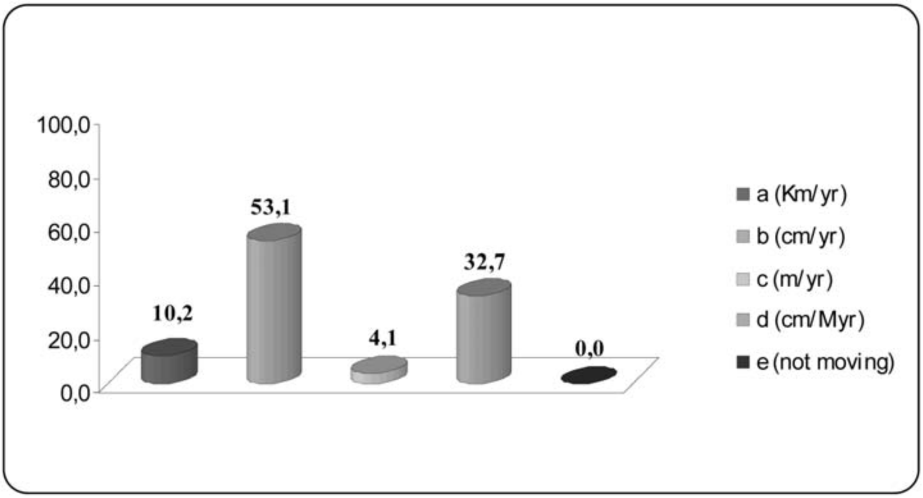

Fig. 1: Percentage of answers to 1st Question.

In the 2nd question on the causes of the movement of tectonic plates (Table 2), one out of two students (51%) answered correctly (transportation currents carry material and energy of the mantle). The second most popular answer (30.6%) (the motion due to rotation of the mantle around the core), shows a lack of understanding of the conceptual content of "convection currents of the mantle". It is presumed that the students have seen a diagram with arrows motion at the mantle and therefore that is the reason for choosing this response. It is obvious that there is also at this issue internal inconsistency and confusion. Percentage of 18.4% chose responses related to the density and gravitational pull, answers that are clearly situated in the field of upper secondary school, far from any connection to the geological science. It is noted as a positive remark that none of the students responded that the tectonic plates do not move (Fig. 2).

Table 2.

2nd Question: Tectonic plates movement is the result of:	Answers
a. mantle and core different densities	4
b. energy of the sun and the attraction between the planets	5
c. the rotation of the mantle around the core	15
d. mantle convection currents that transport material and energy	25
e. none of them, since the tectonic plates do not move	0
total	49

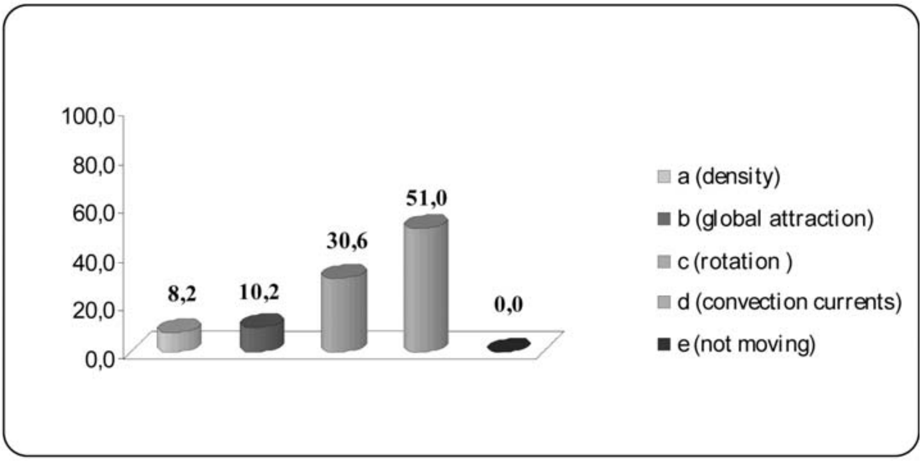

Fig. 2: Percentage of answers to 2nd Question.

In the 3rd question on the convergence of tectonic plates (Table 3), the same percentage of correct answers (53.1%) was repeated with great consistency. It is formed, at a secure way, a picture where one in two respondents owns the principles of the theory of tectonic plates (Fig. 3).

Table 3.

3rd Question: When two tectonic plates converge, we expect to find at their boundary:	Answers
a. superficial and deep earthquakes	9
b. volcanoes and mountains	4
c. subduction zone	10
d. all of them	26
e. none of them	0
total	49

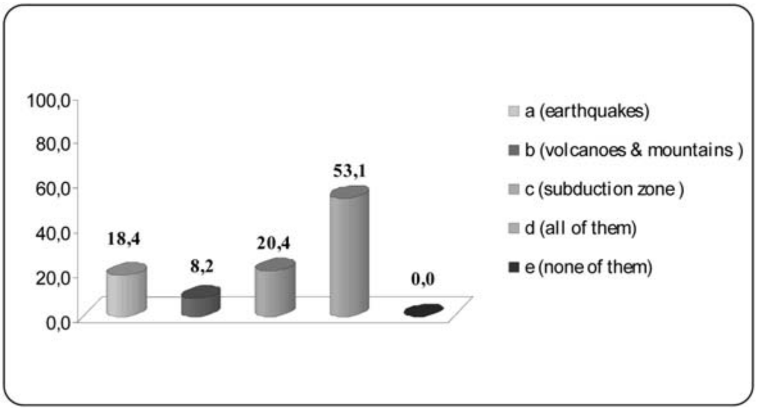

Fig. 3: Percentage of answers to 3rd Question.

The 4th question about the structure of the lithosphere (Table 4), the same percentage of correct answers (51%) is repeated. It is clear that there is a fully polarized sample of respondents between those who possess the basic theory and those who do not, at a ratio of 1 to 1. The rate of 18.3% that chooses a totally incorrect response, that the lithosphere consists of the core plus mantle, away from any relationship and contact with the geological science, is repeated (Fig. 4).

Table 4.

4th Question: The lithosphere consists of:	Answers
a. the core and the mantle	6
b. the crust and the lower mantle	12
c. the crust and the upper mantle section	25
d. the core and the lower mantle	3
e. none of these	3
total	49

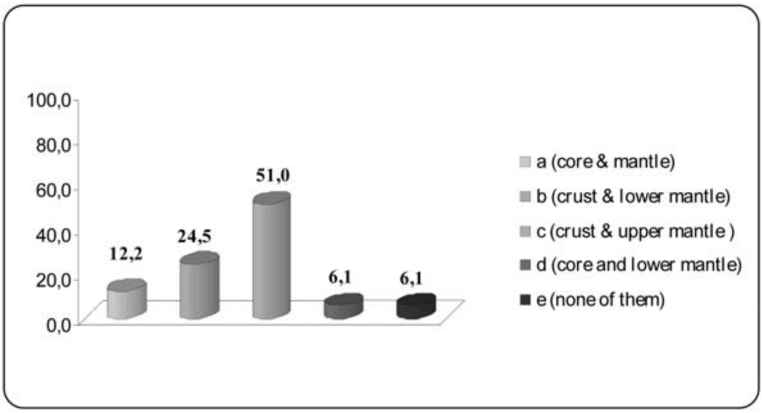

Fig. 4: Percentage of answers to 4th Question.

In the 5th and final question on the divergence of lithospheric plates (Table 5), the percentage of correct answers significantly reduced (32.7%). It is worth to make two observations: a) The high percentage of all possible answers shows a complete confusion. Typically, the cumulative rate 28.6% answers geological unaccepted, such as that at the divergence boundary we expect to find deep earthquake zone or subduction zone. b) A significantly higher percentage of correct answers are observed in the question about the boundary of convergence (53.1%) than the boundary of divergence (32.7%) (Fig. 5).

Table 5.

5th Question: When two tectonic plates diverge, we expect to find at their boundary:	Answers
a. deep earthquakes	9
b. subduction zone	5
c. mid-ocean ridge	16
d. all of them	9
e. none of them	10
total	49

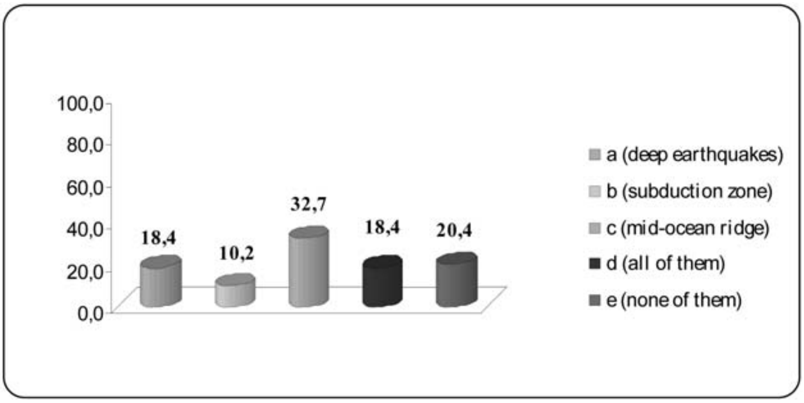

Fig. 5: Percentage of answers to 4th Question.

As the zero percentage of the reply that «the plates do not move» in two questions reveals, one of the key questions of research was answered positively by first-year students of Geology.

Whether this pre-existing perception is a part of the school-obtained knowledge or a result of the popularization of the theory of tectonic plates from the information media and society is a matter of further investigation.

One out of two students understands correctly the basic concepts of the theory of tectonic plates and the causes and effects of Geodynamic frame worldwide. This result agreed with similar studies about the conception owned by students (aged of 16-18) on tectonic plate's theory, according to international literature (King C., 2008).

About 50% of the questioned students understand with internal consistency and in a systematic way, both the geometry and the kinematics of the tectonic plates, with a satisfactory understanding of the rate at which these phenomena dynamically evolve.

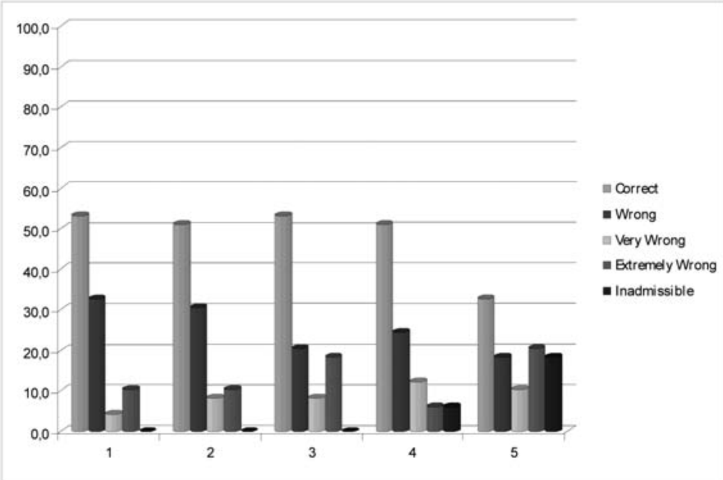

Fig. 6: Quantification of Conclusions.

One in four students has confused, without systematic knowledge and structure, getting information and data without a conceptual link, nor a deterministic result. This is a cognitive system which is a legacy from school knowledge as well as a wider social reality without any connection to the theory of tectonic plates.

One of the most interesting insights from this research is the fact that significant difference in the distribution of responses is observed between two similar questions about the convergent and divergent boundaries of tectonic plates.

We believe that the high percentage of correct answers to the question about the phenomena caused by the convergence of plates, compared with the corresponding low for the resulted phenomena of the divergence, demonstrates the effect of the fact that the Greek area is at a convergence boundary of the African and the Eurasian plate. Whether at school or from the information media and information, or otherwise in any form of simplified knowledge, it seems logical that we are better informed in geological phenomena on the convergence and less in the divergence of the plates, in our country (Greece).

In Greece, from textbooks to newspapers and magazines, there is a distinct orientation on the causes and effects of convergent margins rather than divergent. It is speculated that if the same survey was conducted in Iceland, the obtained results on convergence and divergence would be the opposite.

The conclusions could be summarized as:

All first-year students have satisfactory knowledge on the continuous movement of tectonic plates.

One out of two questioned students has systematic and consistent knowledge on the principles of the theory of tectonic plates, both at a conceptual and at a deterministic level, as well as in terms of geometric, kinematic and dynamic analysis.

One in four students has incomplete geological knowledge on the theory without any consistency and systematic approach.

The position of our country in the geodynamic frame determines the level of perceptions of students about the boundaries type of tectonic plates and this could explain the heterogeneity observed in the responses on the convergence and divergence (Fig. 6).

4. Acknowledgments

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FOLLOWING THE TRACES OF NAXIAN EMERY – AN IMPLEMENTATION OF ENVIRONMENTAL EDUCATION IN GEODIDACTICS

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Abstract

During the school year 2007-08 the environmental team of Naxos 2nd Junior High school accomplished the project entitled "Following the traces of naxian emery". The emery related topic was chosen due to the great importance of this mineral to the island's life and geoenvironment. The main purpose of this project was to inform the students and also a broader public, outside Naxos, about emery - a material that played, since antiquity, a significant role in naxian society and culture, and Greek history in general. The project also intended to sensitize the students and the local community relatively to the sustainable development of regions that suffer of population and cultural decline. In a framework of research and artistic creation, the team created educational material concerning the emery issue, which is available to other schools – "The emery educational kit". This consisted of a) an information booklet concerning the stone, b) a puzzle game relative to emery mining, c) an educational board game about emery and d) a documentary film produced by the team and entitled "Following the traces of naxian emery".

Key words: *naxian emery, emery educational kit, constructivist learning theory, situated learning, sustainable development, Mining Park, Naxos, Cyclades.*

1. Introduction

Decisive factor for the development of Cyclades islands, since antiquity were their mineral resources (marble from Paros, emery from Naxos, silver from Sifnos, pumice and obsidian from Milos). (Agriantoni, 1998; Kotsakis, 2003). Emery, "Smyrigli" as Naxians call it, is known since the antiquity as "Naxian stone". It is located underneath the mountains of Naxos in lenticular formation. According to the most dominant theory, emery developed through the process of metamorphism of bauxites (Urai and Feenstra, 2001; Feenstra and Wunder, 2002). This metamorphism is calculated to have taken place during the Alpine deformation (75.000.000-25.000.000 years ago) under special conditions of pressure and temperature. It contains a large mineral variety. Corundum ($A1_2O_3$) is the principal component varying from 55-65%, in the first quality, to 50-55%, in the second quality, and finally < 45% for the third quality. It also contains hematite (Fe_2O_3) and magnetite (Fe_3O_4). Some other materials that may be found as accessory phases include: micas, tourmaline $(Na,Ca)(Li,Mg,Al)(Al,Fe,Mn)_6(BO_3)_3(Si_6O_{18})(OH)_4$, kynite ($Al_2SiO_5$), diaspore ($AlO(OH)$), rutile ($TiO_2$), staurolite ($FeAl_4Si_2O_{10}(OH)_2$), vesuvianite $Ca_{10}(Mg,Fe)_2Al_4(SiO_4)_5(Si_2O_7)_2(OH)_4$,

Fig. 1: A pylon and a bucket of "Enaerios", the aerial system of emery transportation.

pyrite, sillimanite (Al_2SiO_5), chlorite ($Mg_6Si_4O_{10}(OH)_8$), feldspars, apatite $Ca_5(PO_4)_3(OH,F,Cl)$, garnets (Nikolaou, 2005; Christofidis and Soldatos, 2009).

Corundum is what makes emery a precious product. It is the reason why emery is noted for its great hardness and its abrading attributes. Specific weight of emery is around 4 and its hardness is between 7 and 9 on MOHS scale, depending on the quality (Nikolaou, 2005). Emery is mainly used for the smoothing of several surfaces, such as metal, glass, wood, minerals, in sand blast and as an anti-slipping material for the construction of roads.

Naxos, Samos, Heraklia, Sikinos, Paros and Ikaria are the Greek islands where emery is found. The best quality is in Naxos where the mining takes place. American and Turkish emery are also known but they are of poorer quality.

Naxian emery was one of the more significant Greek minerals for a great period of time. Naxos has long been the main emery production centre of Europe. The existence of the precious rock was located in Naxos during Ancient times. Then it was used for the creation of artefacts such as the famous Cycladic statuettes. (Kotsakis, 2003). Emery is found mostly on the mountain Ammomaxi, in northeastern Naxos, between the gulfs of Moutsouna and Lyona, near the villages Apeiranthos and Koronos. It is a region with great hypsometric differences and intense dismemberment. Geologists calculated emery reserves in that area to approximately 2.200.000 tons. The mining right, since the Turkish domination, was a privilege of the inhabitants of 6 villages: Apeiranthos, Koronos, Danakos, Mesi, Skado and Keramoti.

Emery has been a very important factor of Naxos' prosperity mainly for the first half of the 20th century, resulting to being one of the main factors of formation of the environment as well as the society of mountainous Naxos. (Archontakis and Giannoulis, 2001). Primarily emery, after being extracted, was transported to Moutsouna bay by donkeys. "Enaerios" was constructed during the years 1926-1929. "Enaerios" is an aerial system of transportation using wire ropes and buckets (Polyzos, 1997). It began functioning in 1929 and it consisted of 72 pylons, wagons, buckets, loading installations, engine rooms and depositories (Balodimou, 2003). This aerial system of transportation is one of the few that still exist in Greece (Fig. 1). It functioned until 1978. Since then, emery has been transported with trucks, through the road that connects the mines with the port of Moutsouna (Fig. 2), as the aerial transportation to the port, was thought to be uneconomical (Frangiskos, 2003).

From the post-war years and on, a declination in the emery mining has occurred. In the 90's, the natural emery was pushed aside commercially, because of the production of artificial corundum, and the

Fig. 2: The port of Moutsouna, where once emery was loaded into the barges.

expansion of cheaper but inferior qualitatively Turkish emery, but also because of the indifference of the Greek state to promote the product in the market. (Zagouras and Ioannidis, 1988).

The emery mines of Naxos, the remains of mining machinery and transportation installations, as well as the piled up quantities of the mineral, feature now to be a commemoration of the pre-industrial period and have been declared preservable by the Ministry of Culture (Gontinou and Loukma, 2006).

Despite the efforts for the solution of the emery problem, the appreciable initiatives of various institutions were not materialized (Louvi, 1996). This also was the case with the more recent study of 1986, which suggested the exploitation of emery and emery areas, through the development of a museum organized by a co-operative institution (Polyzos et al., 1996).

2. Pedagogical framework

2.1 Cross thematic/ interdisciplinary character of the project

The project "Following the traces of Naxian emery", due to its multifarious character, has dictated the use of a cross thematic and interdisciplinary approach, that indicates the close relationship of geodidactics with the didactics of other disciplines.

The starting point of the project was geology and the mineral emery. In order to define the position, creation and properties of this mineral, knowledge that served as a basis for the project, the parallel contribution of geology, geography and chemistry was needed. For the understanding of the uses of the product and the reasons of its fame, we investigated elements of modern technology but also looked back in antiquity, with the aid of archaeology, which has revealed the commercial character of emery since Neolithic era and its use in powerful tools suitable for the smoothing of marble and therefore for the creation of the famous Cycladic statuettes. Industrial archaeology had also an important role in the project, since the team examined the industrial remnants related to emery mining and transportation, in a perspective of presenting them as monuments in a future mining park.

Seeking to comprehend the rights of the Naxian highlanders in mining and sale of emery through time, the group had to consult history. The exploitation of the mineral by the Frank feudal lords changed only in the late 18th century and the exclusive right in emery mining of six mountainous Naxian villages, still in effect, goes back to that time. Emery is also very closely related to economic history and history of trade unions. While working on the project, the students realised the importance of emery in Greek economy, especially during the 19th and 20th century, and learnt about the first trade union of emery and the first strike of the emery miners in the early 20th century.

Finally, a big part of the group's research on the spot had an anthropologic- ethnographic character, since the students examined material culture, poetry and songs, customs and traditions, proverbs and myths, social life in general in the mountainous emery villages of Naxos.

2.2 Learning theories

The project "Following the traces of naxian emery" is based on constructivist learning theory and situated learning.

The constructivist learning theory, in accordance to the cognitive approach to knowledge, that contradicts behaviourism, emphasizes the perspective of the learner. Knowledge does not exist as an external and absolute event, but as a product of interaction between the subject matter and the learner. The constructivist learning theory has two basic points: 1) the starting point of learning is the learner's pre-existing knowledge, attitude and interests on the topic, 2) learning arises by the interaction of the above with experience (Howe and Berv, 2000). The person that is in a process of learning chooses and transforms the information, forms hypotheses based on a mental structure (schemas, mental models) that gives meaning, organizes his experience and allows him to go on further than the given information.

The implementation of constructivist learning theory in education suggests the designing of educational content that can interact with pre-existing knowledge, attitudes and interests of the individuals and can help them create their own meaning. Subsequently, special attention is needed when it comes to studying learners' needs and background. In the framework of constructivism it is generally accepted that the individual is not learning through passive acceptance of learning material. On the contrary, an active participation of the student in the procedure of knowledge construction is encouraged, using as basic tools conversation, social interaction, cooperation and negotiation (Phillips, 2000; Vosniadou, 2002; Anderson et al., 2003; Terwel, 1999). Of course, the above does not imply the exclusion of the benefits of knowledge centered environments, since the well organized and deep knowledge of a material is a prerequisite for designing a correct learner centered environment. An approach for creating curricula that encourage meaningful learning is "progressive formalization" which begins with the informal ideas that each student brings into a learning environment, and help them gradually transform and formalize them (Bransford et al., 1999).

Theory of situated learning regards learning as a multifactorial procedure that is not limited to the individual itself but is determined by a number of socio-cultural parameters (Brill, 2000). In the light of this theory, the activity through which knowledge is developed is not separated by knowledge itself. In other words situations co-produce knowledge through action.

In an effort to trace down the basic features of situated teaching, we can mention the following (Greeno et al., 1996):

- Thinking and problem solving is achieved in a frame of goals that are set by a broader social group.
- Knowledge is inseparably connected to actions.
- The use of multiple cognitive methods (mnemonic and visual aids) is enhanced.
- Cooperation with other members of the group and task distribution is expected.
- Learning takes place through tasks of various grades of complexity, similarly to what happens in real world.
- Learning tasks constitute a part of a completed project, which exists as a final goal.
- The problems do not dictate the way of solving them, but the learner must detect the possi-

ble solutions, as it happens in daily life.

Since theory of situated learning views learning through the practices of a community and the abilities of individuals to participate in them, in teaching level it sets as a goal the encouragement of participation and the creation of an environment in which the learner can apply his/her own new knowledge. This approach turns over the discrimination between "know what" and "know how" and aims to the connection of theory with its application in practical level.

Lave and Wenger (Lave and Wenger, 1991) speak about apprenticeship and underline the importance of authentic participation of an individual in the group's activities and setting of goals. They also consider as learning motivation the individual's desire to be an active member of a community that sets learning as a value. In other words, theory of situated learning considers innate the desire of an individual to define him/herself as part of a community.

3. Description of the program

3.1 Goals

Realizing the great importance of the mineral emery to the island's life and geoenvironment, the environmental team of Naxos 2nd Junior High school chose to accomplish the project entitled "Following the traces of naxian emery". We thought that through this project the students and the teachers involved would get the chance to better familiarize themselves with the mineral that determined the history and the environment of their island. For this project, students of all grades worked together with the teachers Sofia Kritikou and Irini Malegiannaki.

The project intended to sensitize the students and the local community relatively to the sustainable development of regions that suffer of population and cultural decline. The goals of the team were:

- To learn about emery and mountainous Naxos in a pleasant and amusing way.
- To learn how to cooperate as a team.
- To create educational material concerning the emery issue, available to other schools– "The emery educational kit".
- To propose solutions for the sustainable development of the emery mining regions of Naxos island.
- To inform a broader public, outside Naxos, about a material that played a significant role in Greek history.

3.2 Research on the spot

The realization of the project "Following the traces of Naxian emery" was based to a large extent on excursions and research on the spot. The innate curiosity of the children has firstly led the team to the mountainous emery villages Apeiranthos and Koronos. There, the students interviewed ex emery miners, they visited the geological museum in Apeiranthos, the remnants of the aerial railway and a basic mining gallery. Inside another gallery, some of the students took part in a short mining procedure (Fig. 3), while later the students went downhill to the port of Moutsouna, where the mineral was loaded. The kids, disappointed of the nowadays depopulation of the Naxos highland, sought for solutions of sustainable development. They traveled to Athens, where a specialized geologist from the Museum of Mineralogy and Petrology of the University of Athens initiated them to concepts like geo-conservation and geo-tourism. Afterwards, the team traveled to Fokis. There, in the mining park Vagonetto, in Amfissa, they got acquainted with the idea of transforming a deserted mining gallery into a museum. In their way back, the children carried ideas and hopes for the creation of a cultural mining park in Naxos.

Fig. 3: Participation in a short mining procedure in a gallery near Apeiranthos.

3.3 Contents of the "emery educational kit"

The "emery educational kit" includes:

- An information booklet concerning the mineral emery.
- A puzzle game relative to emery mining.
- An educational board game about emery.
- A documentary film produced by the team, entitled "Following the traces of naxian Emery".

3.3.1 The information booklet

The method used for the creation of the emery information booklet was the division of a goal in sub goals. In order to enhance all students' involvement in the investigation of the topic, this was divided up in smaller units given in a query form. The task of each student was to gather information about each question. The unification of the material gathered created the booklet.

3.3.2 The educational game of emery

Keeping in mind that learning through entertainment is more effective (Kousouris and Papadogiannaki, 2005), the team constructed the emery board game (Fig. 4). The game consists of two main panels, one representing the Naxos Island and the other the emery mining regions. The players take the role of emery miners trying to arrive to the Moutsouna port in order to weigh amounts of the mineral. A correct answer to a question relative to emery or a correct dramatization of an act relative to emery mining allows them to proceed closer to their destination. However, many other activities prevent them from accomplishing their goal, for example, a holiday, a gardening task, an illness etc. The winner of the game is the player that arrives first at the port having gathered the greatest amount of emery. With this game the players, besides learning about the emery mining, get acquainted with elements of the tradition and the culture of mountainous Naxos (local dialect, proverbs, feasts, customs, material culture, social relationships).

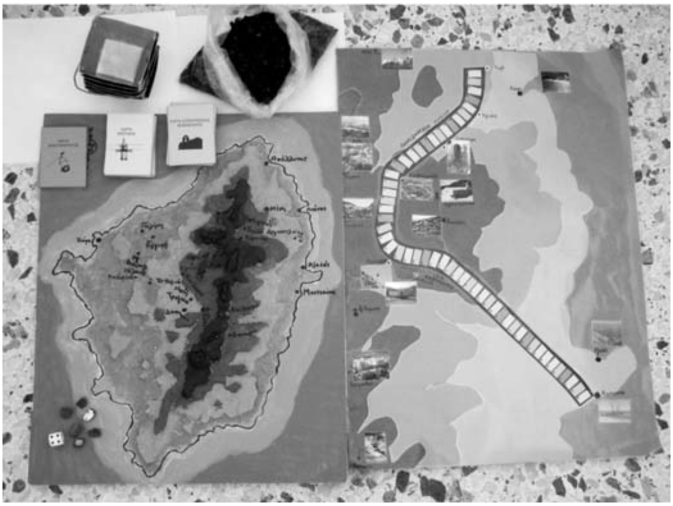

Fig. 4: The emery board game.

3.3.3 The documentary film

Our young cameramen recorded all their excursions with their cameras (Fig. 5). Thanks to the professional director Vaggelis Katsigiannis, the gathered material was brought together into a 35 minute documentary film entitled “Following the traces of naxian Emery”. The film describes the children’s experiences and at the same time gives a lot of information about emery and its mining and transportation process. It also describes the role the mineral played in the formation of the societies of the villages involved in emery mining. By watching this film the viewer gets the chance to follow the progress of the school project and at the same time learn about emery. As far as the impact of the film shooting process to the team’s motivation is concerned, we can point out the following:

- The goal of a film production gave the team strong stimulus and integrated all their actions in a framework of problem solving and artistic creation.
- The use of camera added great charm to the team’s campaign. The children did not just simply take a school trip, but undertook the role of a researcher, a cameraman, a designer of a completed scientific and artistic film. During the realization of the documentary, they had the chance to learn all about the phases involving film producing, camera handling, and dramatization. The collaboration with a professional director gave precious knowledge to the children and the professors, and allowed us to seek an even better result.
- We believe that the shooting of a documentary really helped in the achievement of learning via experience (Learning by doing).

3.3.4 Presentation of the project

As the project of the 2nd High School of Naxos came to an end, the idea of creating a cultural mining park has emerged as a possible solution to the declining and abandonment of the emery villages. All the conclusions and the material produced during the project, including “the emery educational kit” were presented to the public, in a special presentation that was organized in the town hall of Naxos. In the same location, the team also organized a digital photography display concerning the topic.

Fig. 5: Shootings during an interview with ex emery miners, in a traditional house of Apeiranthos.

4. Conclusions

The project “Following the traces of Naxian emery” constitutes an example of application of geodidactics – through a cross thematic framework – in environmental education. Having a mineral as starting point, a school team became engaged in the creation of a complete research and artistic work, addressed not only to the members of the team, but also to the local society and a broader public. The latter worked as a strong learning stimulus for the kids but also for the teachers-coordinators. The students, agents of different interests, abilities and preexisting knowledge, contributed each one in a particular way, to the goal setting and implementation of the project. This way, they escaped the passive approach to learning, largely imposed by the school class and became active creators of a more meaningful learning. Additionally, the framework of a team enhanced learning through social interaction, which allows the individual to achieve accomplishments that exceed its personal abilities, according to Vygotsky’s (1978) “zone of proximal development”. We believe that the project “Following the traces of Naxian emery” constitutes an eloquent example of creative and amusing learning that has left students and teachers a notable remembrance of the school year 2007-8.

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THE STUDY OF HEAVY METAL CONCENTRATIONS IN THE RED MUD DEPOSITS AT THE GULF OF CORINTH, USING MULTIVARIATE TECHNIQUES

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Abstract

Detailed geochemical analyses were performed on the recent sedimentary cover (0 – 15 cm) of the northern flank of the Gulf of Corinth, in western Greece. Man-made metalliferous deposits have been formed on the sea-bed of the Gulf due to the discharge of red mud tailings on the shelf of the Antikyra Bay. The metalliferous deposits have been incorporated in the sedimentation regime of the area. A large grid of sediment samples collected from surface and subsurface red mud deposits and the surrounding natural sediments were analysed for Ag, Al, Cd, Co, Cr, Cu, Fe, Hg, Mg, Mn, Ni, Pb, Si, Ti, V, and Zn concentrations, using Atomic Absorption Spectrometry (AAS). Also, Total Organic Carbon and Calcium Carbonates were determined. Additionally, correlation between heavy metal concentrations and grain-size data was examined. High heavy metal content values were measured on the floor of the Corinth basin, but the highest heavy metal concentrations occur near the discharge site. In subsurface sediments the heavy metal content (Fe, Ni, Cr, Pb, V, Ag, Co, Al, Cd, Ti, Hg) is significantly higher in the red and reddish mud sediments than in the natural mud sediments. The heavy metal content values decrease from top to base within red-mud deposits. Multivariate statistical methods (Cluster and Facto analysis) were applied on the heavy metal composition and grain-size dataset in order to investigate the inter-element relationships as well as the relationships between the geochemical and sedimentological data.

Key words: *red mud tailings, geochemical concentrations, R-mode factor analysis, cluster analysis, Corinth Gulf.*

1. Introduction

The geochemical composition of recent marine deposits in urban and industrialized areas is a result of the contribution of natural environmental factors and a wide range of human activities (Borrego et al, 2002). The marine disposal of industrial wastes such as the bauxitic (red-mud) tailings constitutes an important human input of heavy metals to marine environment (Grey and Baseden, 1976) on a regional scale.

This study deals for the first time with a group of samples which cover the overall study area and constitutes a preliminary presentation of the results. It presents the geochemical signature of surface and subsurface samples in order to establish the distribution of the studied compounds spatially and also temporally via the subsurface sedimentary layers.

This study also aims to explore the inter-relationships of major and minor elements in red-mud slurry and in natural sediments by using multivariate statistical methods, such as factor and cluster analysis. These methods have been applied widely on geochemical data to study their spatial distribution and the interrelations between metal concentrations (Papatheodorou et al., 1999; Papatheodorou et al., 2002; Sanchez-Garcia et al., 2009) and on geochemical and granulometric components (Borrego et al., 2002).

2. Material and Methods

2.1 Study Area

The Gulf of Corinth is an elongated embayment in western Greece (Fig. 1a). The morphology of the northern margin of the Gulf consists of a wide shelf, in Antikyra Bay, which passes through a steeping slope and ends to a deep basin floor at 890 m water depth (Brooks and Ferentinos, 1984). In Antikyra Bay there is a significant anthropogenic input in the sedimentation regime of the area. Massive bauxite residue tailings are being discharged on the shelf floor for more than 40 years from an Aluminum processing plant. As it is presented by Iatrou et al. (2007) these materials have formed significant metalliferous deposits on the shelf and the basin floor and have been admixed with the natural sediments.

2.2 Datasets and geochemical analysis

A large grid of more than 100 short cores have been collected from the seafloor of the study area in order to study the recent sedimentation layer (0-15 cm) which has been affected by the deposition of the red-mud tailings. Surface subsamples were collected from each short core as well as subsurface samples from the majority of the short cores composing a large dataset. Sediment samples were initially analyzed for their grain-size components using sieve-pipette method. Next, major and minor elements concentrations (Ag, Al, Cd, Co, Cr, Cu, Fe, Hg, Mg, Mn, Ni, Pb, Si, Ti, V, and Zn) were determined on a Carbonate Free Basis using total decomposition method through a Perking Elmer 3100 atomic absorption spectrograph. Also Organic Carbon and Calcium Carbonate concentrations were determined.

2.3 Data Treatment

Consideration of the many possible inter-related physical and chemical controls that might be operative in dataset led to the decision that the chemical and physical data should be analyzed separately. Thus in the present study the multivariate analysis was performed on three separate subsets of the original data using the commercial statistics software package SPSS v 14.0. Subset 1 consists of the geochemical concentrations of each surface and subsurface sediment sample, while the subset 2 comprises of the geochemical compositions for the surface samples. The subset 3 incorporates the geochemical compositions and the grain-size components of the surface sediment samples.

Most of statistical methods of data analysis require that the observations conform to normal distribution. Thus, a Kolmogorov-Smirnov test of normality was applied on the three subsets, which showed that not all the variables were normally distributed with 95% confidence interval. Therefore statistical treatment was carried out on subset 1 where the raw data were standardized according to the method used by Reimann and Filzmoser (2000). However subsets 2 and 3 were not subjected on any treatment in order to explore the raw data.

To identify the relationship among minor and major elements that exist in red-mud tailings and in natural sediments as well as their possible sources, subset 1 and subset 2 were analyzed using Factor Analysis. Factor analysis is a multivariate technique of data reduction that examines the interdependence of variables providing knowledge of the underlying structure of data (Davis, 2002). Subset 3 was analyzed applying hierarchical cluster analysis. This was due to the fact that grain-size components were co-dependent variables; therefore factor analysis could not be performed (Davis, 2002). Clusters were produced using between groups linkage method with Pearson correlation as similarity measurement.

3. Results

3.1 Bulk geochemistry and granulometry

Table 1 shows the concentration range and mean in carbonate free basis, of heavy metals, calcium carbonate and organic carbon in the red mud and natural sediments from the Antikyra Bay and the Corinth Gulf. The red-mud tailings are highly enriched in Fe, Ti, Cr, Ni, Co, Pb, and Cu, compared to the surrounding natural sediments. On the contrary, natural sediments are characterized by high concentrations of Mn, Zn, and $CaCO_3$, compared to the red-mud deposits.

Table 1. Bulk geochemical concentrations of red mud and natural sediments in Antikyra Bay and Corinth Gulf.

	Red mud in Antikyra Bay			Red mud in Corinth Gulf			Natural sediments		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Fe [a]	30,4	40,4	35,8	33,7	36,7	35	4,92	16,92	8,42
Ti [a]	5,1	5,8	5,4	2,31	2,32	2,31	0,11	1,69	0,53
Al [a]	11,9	13,8	13,1	11,5	12,4	12,1	0,1	10,82	7,29
Si [a]	5,4	5,8	5,6	6,2	6,8	6,5	6,37	38,12	21,46
Mg [a]	3,05	8,96	5,30	4,30	10,15	6,47	4,04	12,14	6,29
Pb [b]	195	159	162	111	145	131	-	101	30
Cu [b]	110	148	133	125	137	133	29	101	57
Hg [b]	4,8	5,9	5,0	2,6	3,2	2,8	-	2,1	0,34
Co [b]	81	127	103	83	100	92	-	58	32
Cr [b]	2950	4312	3441	1030	1210	1120	-	753	207
Ni [b]	1498	1728	1624	1126	1169	1147	65	854	231
Ag [b]	7,6	12,1	9,6	6,0	8,2	7,3	-	7,0	0,83
V [b]	601	718	673	548	600	571	58	222	142
Cd [b]	6,0	11,6	10	6,5	11	7,9	-	9,5	0,7
Zn [b]	95	112	108	124	143	135	89	326	218
Mn [b]	800	1483	1325	2338	3501	2914	1292	8674	4044
$CaCO_3$ [a]	30,25	85,87	48,88	24,04	65,55	44,01	35,13	51,19	46,21
Corg [a]	0,20	2,90	0,58	0,30	1,10	0,73	0,10	3,20	1,02

[a] (%)
[b] (ppm = $mgkg^{-1}$)

Red mud tailings on the shelf and the basin floor are mainly composed of silt and clay fractions (Table 2), whereas natural sediments on the shelf and the basin contain coarser components.

Table 2. Bulk granulometric composition of red mud and natural sediments in Anikyra Bay and Corinth Gulf.

	Red mud in Antikyra Bay			Red mud in Corinth Gulf			Natural sediments		
	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
sand (%)	0,1	4,9	1,8	0,1	37,3	2,7	0,5	94,6	44,2
silt (%)	34,7	53,2	44,5	33,7	66,1	43,2	2,8	50,6	26,4
clay (%)	46,6	61,1	53,7	23,1	65,9	54,1	2,7	64,0	29,4

3.2 Subset 1

An R-mode factor analysis, using a varimax solution, was applied to the full geochemical dataset (18x162) using the standardized data. Based on a combination of common criteria for factor selection used by Davis (1986), the most significant five factors were taken. The five factors account for more than 82 % of the information among the variables. Communalities are high (>0.70) for all variables. The five-factor model explains the variability for all variables and can be used to indicate the geochemical processes that modulate the composition of the recent sedimentary cover of the study area, without losing any significant characteristics.

Factor scores are plotted to describe relationships between samples. The temporal (with depth) distribution of factor scores was presented by plotting the score values of each short core along sampling traverses with an east-west direction. Each short core is depicted with the surface and subsurface sub-sample sites.

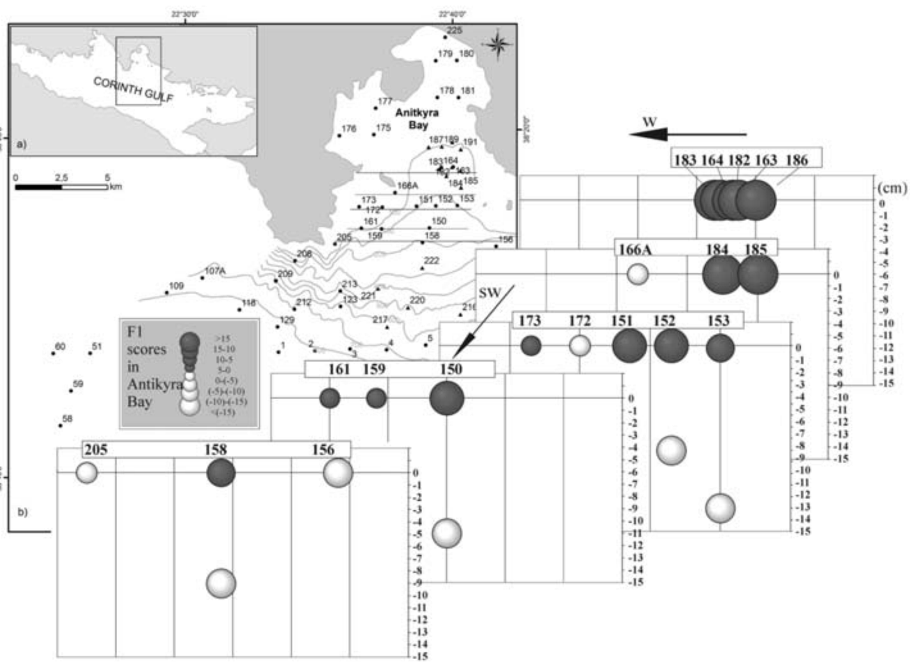

Fig. 1: (a) Study area; (b) Temporal distribution of factor 1 scores on selected sample sites in Antikyra Bay versus sediment depth (in cm).

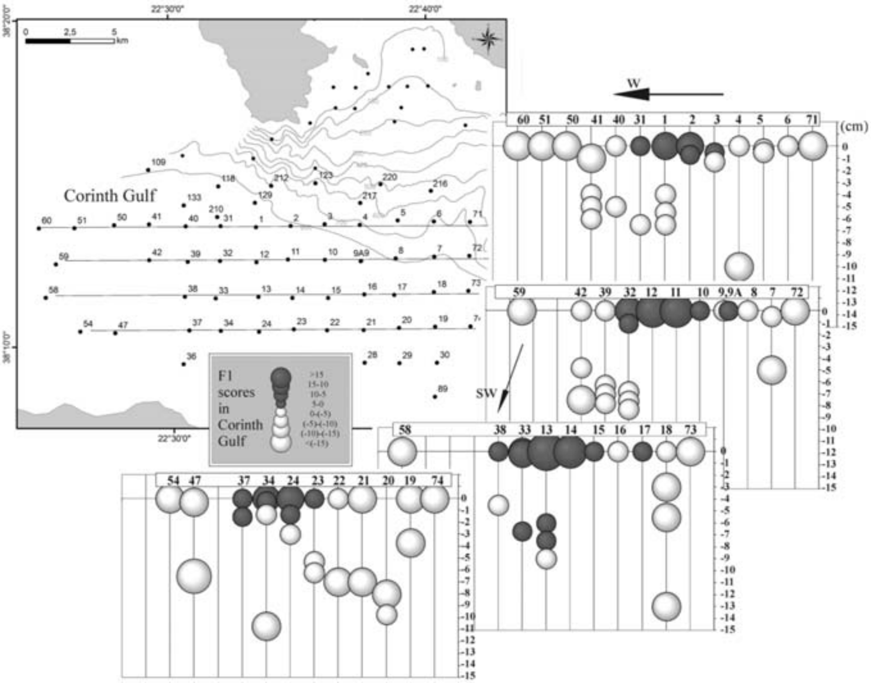

Fig. 2: Temporal distribution of factor 1 scores on selected sample sites in Corinth Gulf versus sediment depth (in cm).

The first factor (F1) explains the largest proportion (46.42%) of the total variance and has high positive loadings on Fe, Ti, Al, Pb, Cu, Hg, Co, Cr, Ni, Ag, V and Cd. These metals are associated with red mud tailings. The temporal distribution of F1 scores on the surface and subsurface sample sites shows that the high positive values of this factor coincide with the red-mud tailings deposits. Higher values are observed among the surface red mud samples. The highest values however are in the surface red-mud samples from Antikyra Bay (Fig. 1b). Factor scores obtain lower positive values in the subsurface samples, that is F1 decreases with depth (Fig. 2). F1 is considered to be a red-mud factor which presents the variation of the red-mud tailings geochemical composition from past (subsurface layers) to present (surface layer).

The second factor (F2) explains a significant portion (10.9%) of the total variance. F2 is a negative factor with high loading values on Si and Mg. According to the temporal distribution of factor scores F2 has higher negative values in the surface and subsurface samples which are not associated to red-mud tailings but are natural sediments.

However, no significant variation was observed in the score values between the surface and subsurface natural sediment samples. The samples with the high score values also show high levels of concentration on Si and Mg. Therefore, F2 may explains the association of Mg with the silicate fraction of the sediments.

The third factor (F3) explains a significant part (10.7%) of the total variance and shows high negative loadings on Mn and Zn. Factor 3 has higher negative factor scores on non red-mud sediments. Score values are higher on the surface samples of the short cores from the basin floor and

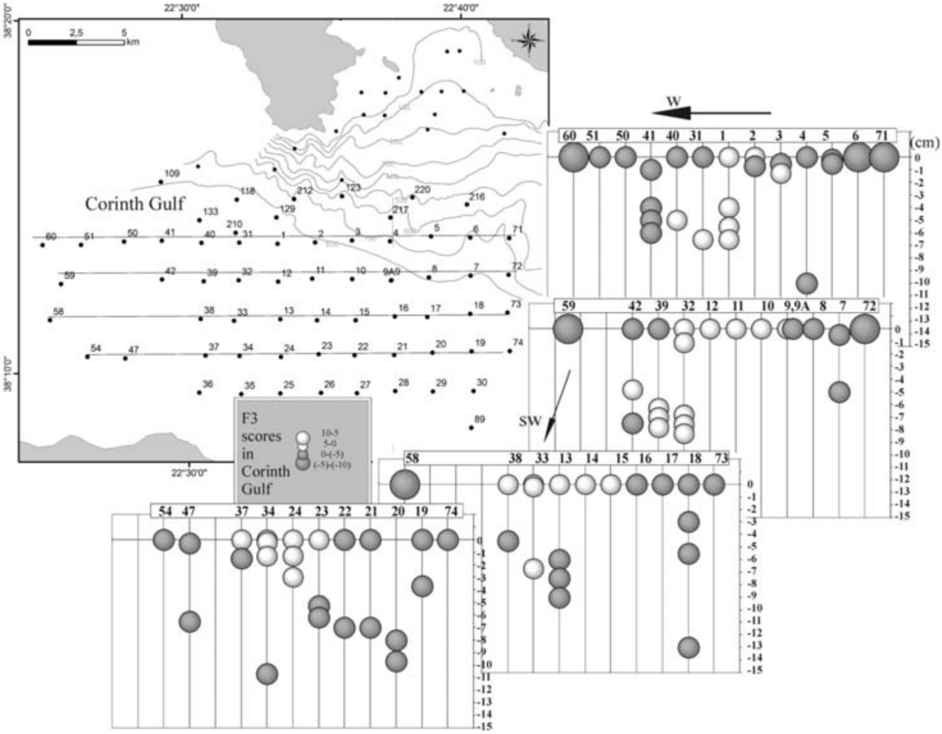

Fig. 3: Temporal distribution of factor 3 scores on selected sample sites in Corinth Gulf versus sediment depth (in cm).

especially those on the east and west extremities of the basin (Fig. 3). These samples also show high levels of Mn and Zn. F3 may accounts for the Mn-hydroxide phase of the sediments which has absorbed Zn.

The fourth factor (F4) explains 7.3 % of the total variance. F4 has high positive loadings in $CaCO_3$ According to temporal distribution of this factor, high factor scores show primarily natural sediment samples and few surface red mud samples. These samples have higher percentage of sand component and therefore this factor could explain the carbonate-sandy fraction of sediments.

The fifth factor (F5) explains 7.2% of the total variance and has high negative loading values in Corg. Temporal distribution of factor scores shows that it has higher values in natural surface /subsurface sediments and in few red-mud samples located in the periphery of the basin floor. On the contrary the lowest values are observed among the red-mud samples on the shelf and in the central basin. F5 accounts for the organic fraction and cannot be associated with another mineral.

3.3 Subset 2

Subset 2 consists of the geochemical raw dataset which involves the metal concentrations of the surface sediment samples (18x101). R-mode varimax factor analysis was carried out on the subset 2 and the four most significant factors were selected. They account for the 82.52% of the total variance. Communalities are high (<0.69) for all variables (Table 3).

Table 3. R-mode varimax factor matrix of geochemical data for subset 2.

Variable	F1	F2	F3	F4	Communalities
Fe	0.87				0.88
Ti	0.70	0.48			0.78
Al	0.81				0.70
Si	-0.67		0.57		0.77
Mg	-0.75				0.77
Pb	0.78	0.51			0.88
Cu	0.86				0.80
Hg	0.83				0.86
Co	0.82				0.76
Cr	0.76	0.50			0.87
Ni	0.80				0.90
Ag	0.79				0.91
V	0.76	0.47			0.89
Cd	0.75	0.45			0.79
Zn		-0.79			0.73
Mn		-0.85			0.74
$CaCO_3$			0.93		0.89
Corg				-0.89	0.95
Variance explained (%)	49.1	17.6	9.0	6.8	
Cumulative variance (%)	49.1	66.7	75.7	82.5	

Factor 1 explains the largest proportion (49%) of the total variance and has high positive loadings on Fe, Ti, Al, Pb, Cu, Hg, Co, Cr, Ni, Ag, V and Cd. These positive values are opposed by moderate negative loading values on Si and Mg. The surface distribution of Factor 1 scores (Fig. 4) depicts the bipolar nature of this factor. Factor 1 primarily expresses the spatial distribution of the red-mud components and secondary the spatial distribution of natural sediments on the Antikyra shelf, especially those that are of silicate composition.

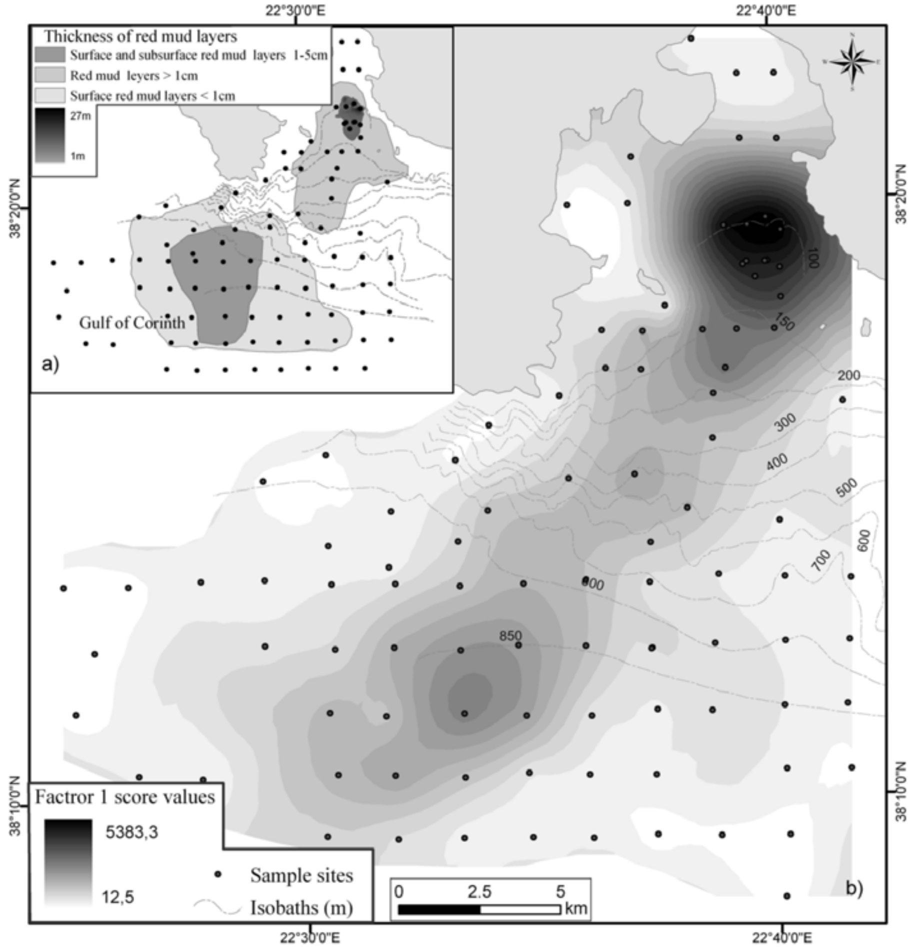

Fig. 4: Spatial distribution of Factor 1 scores of subset 2. Inset shows the surface distribution of red mud deposits on the study area (*modified from Iatrou et al, 2007*).

Factor 2 explains the significant proportion of 17.5% of the total variance. Factor 2 show high negative values on Zn and Mn. The spatial distribution of factor scores shows that high values are on the surface natural sediments on the western part of the Antikyra Bay and on the natural sediments deposited on the east and west extremities of the basin floor (Fig. 5).

Factor 3 explains 9% of the total variance. Factor 3 exhibits a high positive loading on $CaCO_3$ together with the moderate positive loadings for Si. Spatial distribution of factor scores shows that high values exist on the coastal area of Anikyra Bay (<100m water depth) and on the eastern side of the Corinth Gulf basin. Factor 3 indicates that the natural sediments composition is the result of a coarser carbonate fraction with silicate components.

Factor 4 accounts for the 6,8 % of the total variance and is a single variable factor with a negative pole on organic carbon. Surface distribution of factor scores show that Factor 4 describes the samples that are not associated with red-mud tailings.

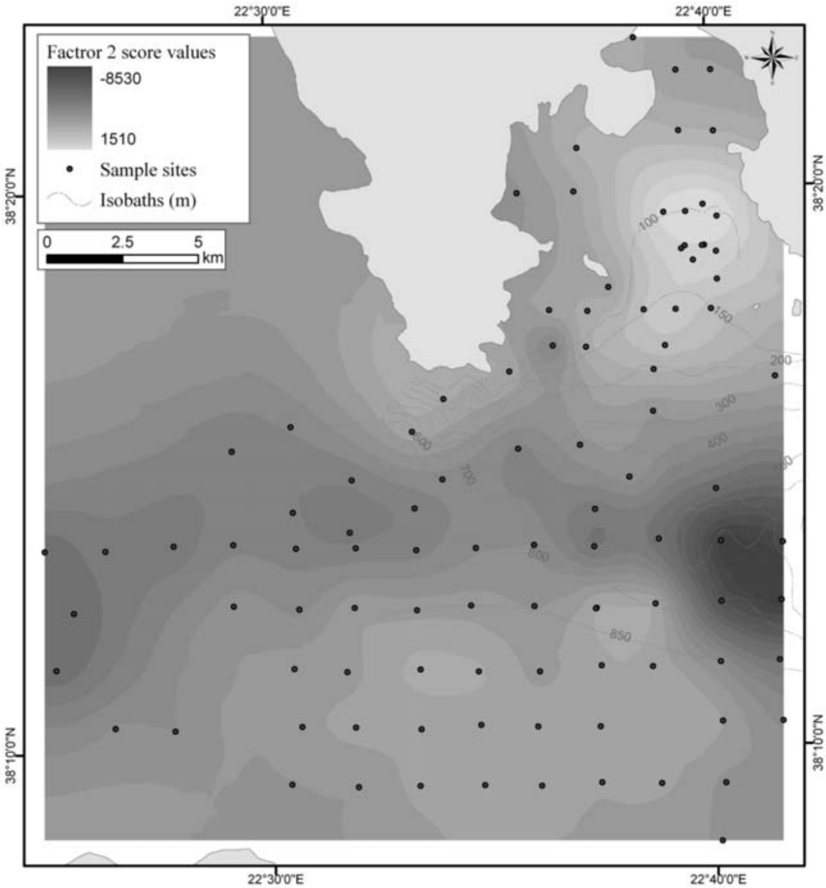

Fig. 5: Spatial distribution of Factor 2 scores of subset 2.

3.4 Subset 3

Hierarchical cluster analysis was carried out on the subset 3 which combines geochemical and granulometric data. As Fig. 6 shows two clearly defined clusters are obtained. C1 clusters V, Ag, Ti, Fe, Pb, Ni, Hg, Cd, Cr, Co, Cu, Al, and silt, clay. These heavy metals are associated with red mud tailings therefore they show strong interrelations. Silt and clay fractions describe the granulometric composition of the red mud tailings. Therefore C1 expresses the geochemical and grain-size signature of the tailings.

C2 can be divided into two sub-clusters. C2a clusters Si, Mg, with $CaCo_3$ and sand fraction. These cluster elements are not associated to red-mud tailings. Therefore C2a group may express a natural sedimentation component such as siliclastic and carbonate fraction of sandy components, indicating the complex origin of the natural sediments.

C2b clusters Mn and Zn with organic carbon. This cluster expresses the background sedimentation components, which are also not related to red-mud tailings. Organic carbon however shows a very weak similarity to the other two cluster elements. C2a and C2b join together at a relatively higher level, possibly implying a common source.

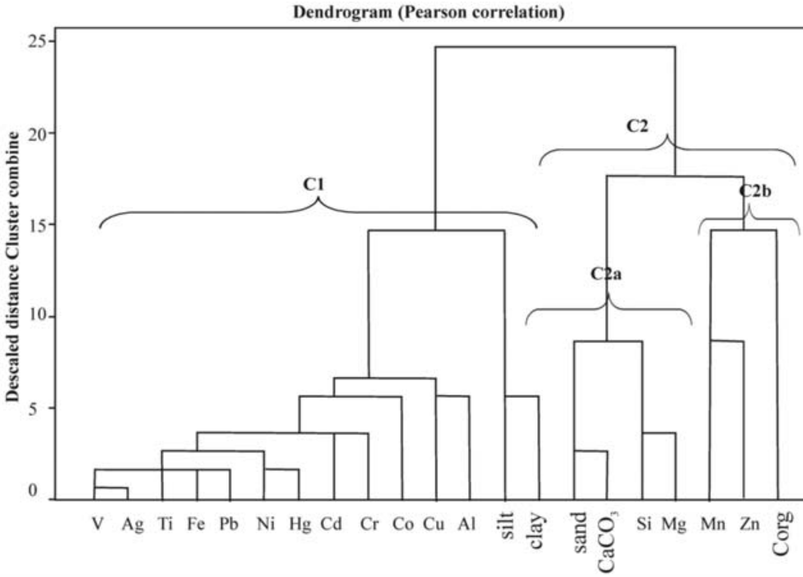

Fig. 6: Dendrogram from cluster analysis of subset 3 between geochemical and granulometry components.

4. Discussion - Conclusions

The red-mud tailings are highly enriched in certain heavy metals, such as Fe, Ti, Al, Pb, Cu, Hg, Co, Cr, Ni, Ag, V and Cd. The disposal of the tailings primarily on the shelf of Antikyra Bay and secondarily, through gravity driven flow processes, on the basin floor of the Corinth gulf (Iatrou et al., 2007) contributes to the abundance of heavy metals concentrations which alter significantly the background levels.

The performance of R-mode factor analysis on the two subsets 1 and 2 dealing with the total geochemical dataset allowed the presentation of specific trends to different dimensions for each subset. Subset 1 provides insight into the temporal distribution of components of the red mud tailings and natural sediments. Subset 2 presents the spatial distribution of those components. The combined analysis of bulk geochemistry and granulometry provided further information regarding the granulometric signature of red mud tailings and the origin of natural sediments.

The effect of the red-mud tailings on the geochemical regime is verified by the fact that the most significant factor describes the red mud components. As it is presented by the distribution of the red mud factor, the score values are higher in the surface sample sites from the Anikyra Bay shelf floor. In addition there is a significant decrease on the score values between the shelf and the basin floor, in all data samples. The above are verified by the geochemical composition of the sub-samples that indicate a decrease on the levels of heavy metals with depth, in the subsurface sediments and shows a significant decrease on heavy metal concentrations between the shelf and the basin. Although the above may be explained by differentiation of the geochemistry of the red mud tailings over the discharge period, mixing processes cannot be excluded. Therefore, red mud tailings could undergo mixing process from the first deposition site on the shelf to the final resting site on the basin floor as it is indicated by the decrease in metal composition along the same direction. The heavy metals that are associated to red mud tailings correlate well with silt and clay fraction of the sediments, indicating the fine sedimentary texture of the tailings.

The factors that express the natural sediments account for less significant proportions because of the strong geochemical masking of the tailings. However, they are able to depict the geochemical signatures and present indications about their origin.

Factor 2 from the subset 1 analysis coincides with the negative pole of factor 1 from the subset 2 analysis. They express the distribution of Si and Mg. However Si is also described by the factor 3 of the subset 2 analysis which is considered to be a carbonate factor. This multiple appearance of Si may indicate the complex origin of the natural sediments. They consist of silicate fraction and also by carbonate components. Asserting the previous, cluster analysis correlates Si, Mg and $CaCo_3$ to sandy fraction indicating that the natural sediments which exist on the coastal area of the Anikyra Bay shelf are characterised by coarser particles.

Factor 3 from the subset 1 coincides with factor 2 from subset 2. They both account for the distribution of Zn and Mn. These elements have higher concentration among the natural sediments, particularly in those at the east and west extremities of the basin floor. Thus it is depicted the natural sedimentation which is associated to Mn-hydroxide phase of sediments.

Factor 5 from subset 1 and factor 4 from subset 2 both explain organic carbon content. In cluster analysis organic carbon correlates at a higher level with Mn and Zn. Thus it may be suggested that Corg cannot be associated to another component. This is also supported by the spatial distribution of Corg on the study area (not given here) which does not exhibit specific trends.

5. Acknowledgments

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SEA SURFACE TOPOGRAPHY IN THE GULF OF PATRAS AND THE SOUTHERN IONIAN SEA USING GPS

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Abstract

The topography of the sea, which is changing continuously mostly due to tides, meteorological forcing and climatic changes, is very poorly known in both regional and global scale. In our work we apply a new method, "GPS-on boat", based on differential (DGPS) or kinematic GPS for the recording of the Sea Surface Topography (SST) in the Patras Gulf and the southern Ionian Sea. Analysis of data collected permitted to compile a first map of Sea Surface Topography in the study area. The application of the methodology that we present seems also quite promising for the accurate determination of the Geoid in coastal areas, in which other methodologies provide lower quality results.

Key words: *GPS, Sea Surface Topography (SST), Geoid, GPS-no boat, Ionian Sea.*

1. Introduction

Sea Surface Topography (SST) roughly coincides with a surface of constant gravity, the geoid, representing the zero level for height measurement on land. The S.S.T. is usually poorly known, especially in closed gulfs and near-shore areas, which are not properly covered by satellite data merely focusing on oceans. The knowledge of the topography of the sea is important for various reasons, including geophysical (gravimetry-related) studies, meteorological models and climatic change studies. In the past, models of the geoid and the mean sea level for Hellenic area have been presented (Tziavos and Andritsanos, 1999; Andritsanos el al., 2000, Pavlis and Mertikas, 2004).

This paper summarizes results of a first attempt to measure SST along certain traverses in the Ionian Sea and the Patras Gulf using GPS, in particular the method GPS-on-boat. GPS have been widely used for geoid determination on land (Fotopoulos et al., 2000), but the on-boat application are new.The details and results of this technique, which may provide optimum results at coastal areas and semi-closed gulfs, are presented below.

2. Methodology

The method of 'GPS-on boat' is based on kinematic GPS (Smith, 1997), the simultaneous tracking of satellites by a moving ("rover") receiver and by one or more stable ("base") receivers on stable ground. The apparent changes of the position of the base receiver permit corrections to the computed coordinates of the rover receiver. This technique requires that both receivers are at relatively short distances, usually up to a few or a few tens of km, so that ambient conditions are quasi-similar, and

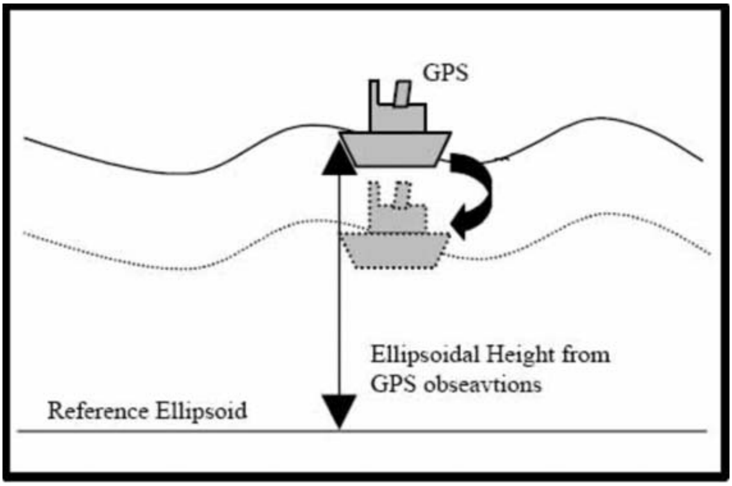

Fig. 1: The "*GPS- on boat*" methodology. The rover GPS receiver calculates directly the instantaneous elevation of the boat relative to the reference ellipsoid. Filtering of the short-term effects (fluctuations of the sea-level shown as two different levels) permits an accurate elevation of the SST along the boat track.

may permit up to mm level accuracies (Nickitopoulou et al., 2006). In longer distances, this error maybe of the order of tens of cm (Psimoulis et al, 2007), although there is the possibility of high accuracies at distances >100km (Kashani et al., 2005).

In our study the rover GPS was mounted on a boat which was sailing on the sea-surface, and the computed coordinates were corrected using recordings from base stations on land. Apparently, the elevation of the rover receiver was reflecting the instantaneous position of the rover receiver in reference to the ellipsoid (Fig. 1). This elevation represents the juxtaposition of the SST elevation along the boat track, noise introduced by waves and other meteorological events, elevation differences introduced by tilting of the boat and measurement errors.

However, waves are transient effects usually with a period of a few seconds, the track of sailing boats is relatively smooth but with a zigzag pattern, while the tilt of the boat can be recorded during the sail. Hence, sampling of satellite signals at a rate of 15 second and filtering of the instantaneous coordinates of the rover using statistical approaches permit to minimize all these sources of noise and obtain filtered coordinates, with the vertical coordinate describing the SST with accuracy better than 15cm.

3. Data

The experiment was conducted from 25 June to 3 July 2008. A Topcon HipperPro type GPS receiver was mounted on a 43ft long sailing boat sailing has been used. The sampling rate of the rover and of base receivers was 15sec. In addition, weather data (intensity and wind direction, the atmospheric pressure, temperature and moisture), as well as the slope of the boat were systematically collected throughout the experiment.

4. Analysis

Kinematic coordinate recordings from each traverse were analyzed in combination with recordings from the nearest base stations using the PCCDU and Pinnacle software. In certain cases (boat in

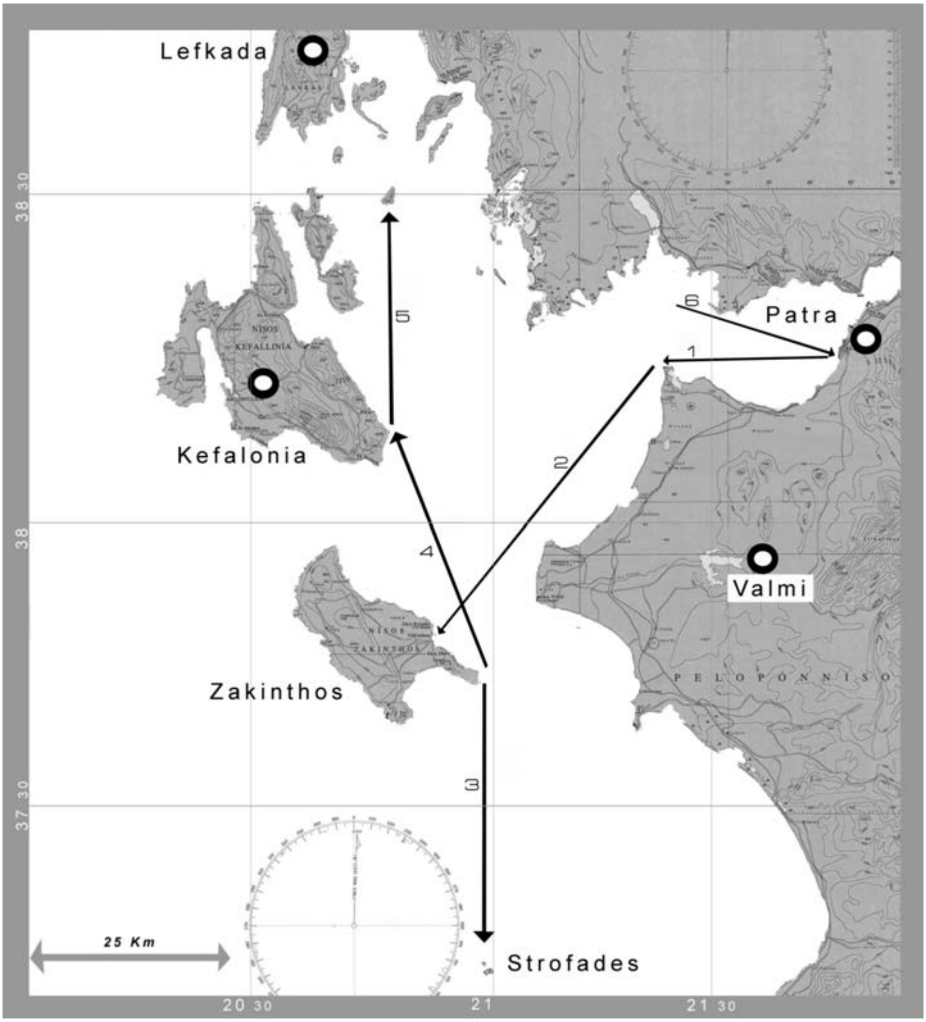

Fig. 2: General map illustrating six (6) different routes of scanning the surface of sea and geodetic GPS base stations. These stations are located at the University of Patras, the Village Valmi, Lefkada and Kefalonia.

harbour) mean values of sea-level elevations were obtained. Finally, the elevation of the rover receiver above the water was subtracted.

Obtained records were characterized by various types of noise, as shown in Fig. 3. This noise was removed adopting the following procedures:

(1) outliers were removed.
(2) systematic offsets with amplitude of tens of cm, sometimes characterizing GPS data for intervals of up to 10min long (see Nickitopoulou et al., 2006), were corrected.
(3) scatter in data revealing random noise was removed using a moving average filter.

In addition, tidal corrections, of small magnitude in the area (<10cm) were also made, and mean values of elevation along straight lines (instead of zigzagged lines of the boat track) were computed.

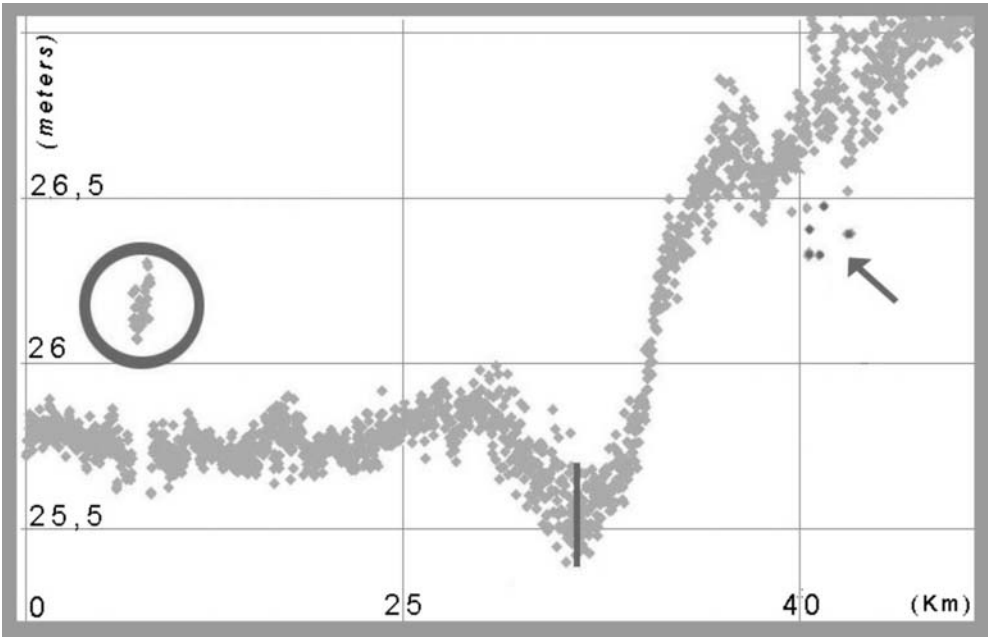

Fig. 3: Recordings of the boat elevation relative to the ellipsoid indicating several types of noise: random (a spread of data), systematic (a systematic offset marked by a circle) and outliers (marked by an arrow). Extract from the June 28th 2008 record.

Following this filtering and correction process, a final set of coordinates of the boat position was available. These coordinates indicate the SST elevation along the traverses. The mean sea surface elevation error was smaller than 15cm. This is due to the imperfections of the atmospheric model as well as to the large distance of GPS base stations from the mobile GPS (Genrich and Bock, 2006) and the multi-reflection of the signal (Leandro, 2009). This analysis is, however, preliminary, and can be repeated using data from additional base stations and different atmospheric models (Kashani et al., 2005) to obtain accuracies one order higher.

5. Sea Surface Topography Maps

Figure 4 illustrates the mean elevation of the sea along six traverses. The contours define the Sea Surface Topography around the traverses. These results indicate a smooth drop of the topography and the geoid in the Patras gulf and the southern Ionian Sea. Moreover, these are consistent with the geoid maps of the broader regions derived using other methods (Andritsanos et all, 1995; Cocard et all, 2002).

6. Discussion

The technique presented above provide high accuracy results and resolution maps of the geoid and of the Sea Surface Topography, especially in closed waters not covered by satellite data. The accuracy claimed of 15cm is an upper level of the method, and it can be reduced using data from other GPS base stations (e.g. Strophades islands) and more refined models. The method proposed is rather expensive because it requires data collected by boats. However, its accuracy can be much higher and using interpolations may provide detailed maps of the SST for different users.

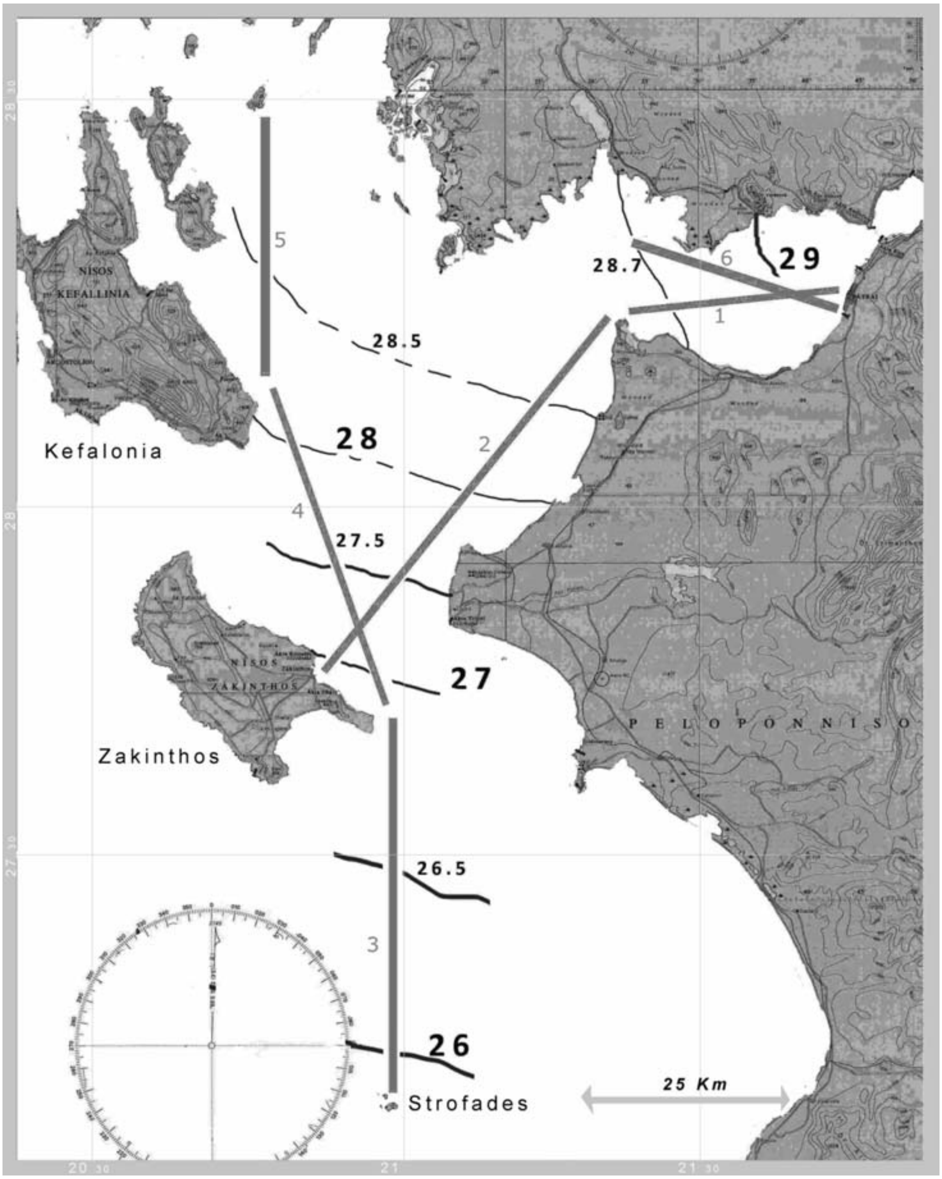

Fig. 4: Sea Surface Topography contours along six traverses.

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RESEARCH PROJECTS TO STUDY THE SEA FLOOR AND SUB-BOTTOM SEDIMENTS FUNDED BY THE RECENT EUROPEAN COMMISSION FRAMEWORK PROGRAMS: THE I.G.M.E. PARTICIPATION

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Abstract

Since 1983, after the participation of Greece in the European Union (EU), IGME has carried out many research projects relevant to earth sciences funded by the European Commission (EC). Especially in the sector of Marine Sciences, a number of projects have been funded in cooperation with other European Institutes. The main targets of the research projects were relevant to the tasks described in the various framework programs (FP) evaluated by the EC, with the tasks changing according to the decision of the European Parliament. The marine projects became gradually larger in terms of the number of the participating Institutes while their target focused more toward to the society needs such as the sustainable energy resources and environmental problems. In this presentation we will describe the research projects relevant to the above targets that were carried out in the last 10 years partly or entirely in the Greek seas.

Key words: *Hyace, Anaximander, Hermes, Hermione, European Projects.*

1. Introduction

1.1 EC Priorities and relevant Projects

Description of priorities

The priorities of the projects that will be described are related in general to the research on the Gas Hydrates (GH) present in the sea sub bottom and to environmental problems affecting the marine realm. GH were targets in the projects HYACE and ANAXIMANDER, and the environment by the projects HERMES and HERMIONE.

GH are ice crystals composed of 6 to 8 H_2O locking a molecule of hydrocarbon in solid forms, usually methane. They are present in sedimentary layers and were first observed at the beginning of the 20th century during oil drillings in ice land areas,. During the 1970's they were firstly reported within the sub bottom layers in the deep seas due to a sudden increase in the sound velocity, that was diminished in the underlying layers. During the following decades an impressive quantity of GH was found on or below the oceanic sea bottom. Today it is estimated up to over 90% of GH in the earth is present at the deep ocean sub-bottom sedimentary layers (Fig. 1).

This caused the interest of many countries (such as USA, EU, Japan, India, China, S. Corea) considering GH as a possible sea floor energy source, but also as a possible impact in the sea floor insta-

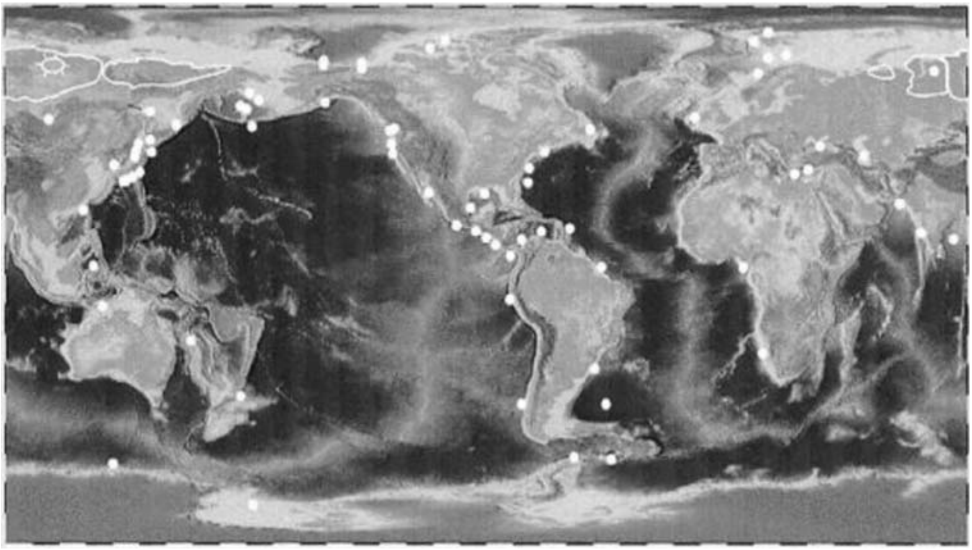

Fig. 1: The worldwide presence of Gas Hydrates.

bility caused by an eventual future GH dissociation and release of the methane. For example many large sediment slides on the continental slopes were understood in the context of the gas hydrates. This is because if only part of the gas will be released due to a sediment failure and be entrapped might result in a climate change. Apart of these the recent estimations indicate that the total of carbon in the GH world wide is in the volume of about 500 Gt that is about 5% of the carbon present in the earth (Milkov, A.V. 2000; Fig. 2). With this estimated amount, the globally available carbon in GH is high, taking into account the fact that conventional fossil fuels are getting more and more exploited.

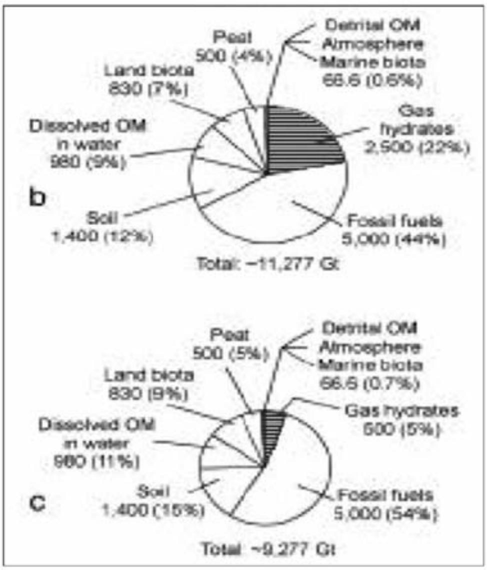

Fig. 2: Schematic representation of the organic worldwide presence of Gas Hydrates (in Gt) by Milkov 2000.

The study though of the unique environment of the GH presents a number of considerable difficulties related to their remote location, the great sea depth, the need of new tools for in situ sampling and sample conservation and integrity, the examination of their characteristics and properties and the release of the entrapped methane. As it turned out thou from recent marine GH research, mainly from exploration but also from exploitation studies, the marine GH occurrences are lacking substantial reservoir characteristics to warrant economic exploitation. This scepticism, already expressed some years ago, has not yet been overcome. Another main problem also originates from the non-existence of a cap rock package on top of the GH containing sediments.

In respect the environmental issues, the study of problems on biodiversity, structure, function and dynamics of ecosystems along Europe's deep-ocean margin has been gradually becoming a main task for a comprehensive European Ocean and Seas Integrated Governance Policy. Actually it represents now the first major attempt to understand European deep-water ecosystems and their natural environment in an integrated way (geosphere, hydrosphere, biosphere in pan-European range). This must be carried out in the European margin from Norway to the Black Sea, instead of studying just one area in one region alone. Thus the targets have been to compare and contrast a suite of key environments around which, by virtue of their geographic locations, to experience quite different environmental settings. Important targets were the extensive study of the dynamic structures, of all shelf, slope and rise of the European seas. These researches required urgent study because of their possible biological fragility, global relevance to carbon cycling and/or susceptibility to catastrophic events and to global change. The participating members, Institutes and private companies were urged to cover as many as possible European countries, within and beyond the EU.

2. Description of projects

2.1 Project HYACE

The project was named HYACE for "Hydrate Autoclave Coring Equipment" and was carried out from 1997 to 2000. It had as target the construction of a corer that could be lowered within the seafloor drilling tubes, in GH containing layers, collect GH and keep them in situ conditions for laboratory studies (Amann 1998, 2000, Perissoratis et al., 1998).

The corer was designed to sample marine sediments in a down hole conditions and bring it on board while maintaining as many down hole parameters as possible. Particular targets were sediments on the deepwater covered continental slopes containing GH. The main general goal of the project was to contribute to the systematic ground trotting of sampling and analysis of GH in their natural environment. In parallel a main target was also to obtain the information on GH and the detailed knowledge of their geology and to predict the changes on pressure and /or temperature during their dehydration processes.

The plan included formation of a corer with three sampling tools, a push, a rotary and a percussion tool to be used depending to the characteristics and the hardness of the sediments to be sampled. Positive areas where these corers can be used included the North Atlantic, the Eastern and Northwestern Pacific Ocean, and other European seas. For this purpose marine geological field work was carried in 1999 south of Peloponnesus, where study of previous seismic profiling data showed possible presence of GH, but the researches showed that the sub-bottom horizons did not contained GH. In spite of the fact that in 1996 GH were already discovered and collected in the Anaximander seamountains in the Eastern Mediterranean. Nevertheless The HYACE corers were successfully used during drilling ODP project Leg 194 in the Pacific Ocean (Fig. 3, 4).

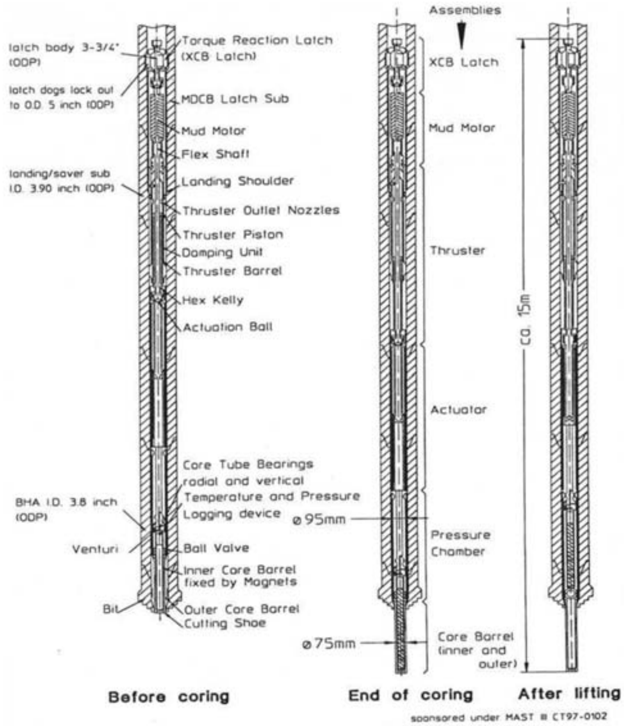

Fig. 3: The Autoclave core sponsored under MAST III.

Fig. 4: Gas Hydrates crystals collected during the Anaximander cruises (a, b). Gas Hydrates from the Pacific Ocean /GEOMAR cruise (c, d).

In the HYACE project participated, exept IGME, Institutes from Germany, France, Spain, The Netherlands, and The United Kingdom, Coordination was the Technical University of Berlin.

2.2 Project ANAXIMANDER

Based on the discovering of GH in the Eastern Mediterranean during general marine researches in the Mediterranean from 1996 to 1999 (Woodside et al., 1996,1999), by Dutch and Russian research ships a project was proposed at the Anaximander Mountains (Mts) and funded by the EC in 2002. The project named ANAXIMANDER "Exploration and Evaluation of the Eastern Mediterannean Sea Gas Hydrates and the associated deep biosphere" was carried out from 2002 to 2006 during which two 15 days field works were carried out in 2003 and 2004 respectively. According to the previous experience in HYACE and other researches, an integrated approach was needed for a successful consideration of the above diverse and difficult challenges and the research team constituted to undertake this task (Fig. 5) because the selected area for conducting the GH study, has a quite deep average sea bottom depth, over 2000 m and bottom temperature 12-14°C. In addition to the presence of GH a characteristic unique and rich biota was observed along with occurrence of abundant methane. Thus the research team of ANAXIMANDER (Perissoratis et al. 2004) had to proceed beyond the current knowledge by using appropriate and innovative coring and sampling instruments to obtain and bring on board undisturbed "pristine" cores. The purpose was to carry out sub-sampling with minimum distortion on the various GH containing sediment properties and keep the associated bio-communities unaffected. Also applied a methodological experimental innovation in order to analyze and then synthesize the laboratory results of the GH containing sediments, their dissociation kinetics processes, and the associated deep biosphere. At the same time and during this research previously unknown potential GH occurrences were continuously discovered within the EU economic zone (offshore Eastern Spain, offshore Portugal, Black Sea, Northern Atlantic, North Sea), and this caused the outcome of the ANAXIMANDER project particularly important.

The research was carried out by using a deep low sidescan sonar and sub-bottom profiling. The data indicated that there are areas where there is a high gas content in the sediment and possibly seeps. Initially the three principal targets for sampling of GH in the Anaximander Mountains region were the Amsterdam, Kula, and Kazan Mud Volcanoes (MVs) where GH were sampled during the earlier cruises by. During the project discovered two new, previously unknown, MVs that were named Athina and Thessaloniki MVs. The first research however was carried out (May 2003) the Amsterdam MV because it appeared to have the larger central area where GH could be sampled, as Amsterdam MV was considered the most active of the MVs in the area. At previous targets, also Kula MV was sampled. Then during the second cruise (November 2004) the MVs Kazan, Athina and Thessaloniki were studied. All these targets were within the GH stability zone; thus it was assumed that these areas constitute areas of GH presence as long as there is a sufficient source of GH presence. The continuing preliminary examination of the existing data in the Anaximander Mountains region confirmed the initial choices of sites and indicated the whole area as a potential GH occurrence. All these sites span a considerable range of water depths, from 2236 m, slope of Amsterdam MV, to 1263 m at the summit of Thessaloniki MV, the latter depth coincides with the upper boundary of the hydrate stability zone (Lykousis et al., 2004, a,b; Perissoratis et al., 2006, 2007). Also the mud breccia recovered from all mud volcanoes (Amsterdam, Kazan, Kula, Athina and Thessaloniki) contained numerous rock clasts from the deep seated strata of Mts.

The researches undertaken by IGME were the depositional processes, the GH presence, the mud volcanic activity and the geological evolution of the Anaximander area.

The mud volcanoes in the Anaximander Mts erupted a poorly sorted matrix-supported breccia, con-

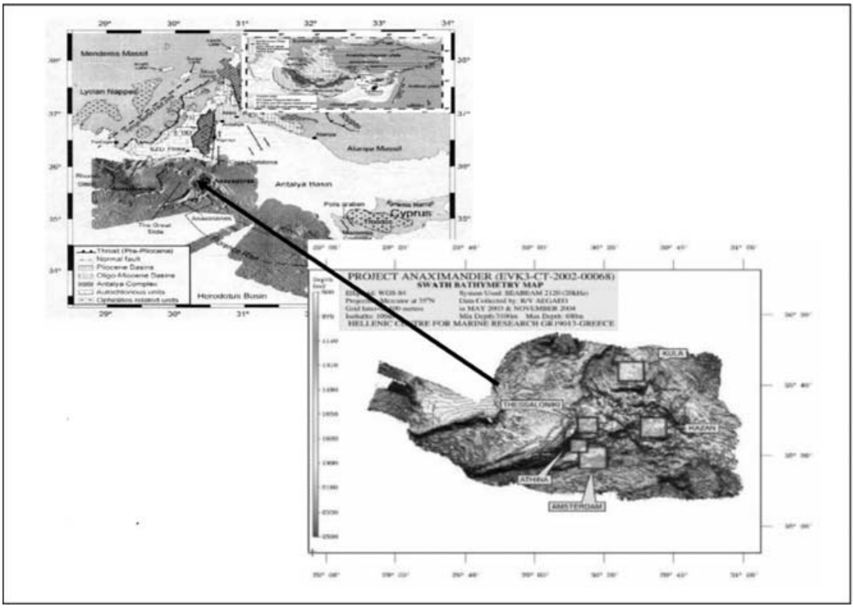

Fig. 5: The detailed bathymetric map of the Anaximander Mountains (Anaximander project) and its adjacents areas (by Ten Veen et al. 2004).

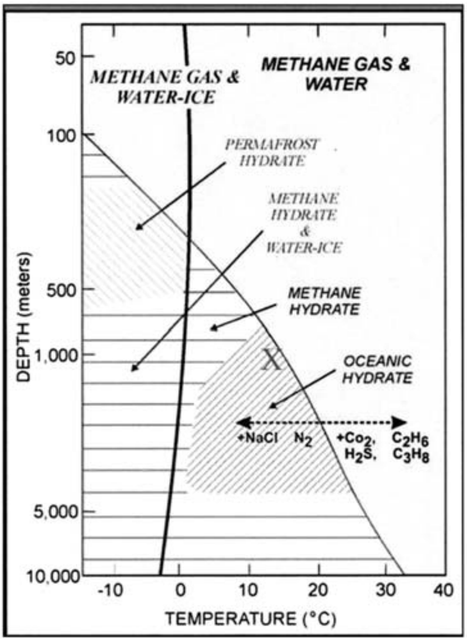

Fig. 6: Schematic representation of Gas Hydrates Stability Zone (GHSZ) –X the case of Thessaloniki Mud Volcano.

taining rock clasts derived from lower lying formations. Thus, the morphology, petrography and biostratigraphy of the mud breccia clasts from Amsterdam, Kazan, Kula, Athina and Thessaloniki MVs (Fig. 4) helped us in outlying the deep stratigraphy and hence to obtain a better understanding

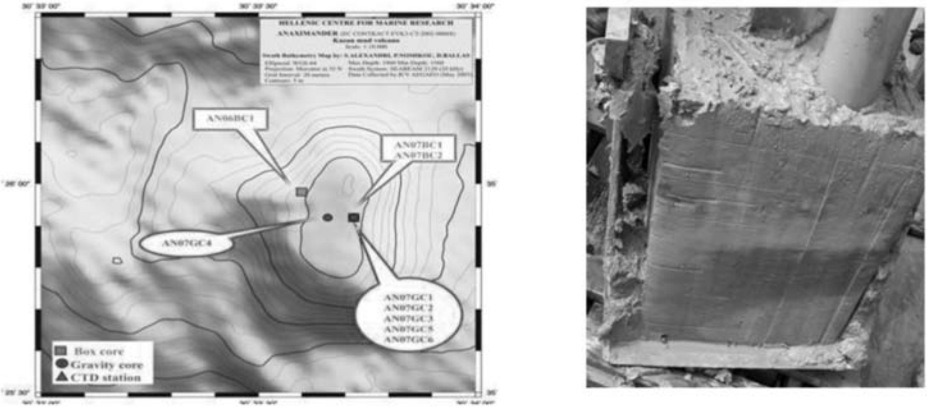

Fig. 7: Lithological sequence of AN06BC1 box core and the bathymetric map of Kazan Mud Volcano (courtesy D. Sakellariou and S. Alexandri).

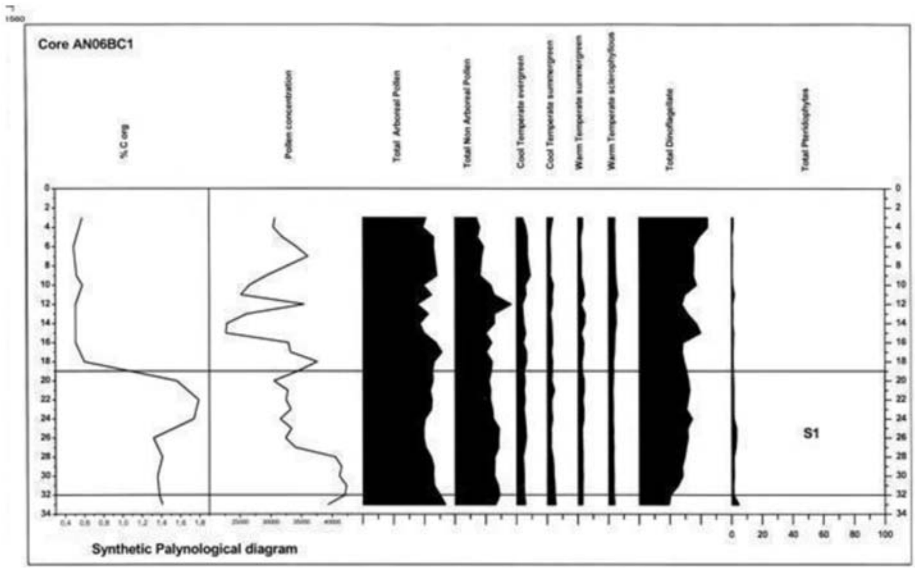

Fig. 8: Synthetic representation of selected palynomorph fossils included in the pelagic sediments.

of the formation and geological evolution of the Anaximander mud volcanoes. Also microfacies analyses (foraminifera) and petrography carried out on thin sections through microscope and X-ray diffraction (XRD) analyses provided a more precise estimation of the relative age of the source rock formations and a subsequent determination of the depositional environment during the rock formation (Ioakim et al., 2004, 2005; Casas et.al., 2006). The Eastern Mediterranean is characterized by repeated stagnant anoxic episodes (Figs 7, 8) and volcanic eruptions that resulted in the deposition of sapropels and ash layers that in turn permitted the correlation from core to core. According to the obtained data (C14 measurements, the tephra and isotopic chronology) and the presence of the Sapropel S1 led to interpret a volcanic reactivation about 10 kyrs approximately (Ioakim, et al., 2004, 2005; Lykousis et al., 2005; Vougioukalakis, et al., 2005).

In respect to the GH presence the data do not permit an unequivocal decision as to the base of the GH stability zone (GHSZ) and we had to rely on the thermodynamic data in order to assess its depth and, eventually estimate the volume of GH present. According to these data the calculated depth of the base of the GHSZ (Fig. 5, 6), ranges between 125 and 240 m. We assumed a depth of 150 m and calculated the volume of sediment containing GH in the Eastern Mediterranean to 22.5 km^3. Considering the percentage of GH in the sediment about 10%, the volume of GH in the Anaximander area was estimated at 0.25 km^3.

In the Anaximander project the eight participants were from research Institutes from Greece (IGME coordinator, HCMR), Germany, The Netherlands and Spain.

2.3 Project HERMES

The HERMES project stands for "Hotspot Ecosystem Research on the Margins of the European Seas" and provided new research into the study of the European sea bottom all around the European seas. The project had to answer how the various human activities in combination with the expected climatic changes will affect the sea environment in Europe. It started in 2005 and ended in 2009.

The project targets were the following: How human activities interfere with ecosystems? How vulnerable are ecosystems to man's intrusions? How quickly are they able to recover? Can we mitigate the negative environmental impacts of man's activities and reach a sustainable balance? Can EU realize its commitment to sustainable development and international treaties ? And finally what is the likely effect of global change on an ecosystems stability. Thus to answer these questions HERMES focuses particularly to ecosystem "hotspots" that are strongly physically mediated hydrogeological structures, including: unstable slope systems, canyons, deep-water coral habitats, cold seeps, gas and associated with dynamic geological and/or hydrates, mud volcanoes and anoxic microbial systems. These important systems required study because of their possible biological fragility, global relevance to carbon cycling and/or susceptibility to catastrophic events and to global change.

For IGME parts of the targets of HERMES project was a follow up work of the Anaximander project and were related in obtaining more knowledge on two main subjects: First the specific role and characteristics of the Gas Hydrates (GH) in terms of a possible impacts to the climate in case of their dissociation and a methodology for its possible use as an energy source. Second to study the climatic changes mainly in the last 32.000 years BP up to now, documented on micropalaeontological data and isotopic analysis obtained from the sediment analyses in two long gravity cores collected from greater area of Amsterdam MV and in the offshore area south of Crete. During the Hermes project were also examined further the interpretations of the palaeoenvironmental conditions and the link of the geological processes with the presence or absence of Gas Hydrates (Ioakim et al., 2004, 2005; Perissoratis, et al., 2007). In addition, the geological relation was examined existing between the sub bottom sedimentary horizons and the rock formations outlying at the sea sub-bottom with the sedimentary horizons present in the adjacent land of the Greek islands and at South Turkey.

For the possible environment impact of the released methane presented in the area, two scenarios were considered. First continuous methane release, with slow release rate and microbial mediated oxidation in the sediment or in the water column with no methane entering to the atmosphere. Second instantaneous release of free gas (out burst event) rapid released rate, no reaction in the sediment nor in the water column, absence of biologically mediated nor organic oxidation of methane and immediate release into the atmosphere.

With the data at hand and taking into account the great depth of GH field in the area (from 2500 m to 1260m) it was conclude that in both scenarios the possibility of a geological hazard to occur and affect the nearby land (great slide, explosive event, tsunamis) is low to negligible even by assuming a 10m sea level lowering and 1ºC decrease in temperature and an increase in salinity. As for the possibility of the use of methane present in the GH as an energy source, the data indicated that the quantity of methane is insufficient, and the hydrate density within the sediment is rather low. In addition the event of methane production is today cost preventing due to the great sea water depths, the remote location and the absence of offshore infrastructure. However more in depth researches are needed to fully evaluate the occurrence of GH and the total amount of GH at the Eastern Mediterranean area.

For the Palaeoclimatic – Palaeoceanographic conditions, the data showed that the sediments center of MVs constituted by mud breccia and in many cases included gas hydrates. In the sediments around the MVs there were hemipelagic sediments that contained the sapropelic layers S1 and S2 as well as the volcanic ash layer Y2 (Ioakim, et al., 2005; Vougioukalakis et al., 2004). The dating of all these horizons provided the palaeogeographic and palaeoceanographic reconstructions of the area and indicated that there is a specific correlation between the north Eastern Mediterranean sub bottom stratigraphy and the statigraphy of the Alpine Belt that outcrops at the adjacent land northwards (Eastern Greek islands, Southern Turkey). The volcanic ash layer Y2 was related to the Cape Riva eruption of Santorini (around 21 Kyrs ago). According to the obtained data (C14 measurements, the tephra and isotopic chronology) and the presence of the Sapropel S1 it is concluded that the volcanic reactivation takes place in a period of about 10 kyrs.

In the HERMES project participated over 50 Scientific Centers and Universities from almost all European countries. Local Coordinator in Greece was HCMR.

2.4 Project HERMIONE

The Hermione project (Hotspot Ecosystem Research and Man's Impact on European Seas) is again a follow up of the ended Hermes project, started in 2009, has three years duration and plans to investigate ecosystems at critical sites on Europe. These are the deep ocean margin, including Mediterranean, Northeast Atlantic, and part of the Antarctic Ocean. It has as target to clarify specific adaptations of deep sea organisms inhabiting seamounts and the adjacent deep-sea basins in relation to their ecology. It will also provide new insights into the importance of the different structural and functional attributes of biodiversity in functioning of seamounts ecosystems.

3. Conclusions

The results in each of the projects were briefly by the present authors are described in the previous sections and of course represent team work not only of the authors but of all participants. However the important general outcome of these EC funded scientific researches is that this cooperation is presents the opportunities to work with the best research centers in Europe. At the same time provides the necessary funding for both carrying out the research in our areas and update the laboratory and field instruments. The continuous participation in meetings and seminars, the presentations of the preliminary and final results, the submission of the necessary final reports in time in proper way and form, and finally but not les important, the evaluation by international experts of the final reports, both in their scientific and economic aspects are very important. As a result of the above, a large number of papers by the working groups is published in volumes of international meetings and journals.

4. Acknowledgments

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EVIDENCE OF COLD SEEPING IN PLIO-PLEISTOCENE SEDIMENTS OF SE PELOPONESE: THE FOSSIL CARBONATE CHIMNEYS OF NEAPOLIS REGION

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Abstract

Unique, upright standing, chimney-like structures outcropping in (Plio-)Pleistocene sediments of Neapolis region, SE Peloponese are studied thoroughly. The up to 5m high and 3m wide structures, previously interpreted either as "rhizoliths" or hypercalcified giant sponges or fossilized palm trees, display a wide range of morphological types and are composed of hard, several cm thick, carbonate tube. Their orifice is filled up with muddy, sandy or fine conglomerate material, which reflects the sedimentary nature of the surrounding formation, and is penetrated by numerous whitish, mm-thin, carbonate veins. Their formation and spatial occurrence is genetically associated with two intersecting systems of diaclases/fractures, also sealed with carbonate material. We interpret these structures as non-volcanic, fossil, gas chimneys, related to cold seeping (biogenic methane? seeping). The intersecting diaclases have been used as conduits for the upward fluid migration, thus, the gas seeping process must have taken place after the diagenesis of the host sedimentary formations. The impressive outcrops of carbonate gas chimneys in the Neapolis region is the first evident of cold seeping, eventually related with mud volcanism, in the Plio-Pleistocene sedimentary basins of the Hellenic Forearc.

Key words: *non-volcanic gas chimneys, cold seeping, diaclases/fractures, Hellenic Forearc.*

1. Introduction

This paper aims at shedding light to the origin and formation of the unique, strange, morphologically positive structures which protrude through the Plio(?)-Pleistocene deposits in the area of Neapolis, in SE Peloponese. The main occurrences are on the coast of Agia Marina and Korakas, south and southeast of Neapolis town, and in the area of Vourlopo, north of the town.

Similar structures, close to Plitra and Elea, have been firstly described by Kowalczyk & Winter (1991) and interpreted as "rhizoliths" (Osteokollen) filled by cemented conglomerate, which, due to their resistance to the erosion, outcrop today as positive, column-like structures. Little later, Georgiades-Dikeoulia et al. (2000) studied the outcrop of Agia Marina and interpreted them as hypercalcified sponges belonging to the Ischyrospongia (Sclerospongia and Pharetronidae) of the Class Demospongia. In 2005 Prof. E. Velitzelos published an article in the popular magazine Geotropio (Nr 287, Oct.15, 2005) on the petrified forest of Agia Marina. This author interpreted the

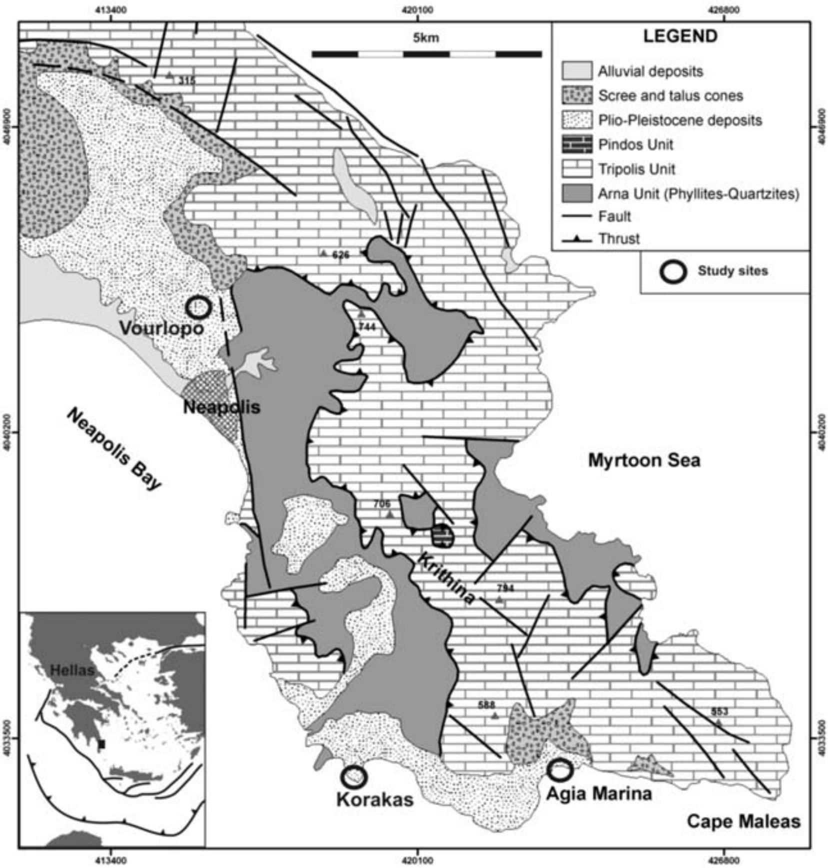

Fig. 1: Simplified geological and neotectonic map of the Neapolis – Maleas Peninsula, modified after Gerolymatos (1999) and Lekkas et al. (1995). The three study sites are marked in open circles.

same structures as in-situ fossilized trees and roots, possibly palm trees, representing the remnants of a petrified forest of Plio-Pleistocene age. In a nicely edited booklet entitled “The Agios Nikolaos-Korakas Geopark”, recently published by the Municipality of Neapolis Vion, the author interprets the findings as fossilized *Rhizopalmoxylon sp*. palm trees, which have undergone a complicate, not fully clarified, fossilization process. Recently, Sakellariou et al. (2007) proposed a fairly different interpretation according to which these structures are fossil carbonate chimneys associated with non-volcanic gas seeping.

In this paper we describe the geological and tectonic setting of the outcrops of Agia Marina, Korakas and Vourlopo of Neapolis region (Fig. 1), we examine the geometrical, structural, sedimentological, geochemical and mineralogical characteristics of these structures and we draw some conclusions attempting to clarify their nature and origin.

2. Geological Setting

The alpine basement of Neapolis-Maleas Peninsula is mainly composed of Tripolis unit limestones and metamorphics of the Arna unit. Thin- to thick-bedded Jurassic limestones and thick-bedded, Upper Triassic limestones to dolomites form the mountainous parts of the peninsula. They tectonically overlay clastic, carbonate and volcanic rocks of the Tyros beds and the metamorphic rocks (metaclastites, thin marbles and metavolcanites) of Phyllites-Quartzites (Arna) unit (Gerolymatos, 1999).

Upper Pliocene(?) – Lower Pleistocene fluvio-terrestrial deposits as well as marine and lacustrine pelites, sandstones, conglomerates and carbonate rocks occur in the morphologically lower and the coastal parts of the peninsula. The Quaternary deposits may be as thick as 250-300m and cover unconformably the alpine basement. They alternate rapidly, both horizontally and vertically and commonly contain layers of terrestrial origin (Gerolymatos, 1999). All three study areas presented in this paper fall into the marine deposits of this formation.

3. Field Results

3.1 Agia Marina

The site of Agia Marina (Lat.: 36° 26.405', Long.: 23° 08.556') is located on the south-facing coastline of Maleas Peninsula, 5km west of Cape Maleas (Fig. 1). Marine mud/sandstone of Pliocene(?)-Pleistocene age (Kowalczyk et al., 1992; Gerolymatos, 1999) outcrop along the coast of the Agia Marina bay. The bedding planes of this clastic formation dip gently to the south. Limestone or dolomite pebbles and rock fragments, <10cm big, occur sporadically, embedded within the mud/sandstone formation. The fauna observed and identified in the mud/sandstone of Agia Marina includes Pecten, Chlamys, Ostrea, Balanus, Echinoids, benthonic Foraminifera, Ostracods and Bryozoans (Georgiades-Dikeoulia et al., 2000).

The marine mud/sandstones are unconformably overlain by a thin conglomerate layer (Fig. 2A). The roof of the mud/sandstone truncates their bedding planes, displays irregular morphology and indicates emergence in subaerial condition and subsequent erosion. The erosional unconformity is followed by the deposition of the <1m thick transgression conglomerate, which is composed mainly of, rounded or angular, limestone or dolomite pebbles derived from the adjacent Tripolis unit Triassic-Jurassic carbonate formations. The deposition of the conglomerate is followed conformably by the formation of a bioclastic limestone of presumably Pleistocene age (Kowalczyk et al., 1992), which forms a well preserved marine terrace.

The entire stratigraphic sequence of the (Plio-)Pleistocene formations (mud/sandstones, transgression conglomerate, bioclastic limestone) of Agia Marina is densely fractured by two systems of vertical to subvertical diaclases (Fig. 2B, 2C). The first system trends NE-SW (N30-60E) and dips with 80°-85° towards N120-150E while the second one trends E-W (N80-110E) and dips with 80°-85° towards N170-200E. The diaclases of both systems are sealed with light grey carbonate material, composed predominantly of calcite. Exposed diaclase-planes are characterised by the presence of dense network of carbonate, mm-to-cm thick veins (Fig. 2D). Some of the diaclases display evidence of small, right-lateral, horizontal displacement.

The spectacular micro-landscape of the Agia Marina site owes its unique character to the presence of column-like, up to 2.5m high and 1m wide structures, which stand upright (Fig. 3A, 3B) on flat morphological terraces, developed parallel to the bedding planes of the mud/sandstones and the bioclastic limestones or protrude through them. Inspection at shallow depths of the Agia Marina bay by divers revealed similar structures rising through the recent sand deposits or standing on the rocky (sandstone) seafloor (Fig. 3D). They display a wide range of morphological types: cylindrical, conical, mushroom-like and mounded (Fig. 3A to 3E).

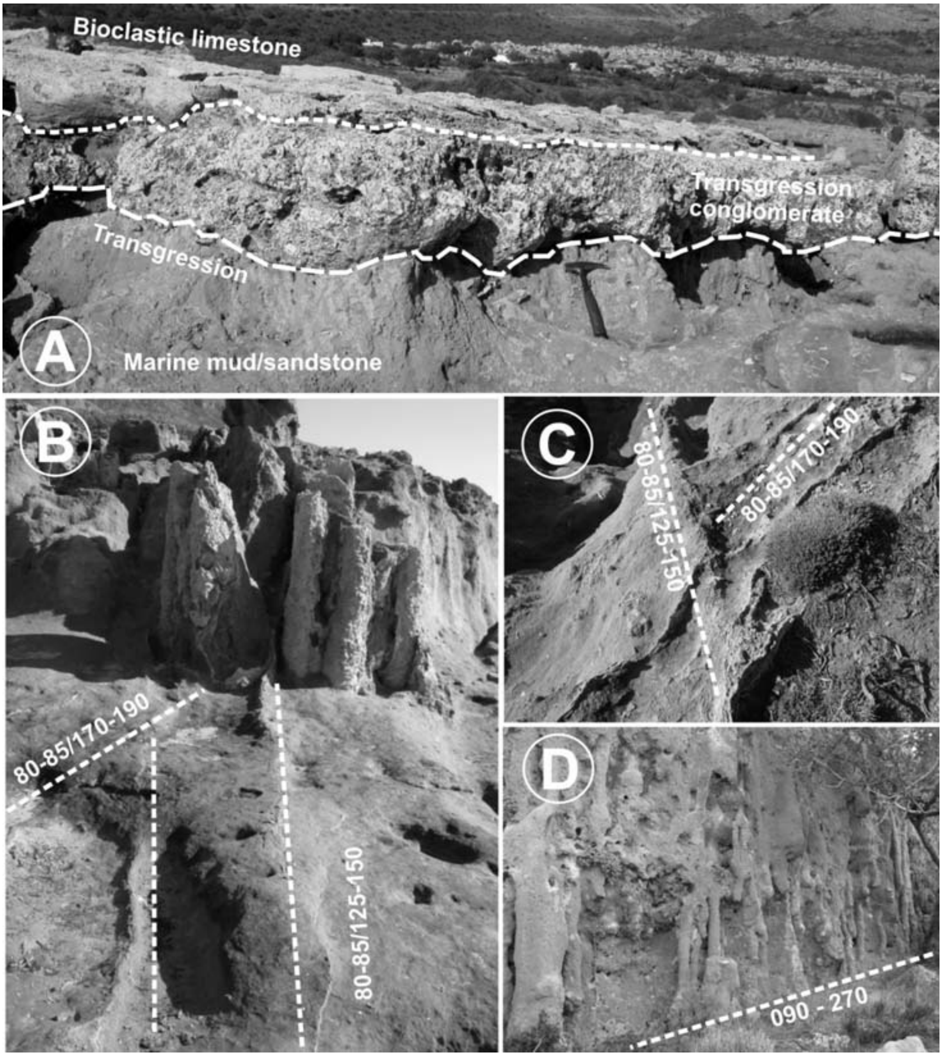

Fig. 2A: The stratigraphic sequence of Agia Marina site.
Fig. 2B – 2D: The two systems of diaclases / fractures in Agia Marina.

They are composed of hard but weathered several cm thick, whitish, carbonate tube. Their orifice is filled up with dark grey, mud/sandstone material, similar to the surrounding host rock, but with numerous whitish, mm-thin, carbonate veins (Fig. 3E and Fig. 6). The chimney-like structures are rooted in stratigraphically lower levels of the Plio-Pleistocene mud/sandstones and penetrate the overlying carbonate terrace formation (Fig. 3F). Their estimated/visible minimum height may exceed 5 m, but there is no secure evidence how deep they go into the mud/sandstone.

From the fieldwork and the field observations in the site of Agia Marina it became obvious that there is a close relationship between the presence of the diaclase systems and the spatial occurrence of the chimney-like structures. Most, if not all of them, are associated with the diaclases, while the biggest ones are always located on the intersection of two diaclases/fractures.

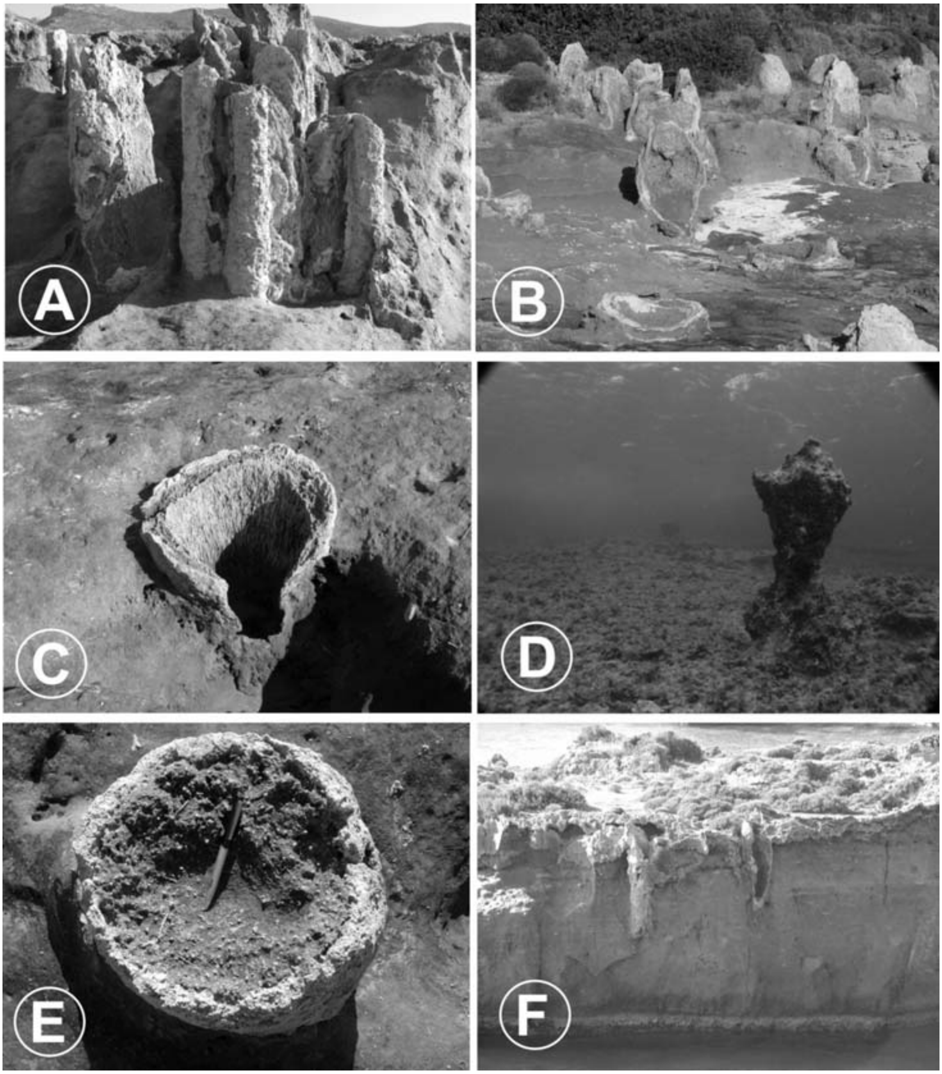

Fig. 3A – 3F: Collection of photos showing the chimney-like structures of Agia Marina. See text for explanations.

Taking into consideration that the sealing of the diaclases is identical with the material which forms the tubes of these structures, it becomes evident that there is a kind of genetical relationship between them and the formation of the carbonate crusts. The fact that these structures have been observed only in areas crosscut by the diaclases network supports this hypothesis.

We suggest that the carbonate structures, along with the formation of the carbonate sealing of the diaclases resulted from the precipitation of carbonate material due to flow of upward migrating fluids occurred after the diagenesis and lithification of the Plio(?)-Pleistocene sediments. This process is similar to the formation of carbonate chimneys, commonly associated with mud volcanism, observed and studied at numerous sites and various depths on the present day seafloor of the world's oceans where active cold seeping, mainly of biogenic methane, occurs.

Fig. 4: A. The stratigraphic sequence of Korakas site. B. The two systems of diaclases / fractures in Korakas with evident right lateral displacement. C. Large Pecten intersected by a carbonate-sealed diaclase.

3.2 Korakas

The study site of Korakas (Lat.: 36° 26.268', Long.: 23° 05.753') is located on the south-facing coastline of Maleas Peninsula, few hundreds m east of the small Korakas village (Fig. 1). Marine sandstone and fine, multicoloured, polymictic conglomerate of Pliocene(?)-Pleistocene age (Kowalczyk et al., 1992; Gerolymatos, 1999) outcrop on the small, rounded peninsula. The bedding planes dip gently to the south, while limestone, dolomite and metamorphic pebbles and rock fragments, <10cm big, occur sporadically, embedded within the fine conglomerate. The fauna observed and identified in Korakas is similar to the one mentioned earlier from the Agia Marina site. The bedding of the fine conglomerates of Korakas is truncated by a planar surface with paleosoil remains and evidence of emergence and erosion. This surface is covered by prograding clastic deposits with sigmoidal bedding which passes upwards to horizontally bedded marine terrace deposits of presumably Pleistocene age (Kowalczyk et al., 1992) (Fig. 4A).

The fine conglomerates of the Korakas study site are densely fractured by two systems of vertical to subvertical, diaclases (Fig. 4B). Like the diaclases of Agia Marina, the first system trends NE-SW (N30-60E) and dips with 80°-85° towards N120-150E while the second one trends E-W (N80-110E) and dips with 80°-85° towards N170-200E. The diaclases of both systems are sealed with carbonate material, which due to its resistance to the erosion, forms very impressive linear ridges similar to massive volcanic dikes. Significant right lateral displacement (>1m) has been observed along the diaclases of the first system (Fig. 4B). It is important to mention that the diaclases occur only along specific zones and do not crosscut the entire formation of Korakas.

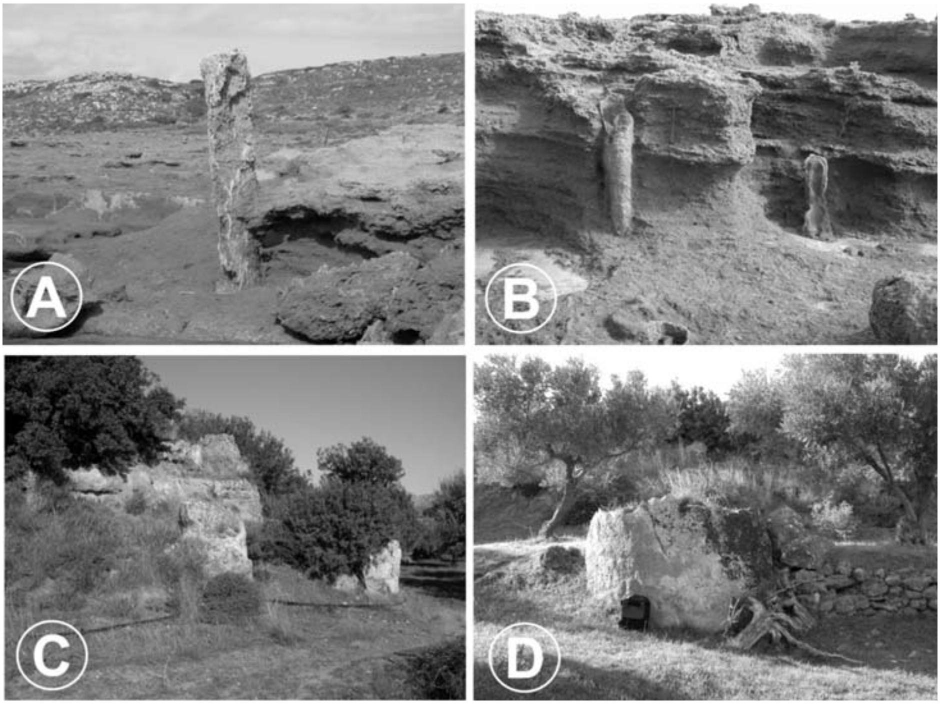

Fig. 5: A – B. Cylindrical chimneys protruding through the fine conglomerates of Korakas. C - D. Huge carbonate chimneys in Vourlopo. See text for explanations.

Column-like, upright standing, mainly cylindrical structures occur in the small rounded peninsula southeast of the small Korakas bay, but not as widespread as in Agia Marina (Fig. 5A & B). They penetrate the gently dipping bedding planes of the fine conglomerates or rise above the surface. The highest structure observed in Korakas exceeds 4m in height (Fig. 5A). Like in Agia Marina, these structures are composed of hard, few cm thick, whitish, carbonate tube. The orifice of the cylindrical structures in Korakas is filled up with multicoloured, polymictic, fine conglomerate, similar to the surrounding sedimentary formation, and is penetrated by whitish, mm-thin, carbonate veins.

The development and spatial distribution of chimney-like structures is closely related to the occurrence of the two diaclase systems. They are always located on and along the diaclases, while the biggest, 4m high, structure has been formed at the intersection of two diaclases/fractures. It is note worthy, that the chimney-like structures have been observed only in areas crosscut by diaclases.

The above observations from Korakas are very compatible with the ones described earlier for the Agia Marina site. We therefore suggest that the precipitation of carbonate material along the diaclases and the formation of the chimney-like structures took place contemporaneously as results of the same process. In analogy to the Agia Marina site, we interpret the Korakas structures as carbonate chimneys developed at sites of enhanced fluid (methane?) flow, which used the existing diaclases network as conduits for their upward migration. The photo of Fig. 4C shows a large Pecten crosscut by a sealed diaclase, a fact which clearly indicates that the formation of the diaclases and the carbonate precipitation postdates the deposition of the sediments and possibly their diagenesis / lithification. Consequently, the formation of the chimneys postdates the deposition and diagenesis of the (Plio?-)Pleistocene clastic formation of Korakas.

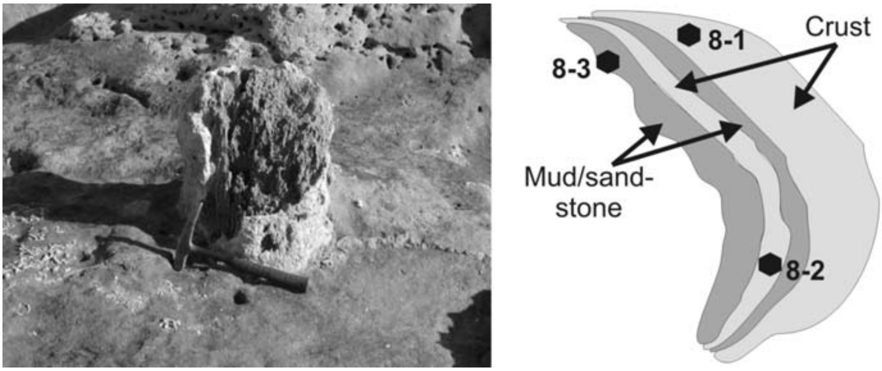

Fig. 6: A small piece of the chimney (shown on the left) was sampled for laboratory analyses (sample 8). The scheme to the right shows the sub-sampling strategy.

3.3 Vourlopo

The site of Vourlopo (Lat.: 36° 31.592', Long.: 23° 03.472') is located about 2km north of the town of Neapolis, on the east-facing slope of a low hill (Fig. 1) and falls into the Plio(?)-Pleistocene marine formation (Kowalczyk et al., 1992; Gerolymatos, 1999). Although the landscape has been altered by agriculture activities, it is evident that like in Agia Marina, marine mud/sandstone constitutes the prevailing sedimentary formation of Vourlopo site. A N-S trending, E-dipping, apparently normal fault displaces the sedimentary formation and forms a steep, 2-5m high scarp along the eastern flank of the hill (Fig. 5C).

Huge, cylindrical, 3-4m wide, column-like structures rise up to 1-1.5m from the ground (Fig. 5D). They occur along a zone roughly parallel to the fault scarp or at a small distance (<10-15m) from it. Despite their large dimensions, they are similar to the Agia Marina and Korakas structures. The outer tube is made of hard, whitish, carbonate crust and their orifice is filled up with dark grey, mud/sandstone penetrated by numerous whitish, mm-thin, carbonate veins.

In the description of the Agia Marina and Korakas sites it was mentioned that the chimney-like structures are associated with a network of diaclases. The landscape of the site in Vourlopo is either altered due to agriculture activities or covered by dense bushes. Nevertheless, remains of the carbonate sealing of diaclases are preserved on the outer tube surface of some of the cylindrical structures.

4. Analytic Results

Samples were taken from the least weathered structures and from vertical veins formed on the planes of the diaclases/fractures of Agia Marina site. The bulk mineralogy was determined using X-ray diffraction (XRD) on powdered samples. The chemical bulk rock composition and major and trace elements were analysed by X-ray fluorescence (Table 1). We present here the results of the analyses of two samples: Sample 5 was taken from the veins developed on the vertical fracture shown in Fig. 2D. Samples 8-1, 8-2 and 8-3 are taken from the chimney-like structure of Fig. 6. The samples 8-1 and 8-2 were taken from the tube while 8-3 from the infill of the orifice.

The thin vein (sample 5) displays carbonate composition (90% CaO) with calcite as the dominant mineral. The tube (samples 8-1, 8-2) of the chimney-like structure is mainly composed of calcite (80% CaO) with subordinate quartz (10% SiO_2), while the significantly weathered fill of the orifices (sample 8-3) displays siliceous composition (52% SiO_2, 30% CaO) and muddy character.

Table 1. Major Elements

Sample	SiO_2 (%)	Al_2O_3 (%)	TiO_2 (%)	Fe_2O_3 (%)	K_2O (%)	Na_2O (%)	CaO (%)	MgO (%)	P_2O_5 (%)	MnO (%)
5	1,82	0,81	0,023	0,13	0,057	0,992	52,57	1,627	0,0110	0,004
8-1	5,89	1,13	0,056	0,37	0,143	2,179	48,03	2,094	0,0140	0,005
8-2	18,94	2,68	0,168	1,14	0,292	1,995	39,00	2,342	0,0209	0,014
8-3	40,68	4,94	0,357	2,34	0,577	2,078	23,69	2,728	0,0215	0,019

5. Discussion - Conclusions

The field observations, structural measurements and sedimentological data from the Agia Marina, Korakas and Vourlopo sites of Neapolis region along with the results of the mineralogical and geochemical analyses presented here lead to the conclusion that the structures, previously interpreted as giant sponges or as petrified palm trees, are fossil, carbonate chimneys of non-volcanic origin, associated with cold seeps. Very similar, column-like structures have been found in Eocene sandstones on the Moesian Platform in the area of Pobiti Kamani, close to Varna, Bulgaria, and have been interpreted on the base of sedimentological and geochemical data as carbonate chimneys related to ancient hydrocarbon seepage (De Boever et al., 2006).

The arguments which support this interpretation are the following: (1) they occur in a marine environment, as indicated from the nature of the host sedimentary formation, which is unlike to have favoured the growth of a forest, (2) they are spatially and genetically associated with a dense network of diaclases/fractures, a relationship not necessary for the distribution of sponges or trees (3) their tubes have calcite composition, like the sealing material of the diaclases/fractures, which is unlike for the fossilisation of trees (4) their orifice is filled up with sedimentary material (sandstone or fine conglomerate) similar to the surrounding host formation, a very unlike composition either for fossil sponges or petrified trees (5) they penetrate through the stratigraphic layers, including the erosional unconformity and transgression surface in Agia Marina, (6) they have been formed after the deposition and the diagenesis of the host sedimentary formation.

Cold seeps in modern marine seafloor environments are associated with a variety of gas releasing processes, such as mud volcanoes and mud flows, gas chimneys, pockmarks, authigenic carbonate precipitation etc (Hovland & Judd, 1988). Actively venting carbonate chimneys and crusts are forming at sites of gas expulsion due to bacterially mediated carbonate precipitation. They have been discovered and studied in many places in the world, including the Gulf of Cadiz (Diaz-del-Rio et al., 2003), the East Mediterranean Ridge (Kopf et al., 2001), the Nile deep-sea fan (Loncke et al., 2004), the Anaximander Mountains (Lykousis et al., 2005) and other places in the Mediterranean and the Black Sea (Mascle et al., 2006 and references therein). They display morphological characteristics very similar to the ones described here from Agia Marina and Korakas. Their occurrence and formation is associated with fluid flow (predominantly methane) and with liquefied mud flow from deeper layers to the seafloor. The upward migration of the fluids takes place along the existing tectonic elements which serve as conduits.

The chimneys of Agia Marina, Korakas and Vourlopo, described here, are associated with a dense network of diaclases and/or fractures, which crosscut the marine Plio(?)-Pleistocene formations of Neapolis region. The diaclases/fractures occur only locally, along narrow zones and do not affect the entire sedimentary sequence. We suggest that the zones of dense diaclases/fractures represent zones of lateral displacement developed after the deposition of the Plio(?)-Pleistocene marine sequence of Neapolis region. The tectonic stresses within these zones resulted in building up the necessary overpressure which initiated the upward migration of fluids, like methane, and gave birth to the precipitation of calcite along the fractures and the formation of the chimneys within the sedimentary sequence.

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ACTIVE TECTONICS IN THE HELLENIC VOLCANIC ARC: THE KOLUMBO SUBMARINE VOLCANIC ZONE

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Abstract

This paper studies the rupture system of the Anydhros Basin, northeast of Thera island, and its relationship to the submarine volcanic activity along the Kolumbo line. Anydhros Basin is a N45^{o}E trending elongate basin bounded by the Ios-Fault-Zone (IFZ) towards NW and by the Anydhros-Fault-Zone (AFZ) towards SE. The AFZ continues southwestwards, crosscutting Thera Island. Swath bathymetry and seismic profiling data indicate that the Anydhros basin sedimentary infill is fractured by vertical, predominantly strike-slip faults, parallel to which the volcanic cones are aligned. We propose that the "KameniKolumbo Line" is an active, 40km-long, strike-slip fault zone. The Kameni-Kolumbo strike slip runs through the volcanoes of Nea Kameni and Kolumbo and controls the spatial distribution of the volcanic cones along the axis of Anyhdros basin.

Key words: *Anyhdros basin, swath bathymetry, seismic profiling, Kameni-Kolumbo strike-slip fault zone.*

1. Introduction

The Hellenic Volcanic Arc has developed in the back arc region of the Hellenic subduction zone, parallel to and about 150km north of the Hellenic Arc (McKenzie, 1970; Le Pichon & Angelier, 1979). The trace of the volcanic arc is delineated by the four main volcanic fields in South Aegean Sea, namely Methana-Egina, Milos, Santorini and Nisyros. The purpose of this paper is to correlate the spatial distribution of the active volcanic occurrences of the Santorini – Kolumbo volcanic field with the tectonic structure of the area and explore possible genetic relationships.

More than 20 volcanic cones aligned on a N30^{o}E trending zone have been mapped on the seafloor of Anydhros Basin, northeast of Santorini (Alexandri et al., 2003). By far, the largest of these submarine cones is Kolumbo, a 3km-diameter cone with a 1500m-wide crater, and a 505m deep crater floor. Kolumbo was last active in 1650 AD, when an explosive eruption produced hot surges across the sea surface that caused 70 deaths on Thera (Fouqué, 1879; Dominey-Howes et al., 2000). A widespread hydrothermal vent field was discovered on the floor of Kolumbo's crater (Sigurdson et al., 2006). High-temperature venting occurs in the northern part of the crater, with vigorous gas emission plumes, and fluid temperatures up to 220^{o}C from vent chimneys up to 4m high.

The Kolumbo submarine volcano was believed to have formed during a single eruptive phase in 1650AD (Fytikas et al., 1990; Perissoratis, 1995). Huebscher et al. (2006) have been able to observe in seismic reflection profiles two cone-like volcaniclastic deposits, which indicate that the Kolumbo volcano evolved from at least two eruptions. Bohnhoff et al. (2006) report that, the highest seismic activity in the area has been observed along the SW–NE striking Santorini–Amorgos zone. Within this zone the submarine Kolumbo volcano exhibits strong seismic activity which is interpreted to be directly linked to the magma reservoir and therein the migration of magma and fluids towards the surface. NE of Kolumbo they observed a similar seismicity pattern with small-scaled activity spots that might represent local pathways of upward migrating fluids or even developing volcanic activity within this zone of crustal weakness. Bohnhoff et al. (2006) conclude that the Santorini–Amorgos zone is presently in the state of right-lateral transtension. Dimitriadis et al. (2009) suggest that the seismicity observed underneath Kolumbo is associated with the "Kameni – Kolumbo Fracture Zone", which corresponds to the western termination of the major ENE-WSW Santorini – Amorgos Fault Zone. Further on, they suggest that the NE Santorini – Kolumbo faults belong to a single rupture system. This interpretation is consistent with the hypothesis of Mascle & Martin (1990), that the Aegean Sea may be considered as a stretching continental domain cut into ENE-WSW trending, elongate crustal terranes which move more or less independently towards the southwest.

Herewith we present results from the data collected mainly during a marine geological survey, conducted around Santorini from April to June 2006, in the frame of a collaborative project (NSF grant OCE-0452478) between the University of Rhode Island (URI-USA), the Hellenic Centre for Marine Research (HCMR-Greece), and the Institute of Geology and Mineral Exploration (IGME-Greece).

2. Methods

We use data obtained during several cruises in the area. First swath bathymetry of the study area was conducted in 2001 using the 20 kHz SEABEAM 2120 swath system on R/V Aegaeo. The second survey took place in 2006 onboard R/V Aegaeo and R/V Endeavor and included complementary swath bathymetry data and refining of the existing map, airgun 10ci single channel seismic profiling (Fig. 1), gravity and box coring and ROV dives. Additional ROV dives have been performed in late 2006 during R/V Aegaeo cruise "Nautilus 2006".

3. Results

The Anydhros basin is a N45^{o}E trending, elongate basin developed between Ios and Koufonisia island to the NW and the Anydhros Islet and Anyhdros morphological ridge to the SE (Fig. 1). Anaphi-Amorgos Basin is located southeast of the Anyhdros Ridge. The network of the seismic profiles presented here was designed to include lines both perpendicular and parallel to the axis of the basin, with the objective of revealing the structure of the basin, its margins and the relationship of the volcanic cones to the fault pattern.

The seismic profiles shown in Fig. 2a, 2b, 2c and 2d run perpendicular to the axis of the basin. The Kolumbo fault in Fig. 2a is in alignment with several features of tectonic or inferred tectonic origin occurring on Thera and Therasia island like (i) the morphological discontinuity (inferred fault) of Kolumbo cape, (ii) the morphological depression (graben) of the caldera's rim between Imerovigli and Kokkino Vouno, (iii) the dense network of SW-NE trending volcanic dikes within this depression, (iv) the northen basin of Santorini's caldera and (v) the SW-NE trending volcanic dikes at the southern tip of Therasia island.

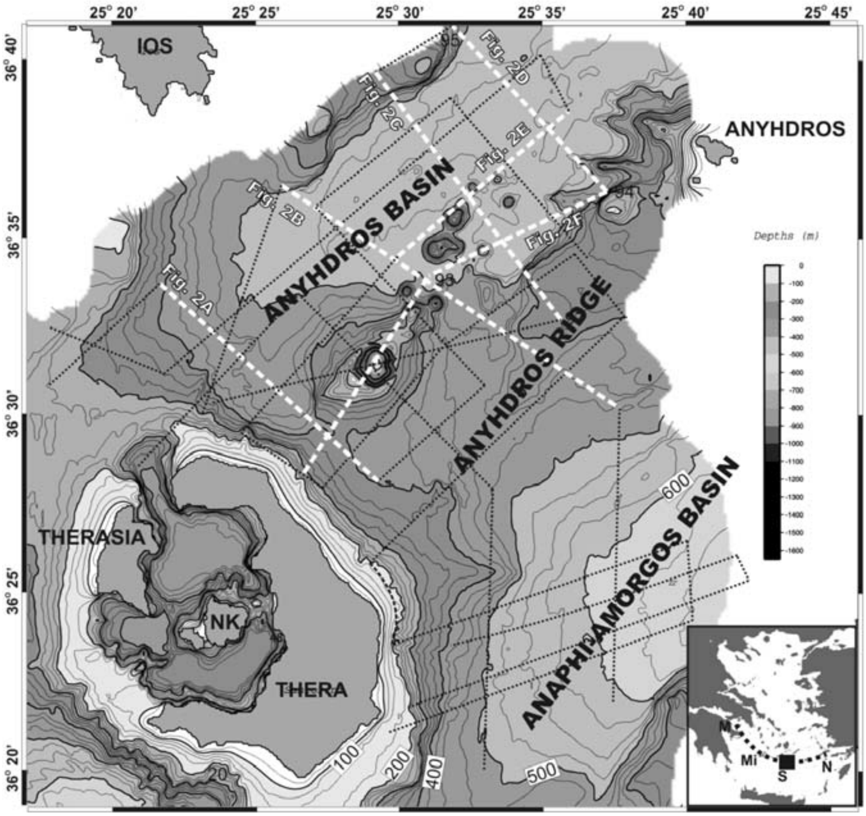

Fig. 1: Swath bathymetry map of the area east and northeast of Santorini Island (extracted from Alexandi et al. (2003) and Sigurdson et al. (2006). Thin black dotted lines show the tracks of the single channel seismic profiles. NK: Nea Kameni. Inset map: the dashed line delineates the Hellenic Volcanic Arc. M: Methana, Mi: Milos, S: Santorini, N: Nisyros.

The profiles of Fig. 2b, 2c and 2d illustrate the characteristic structure of the Anyhdros basin. Both margins of the basin are of tectonic origin and are developed along active faults. The basin is bounded towards NW by a segmented, 50km long, N45°E trending, linear fault zone, which can be traced all along the base of the SE-facing slope south of Koufonisia, Ios and Sikinos islands. Hereafter we call this fault zone Ios-Fault-Zone (IFZ). The SE margin of the basin displays more complicated morphological and tectonic character. It is formed by successive, en-enchelon arranged, fault segments which run N30°E at the southwestern part of the margin and bend towards east-northeast at the northeastern part of it. Hereafter we call this complex fault zone Anydhros-Fault-Zone (AFZ). The traces of the observed faults are shown on the map of Figure 3.

The 15° difference in the orientation of the two basin bounding fault zones results in a significant narrowing of the Anydhros basin towards NE. Thus, the distance between the Ios-Fault Zone and the Anydhros-Fault-Zone is about 30km, measured SW of Thera Island, it becomes 16km across the Kolumbo volcano and decreases to only 8km northeast of Anydhros islet.

The thickness of the sedimentary pile deposited in the Anydhros basin may locally be as large as 500m. No major discordance of sedimentary origin has been observed within the basin infill. The

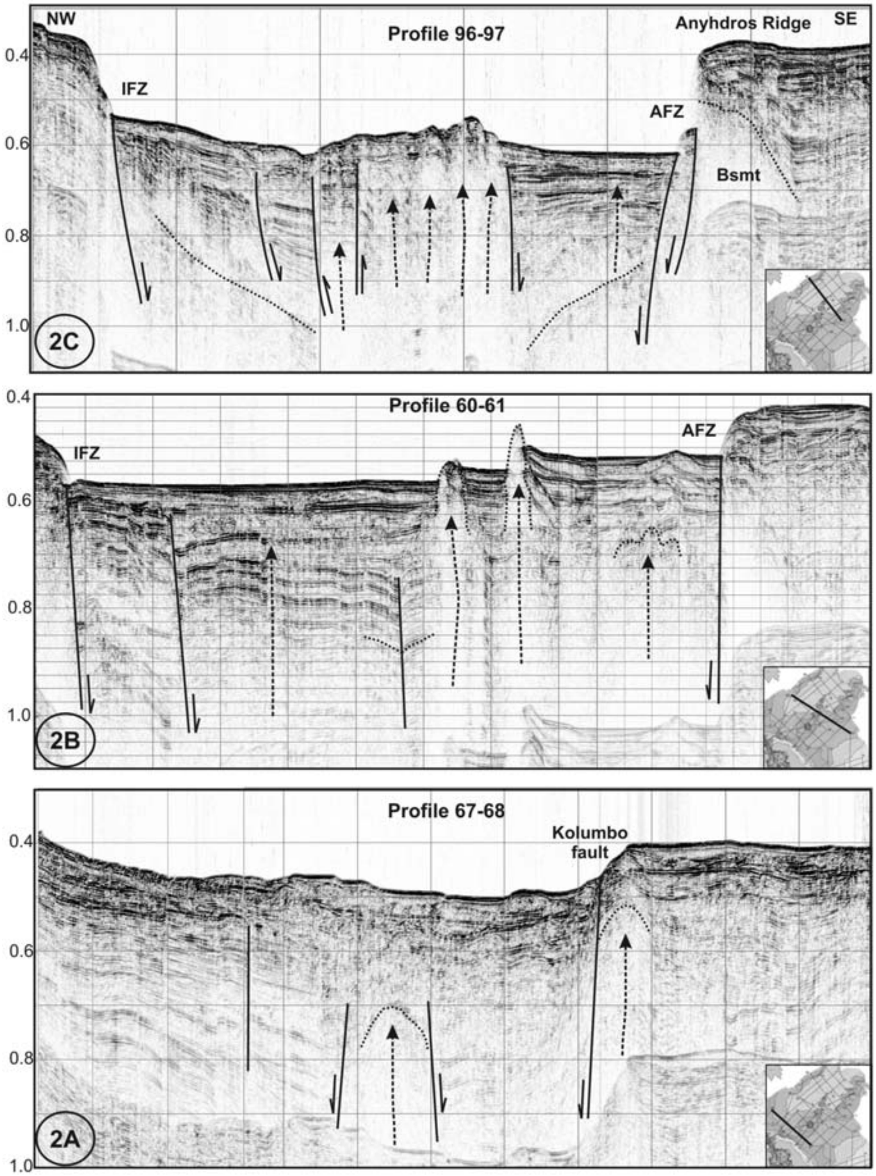

Fig. 2: a – c. Airgun 10ci single channel profiles from the Anyhdros basin. Dashed arrows show ascending magmatic fluids. Dotted lines highlight dominant features of the subseafloor where needed. AFZ: Anyhdros Fault Zone, IFZ: Ios fault Zone, Bsmt: Alpine Basement. See text for explanation and interpretation of the profiles.

sedimentary layers are intensively deformed and ruptured by vertical or subvertical faults, which run parallel to the Anydhros-Fault-Zone. Some of them display normal character, indicating extensional regime, but in most cases, the sense of movement of these faults is not obvious. For example hangingwall and footwall of a certain fault can be distinguished in one seismic line, but this may not be the case for the same fault on the next line. This is a strong evidence to attribute predominantly strike-slip character to these faults and assume a transtensive deformational regime within the Any-

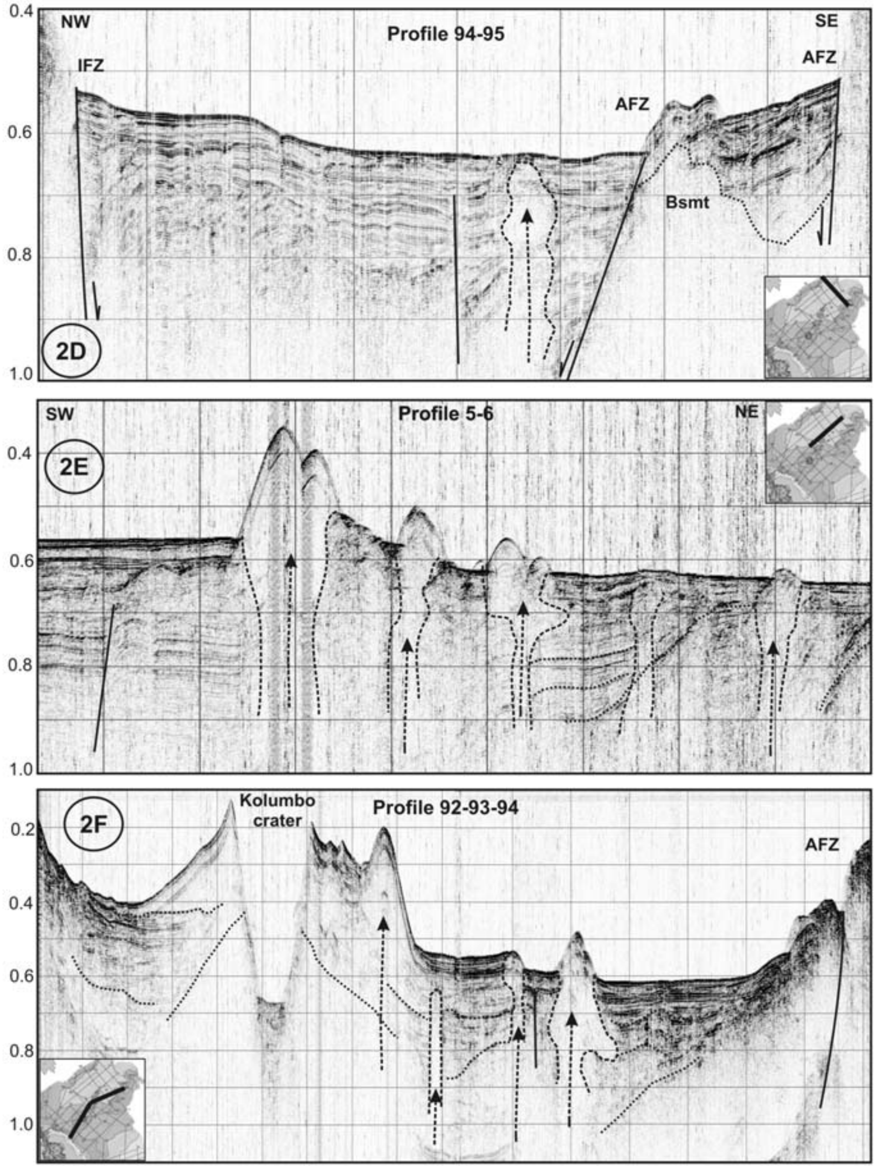

Fig. 2: d – f. Airgun 10ci single channel profiles from the Anyhdros basin. Dashed arrows show ascending magmatic fluids. Dotted lines highlight dominant features of the subseafloor where needed. AFZ: Anyhdros Fault Zone, IFZ: Ios fault Zone, Bsmt: Alpine Basement. See text for explanation and interpretation of the profiles.

hdros basin. This interpretation is in agreement with the right-lateral transtensional character observed from seismological data by Bohnhoff et al. (2006) and Dimitriadis et al. (2009).

Areas of diffuse or transparent acoustic character crosscutting the sedimentary layering of the basin are delineated by dashed lines and indicated by dashed arrows pointing upwards in all six profiles of Figure 2. They are always located below the volcanic domes, while some of them die out before reaching the seafloor. The sedimentary layers are being dragged upwards at their contact to these diaper-like structures. We interpret them as conduits of the ascending magmatic fluids. They are associated with the existing ruptures, indicating that the latter are preferred weak zone for the magmatic fluid flow.

The profile of Figure 2e runs parallel to the long axis, in the middle of Anyhdros basin. It crosscuts the series of volcanic domes aligned on the axis of the basin. It is evident that the size and the height of the volcanic domes decreases towards the northeast, indicating that the volcanic activity diminishes as the distance from Kolumbo increases. Deformation of the sedimentary layers is obvious in this profile too, indicating that the deformation regime is much more complicate than that expected in normal, extensional basins.

The structure of Kolumbo submarine volcano is shown on the profile of Figure 2f. The interpretation of this profile suggests that at least one older volcanic cone exists and is located underneath the present one, indicating that Kolumbo has been active at least once, prior to the 1650 eruption (see also Huebscher at al., 2006). Layered or massive lava flows form the lower part of the present Kolumbo cone and are displayed as stratified, high amplitude, subhorizontal reflectors on the profile. The upper part of the cone shows transparent acoustic character and is composed of tephra deposits produced during the 1650 eruptive phase. This interpretation has been verified by repetitive ROV dives in the Kolumbo crater and at different sites of the inner crater walls.

Further observations during the ROV dives on the 500m deep crater revealed that the observed chimneys, described by Sigurdson et al. (2006), along with ridge-like structures (possible dikes) are mostly aligned in NE-SW direction, parallel to the Kolumbo-Line. This preferred orientation of the volcanic and hydrothermal features may be controlled by the dominant tectonic trend.

4. Conclusions

Integrated evaluation of the swath bathymetry of the Anydhros basin (Alexandri et al., 2003; Sigurdson et al., 2006) and the seismic profiling data presented here indicates that the linear distribution of the volcanic cones is controlled by strike-slip faults which run parallel to the long axis of the basin. These faults have been and are being presently used as conduits for the upward migration of the magmatic fluids. This N30^{o}E trending tectonic-volcanic zone is in line with (i) the northern basin of Santorini caldera, (ii) the morphological (and tectonic?) graben developed on NE Thera island, between Kokkino Vouno and Imerovigli and (iii) the Kolumbo cape in NE Thera Island. It is also in line with the occurrence of dense networks of SW-NE trending volcanic dikes both in the Kokkino Vouno – Imerovigli graben and the southernmost tip of Therasia Island. It is also worthnoting that observations made by ROV dives in the Kolumbo crater indicate that the actively venting hydrothermal chimneys are aligned in SW-NE direction, while similarly directed fractures have been observed both on the crater's seafloor and the steep inner walls.

We conclude that the previously defined "Kolumbo Line" is an active, possibly right-lateral, 40km-long, strike-slip fault-zone. It constitutes a zone of weakness, which has enabled the upward migration of magmatic fluids, the creation of dikes and the development of submarine volcanic cones, with Kolumbo submarine volcano as the most productive among them. Furthermore, we suggest that the "Kameni-Line" is directly related to and displays similar characteristics with the Kolumbo Line. Kameni and Kolumbo Lines represent two en enchelon arranged segments of one single strike slip fault zone developed parallel to the Anydhros Fault Zone. The location of the active Nea Kameni volcano coincides with the relay zone between the two fault segments.

We propose that the Anydhros-Fault-Zone continues southwestwards, crosscutting Thera Island and

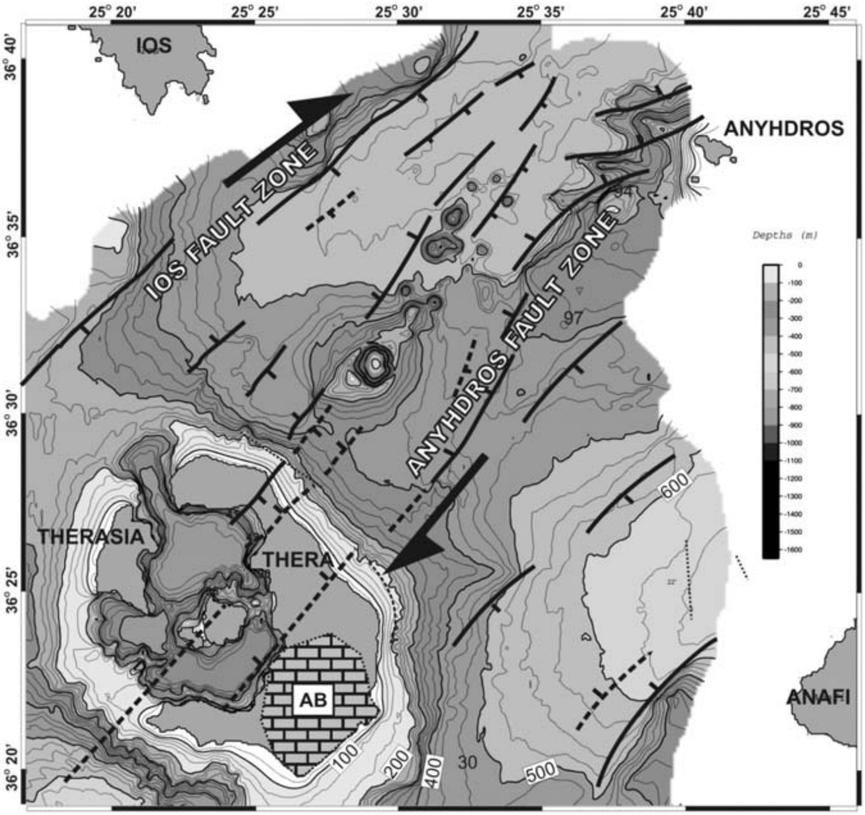

Fig. 3: Tectonic map of Santorini – Kolumbo volcanic field. Swath bathymetry as in Fig. 1. AB:Alpine Basement.

can be traced as far south as Christiana Islet. The prolongation of the AFZ towards the southwest coincides with (i) the southern steep margin of the Santorini Caldera's southern basin, (ii) the northern limit of the alpine basement on Thera Island and (iii) the northern flank of the submarine ridge southwest of Thera. The geological data presented here indicate that the southern part of Thera Island and the Anydhros Ridge form a structural high of the alpine basement.

In addition, we propose that the volcanic activity of the Santorini-Kolumbo field preferentially develops within the transtensional regime which created Anyhdros Basin. The two marginal fault zones of the basin, the Ios and the Anydhros fault zones, may be considered as the two main splays of a single strike slip fault zone which runs underneath the basin and along its axis. Together with the intrabasinal subvertical faults they form a kind of flower structure, typically observed along strike slip fault zones. We call this fault zone hereafter the Kameni-Kolumbo strike slip. This hypothesis explains the transtensional character of the Anyhdros basin and the deformation pattern of the sedimentary infill. It is also consistent with the upward migration of the magmatic fluids and the preferred alignment of the volcanic centres along the basin axis.

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PALAEOCLIMATIC AND PALAEOCEANOGRAPHIC EVOLUTION OF THE MEDITERRANEAN SEA OVER THE LAST 18KA

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Abstract

The aim of the present study is the reconstruction of the palaeoclimatic and palaeoceanographic evaluation of the Mediterranean Sea over the last 18ka based on the distribution of the planktonic foraminifera species. Planktonic foraminifera species have been proven excellent indicators of the palaeoclimatic and palaeoceanographic variability.

The data set of the present study consists of the variability in the abundances of planktonic foraminifera species as has been reported and published in previous studies, after the examination of marine sediments from cores selected all over the Mediterranean Sea. The evolution in the abundance of each planktonic species is examined on a time interval spacing of 1000years suggesting implications for the palaeoclimatic and palaeoceanographic evolution of the Mediterranean Sea for the same time sampling interval (1000yrs). The most pronounced results of this study suggest that: (i) the increase in surface temperature during the warm intervals always follow a decreasing trend from eastern to western areas, (ii) the eutrophication of the Mediterranean Sea in most of the time exhibits a decreasing trend from northern to southern areas, and (iii) during the Holocene two cool spells (at around 8ka and 4ka) seems that had affected the majority of the Mediterranean region.

Key words: *plantkonic foraminifera, spline analysis, palaeoceanographic variability, late post-glacial, Mediterranean Sea.*

1. Introduction

Planktonic foraminifera have proven to be reliable indicators in palaeoceanographic and palaeoclimatic Quaternary studies. Variations in the abundance of selected species correlate with changes in sea surface temperature, in salinity, in food availability and in general changes in the state of the prevailing hydrographic systems in the water column (e.g. Pujol and Vergnaud-Grazzini, 1995). In addition, changes in planktonic foraminifera can be used in biochronology. Within this concept, during the last decades a large number of works publish records of the planktonic foraminifera abundances, obtained from sediment cores, selected from Mediterranean Sea, in order to present the local palaeoceanographic history (Triantaphyllou et al., 2009; Geraga et al., 2010). Thus, a lot of information has been collected regarding long and short duration of paleoceanographic and palaeoclimatic changes.

In this work an effort has been made to collect most of the above data and to present it under a common chronostratigraphic framework. Furthermore the evolution of the spatial distribution in Mediter-

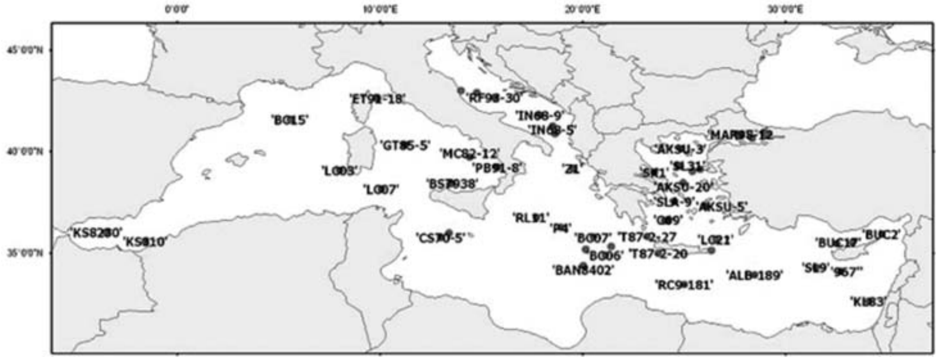

Fig. 1: Map showing the location of the core sediment, used for the construction of the data base of the present work. (SK1: Zachariasse et al., 1997; IN68-9, LC21: De Rijk et al., 1997; KS8230, RL11, ODP967: Emeis et al., 2000; SL11, SL21, SL31, SLA-9: Casford et al., 2002 and Casford et al., 2003; BS7937, BS7938: Sbaffi et al., 2004; AD91-17: Sangiorgi 2003; AGE-5, AEG-3, AGE-19, AGE-20: Aksu et al., 1995; SL9: Principato et al., 2006; T87-2-13G, T87-2-27G, T87-2-20G: Rohling et al., 1993; IN68-5, IN68-21, CS73-34, BS78-12: Jorrisen et al., 1993; RF93-30: Oldfield et al., 2003; ET91-18, GT85-5, PB91-2, PB91-8: Capotondi et al., 1999; ALB-189, RC9-181, KS-09: Cita et al., 1977; MAR97-02, MAR94-05, MAR97-11, MAR98-12, MAR98-07, MAR98-09: Aksu et al., 2002; BC02, BC06, BC07: Principato et al., 2003; MC82-12: Ariztegui et al., 2000; BAN8402, BAN8408: Olausson 1991; CS70-5: Vergnaud-Grazzini et al., 1988; KS310, BC15, LC03, LC07, P4: Hayes et al., 1999; BUC2, BUC12, BUC17: Bukley et al., 1982; C40: Geraga et al., 2000; C69: Geraga et al., 2005; Z1: Geraga et al., 2004; GeoTU KL83: Sperling et al., 2003; NS-14 Triantafyllou et al., 2007).

ranean Sea, of selected plantkonic foraminifera species, following a time interval of 1000years, over the last 18000years, is discussed.

2. Methods

This work is based on the micropaleontological data from 59 sediment cores, published between 1977 and 2006, covering the entire Mediterranean Sea (Fig. 1). A data base was established based on the $\delta^{18}O$ values and the relative abundances of *Globigerinoides ruber*, *Globigerina bulloides*, *Globorotalia inflata* and *Neogloboquadrina pachyderma*, presented in these works.

A common chronostratigraphic framework was determined for all records based on the datings given in these papers in conjunction to the sedimentation rate and the presence of chronostratigraphic horizons (e.g. tephra layers, sapropel S1, isotopic stages, biozones). All the ages were calibrated using the program "calib 5.01" (Stuiver and Reimer, 1993; Reimer, 2000) taken into consideration local values for reservoir effect and ΔR values.

For the purposes of this work, the data base was treated by Splines interpolating method (Fritsch and Carlson, 1980; Kahaner, et al., 1989), produced in MATLAB programming environment, thus all data could be presented with a time sampling interval of 1000years.

The final step included the construction of maps in ArcGIS environment, indicating the spatial distribution of each taxon in Mediterranean Sea, every 1000yrs.

3. Results and discussion

The distribution of the $\delta^{18}O$ values shows that over the last 18000years eastern Mediterranean Sea

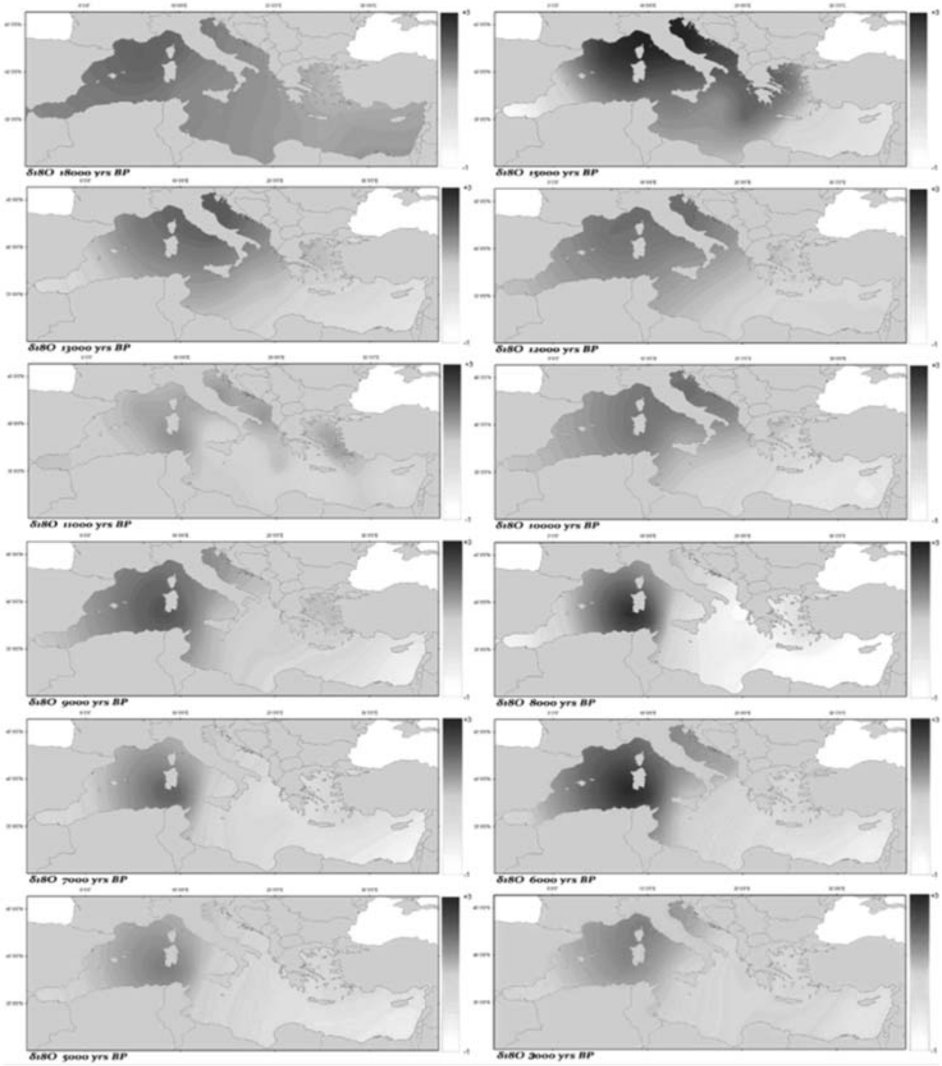

Fig. 2: Maps showing the variation in the distribution of the $\delta^{18}O$ values in the Mediterranean Sea over the last 18000years (see Fig. 1 for the location of the data points).

presents always lower values in relation to the western Mediterranean Sea (Fig. 2). During the last glacial period all the Mediterranean Sea exhibits high positive $\delta^{18}O$ values, although this signal is stronger in the western Mediterranean Sea. The improvement of climate during the late glacial period is more pronounced at the eastern Mediterranean Sea and the establishment of Younger Dryas event (12-11ka) occurs all over the Mediterranean Sea. During the Holocene the most depleted $\delta^{18}O$ values occurs between 9 and 8ka at the eastern Mediterranean sea and coincides with the deposition of the sapropel S1a. Furthermore climatic deteriorations obtained as shifts to more heavy $\delta^{18}O$ values occurs for the entire Mediterranean sea at around 8, 6 and 4ka, although this signal is more pronounced in western Mediterranean Sea. These cold spells coincide in age with cold events recorded in high latitude areas (Bond et al., 1997).

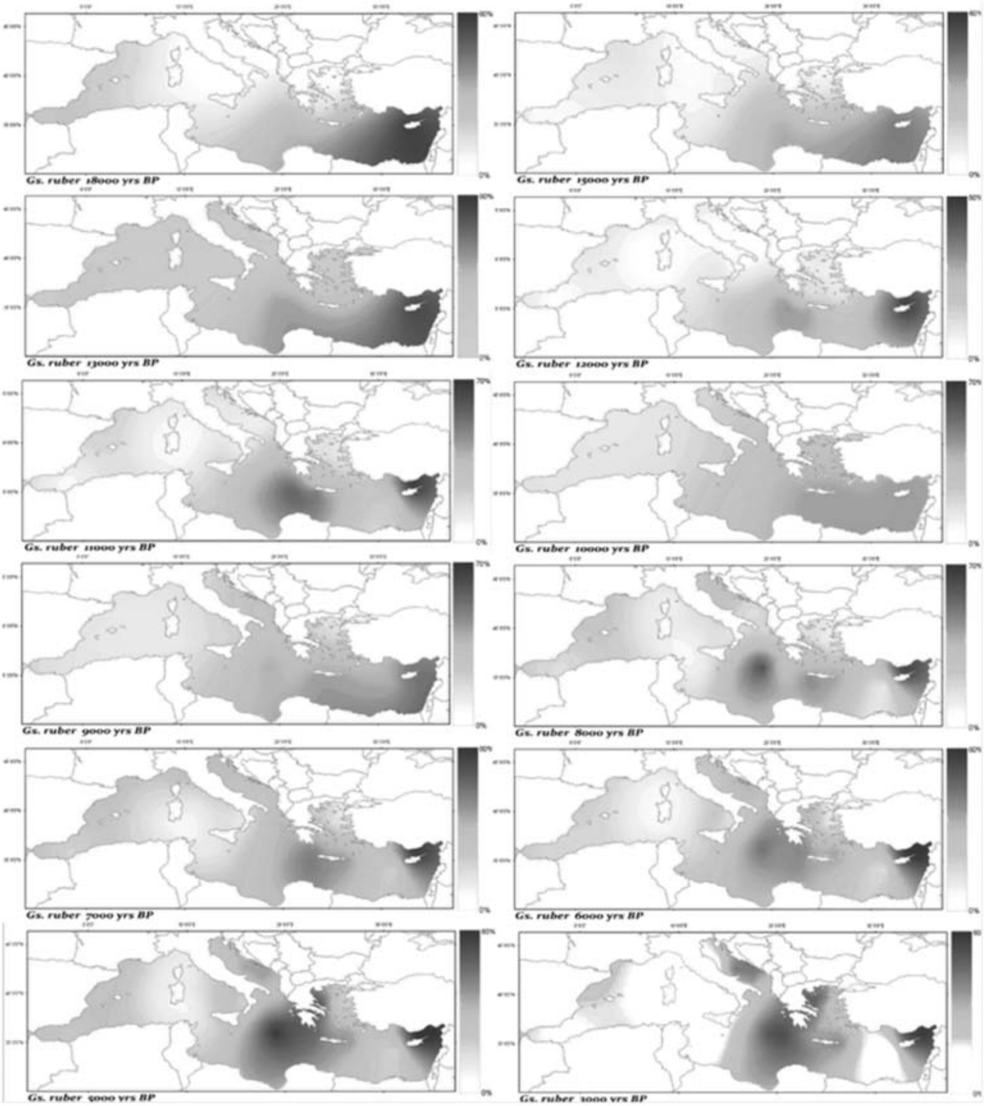

Fig. 3: Maps showing the variation in the distribution of the relative abundances of *Gs. ruber* in the Mediterranean Sea over the last 18000years (see Fig. 1 for the location of the data points).

Gs. ruber prefers warm and oligotrophic waters (Thunell, 1978; Pujol and Vergnaud Grazzini, 1995). The higher abundances of this species occur at the eastern Mediterranean (Fig. 3) for most of the discussed period (last 18kyrs) suggesting the prevalence of warm and stratified waters at the area and the development of more oligotrophic conditions in relation to the central and the western Mediterranean Seas. By the 7000 yrs BP the distribution of this species is similar to that obtained by Pujol and Vergnaud Grazzini (1995) which studied live planktonic foraminifera along a W-E axis parallel to the North African coast. Over the last 3000years, high abundances of *Gs.ruber* also occur at the eastern Adriatic, Ionian and Aegean Seas.

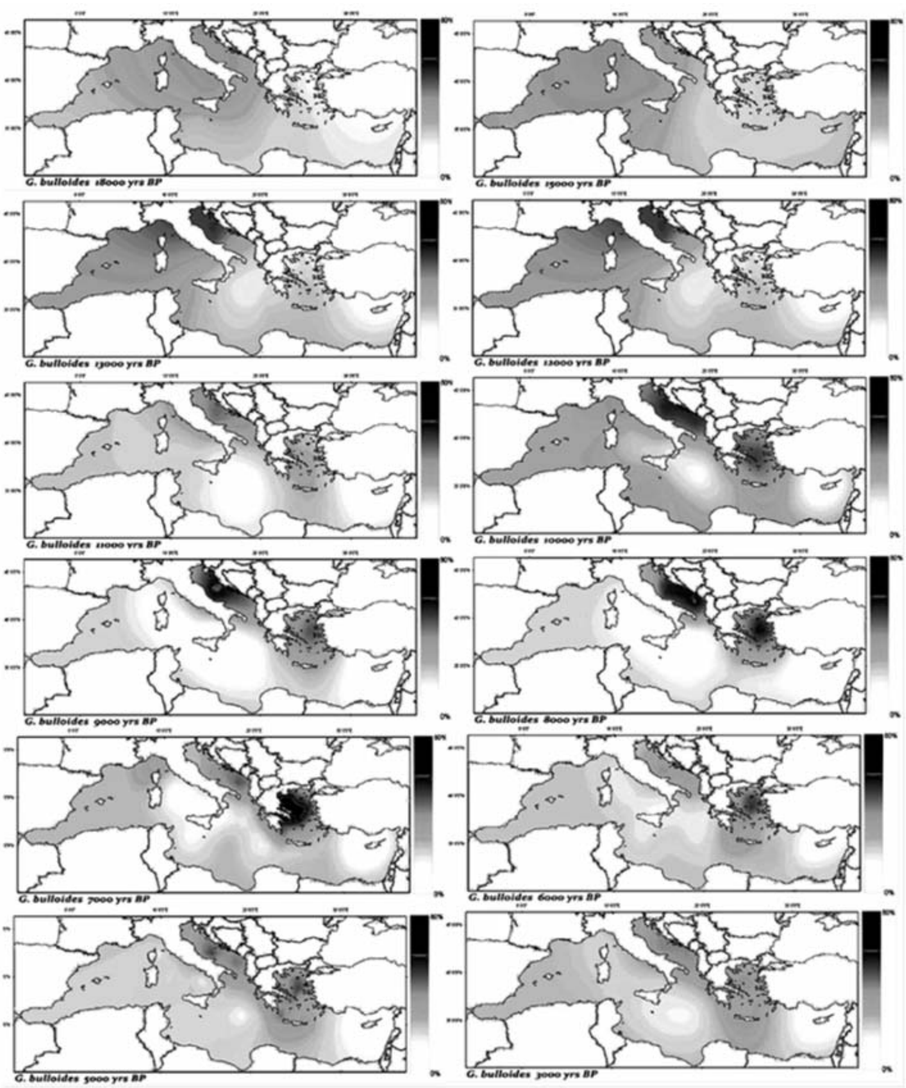

Fig. 4: Maps showing the variation in the distribution of the relative abundances of *G. bulloides* in the Mediterranean Sea over the last 18000years (see Fig. 1 for the location of the data points).

G. bulloides may be found from subpolar to tropical regions and has been associated with high fertility waters in upwelling areas, boundary currents and river discharges (Thunell, 1978; Pujol and Vergnaud Grazzini, 1995). During the glacial period this species appear in high abundance at the northern areas of the western and central Mediterranean Sea (Fig. 4). The development of the eutrophication at this area is complex and is related to frontal systems, boundary currents and river runoffs. Probably was the latter factor that led to the high frequencies of *G. bulloides* during the Late Glacial Period. Between 10 and 7ka the distribution f *G. bulloides* exhibits higher abundance in the eastern Mediterranean Sea. Then it shows maximum frequencies at the Adriatic and Aegean Seas probably in association with increased precipitation and increased river runoffs.

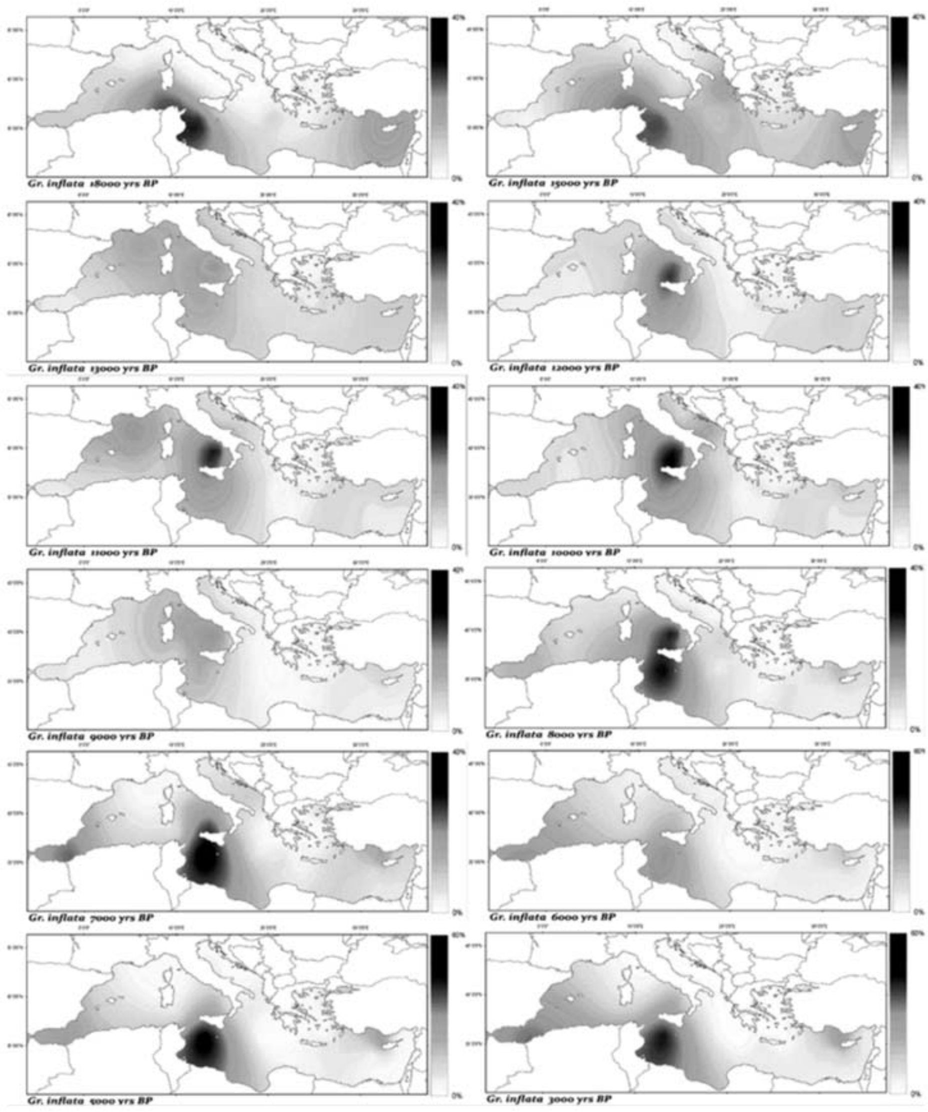

Fig. 5: Maps showing the variation in the distribution of the relative abundances of *G. inflata* in the Mediterranean Sea over the last 18000years (see Fig. 1 for the location of the data points).

G. inflata is associated with cool and winter deep mixing waters (Thunell, 1978; Pujol and Vergnaud Grazzini, 1995). Today, Pujol and Verganud Grazzini (1995) have found high abundances of this species in the Alboran Sea and along the North African coast (close to Sicily Straits). These areas coincide with both the path of the Modified Atlantic Waters and that of the Levantine Intermediate Waters. This distribution pattern of *G. inflata* occurs since the 7000yrs BP (Fig. 5). During the glacial period high frequencies of this species occurs along the North African coast and occasionally in the Tyrrhenian Sea suggesting probably an N-S displacement of the frontal system and of the relevant anticyclone developed in the area.

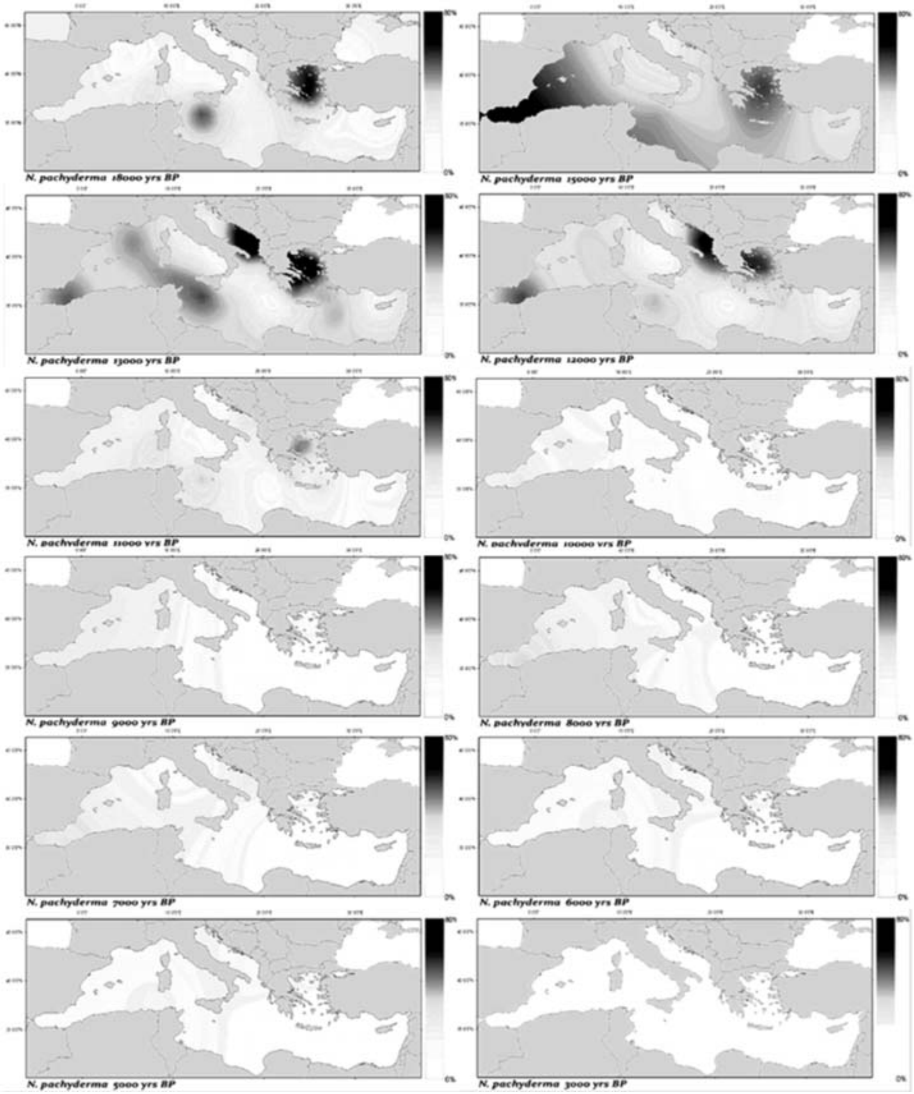

Fig. 6: Maps showing the variation in the distribution of the relative abundances of *N. pachyderma* in the Mediterranean Sea over the last 18000years (see Fig. 1 for the location of the data points).

N. pachyderma occurs from subpolar to tropical regions and is associated with temperatures lower than 12°C and the development of a Deep Chlorophyl Maximu (DCM) layer (Thunell, 1978; Pujol and Vergnaud Grazzini, 1995). In the Mediterranean Sea, high frequencies of this species occur only during the glacial period whilst during the Holocene its distribution is very limited (Fig. 6). Between 18 and 17kyrs BP, this species occurs in high abundance at the Aegean Sea and close to the Sicily straits. During the late glacial period increased frequencies of this species occur also at the Alboran, Balearic, Tyrrhenian and Adriatic Seas. Its high abundance at the western Mediterranean Sea may be associated with the enhanced flows of the Atlantic waters, whilst that at the Aegean Sea (during the Last Glacial Maximum) with the shoaling of the pycnocline (Rohling and Gieskes, 1989).

4. Conclusions

The distribution of the abundance of selected planktonic foraminifera species together with the $\delta^{18}O$ values showed that warmer and more oligotrophic waters prevailed for most of the discussed period in the eastern Mediterranean Sea in relation to the western Mediterranean Sea. The climatic improvement always starts at eastern Mediterranean and follows a western-wards trend. The most eutrophicated conditions in eastern Mediterranean Sea prevailed during the deposition of S1a. Furthermore Mediterranean Sea appears to respond to cold events recorded to high latitude areas during the glacial and Holocene periods, although this signal is always more pronounced in the western Mediterranean Sea.

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ENVIRONMENTAL DEGRADATION OF THE COASTAL ZONE OF THE WEST PART OF NESTOS RIVER DELTA, N.GREECE

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Abstract

The coastal zone is a transitory zone between land and sea. Due to its importance to man, not only for its high food production but also for recreation, sea transportation and industrial activities, coastal zone receives high environmental pressure from him.

This paper deals with degradation phenomena of the coastal zone in the west section of the River Nestos Delta, North Aegean Sea, with special stress on the geomorphological changes in the coastline. The length of the coastline in this part of river Nestos Delta (the Kavala- Chrisoupoli part), from Nea Karvali village to the west, up to the river mouth to the east, is around 35 km long. This section constitutes the biggest and more extended sector of the Nestos Delta; it is the section where the main course and the various branches of the river were located, in the past. Along the coastal zone of this section of the delta many lagoons, sand bars, spits, barrier islands, washover fans, etc. were developed in its geologic past. Some of these geoforms still exist, but the majority of them have been destroyed by physical and/or anthropogenic interventions. Two of the last interventions are the diversion and entrenchment of the river to the east, in early 50's and the construction of two high dams in the river course inland, in 2000. These human interventions deprived this land of flooding waters and sediments resulting in: (a) drying of most of the river channels and courses crossing this area of the river's delta, (b) erosion of the coastal landforms and retreat of the shoreline in the majority of the delta coasts. There are, of course, a few places along the coastline where deposition and accretion are still taking place. In more detail, along the coastline taken into consideration in the present paper, one can meet:

- *stretches with high erosion rates, like the Akroneri Cape (spit), the inner coastline of Keramoti bay (Kokala -Piges coast), the Monastiraki coastline, etc,*
- *stretches with high accretion rates like the Keramoti peninsula/spit, and*
- *stretches at equilibrium or low rate of change like the barrier (spit) west of Akroneri Cape up to Nea Karvali coast and a short stretch of the coastline south-east of Keramoti peninsula.*

Comparing the Delta coastline of 1945 (from available aerial photographs) and the coastline of 2002 (from high resolution satellite images), before the construction of the Thisavros and Platanovrisi high dams (period 1945-2002), it has been estimated that: 88% of the delta and the adjacent coastlines has been accreted while only 12% has been eroded. In other words, there was a surplus of accretion by 76% and the delta was procreated. Comparing the Delta coastline of 2002 (from high resolution satellite images) and the coastline of 2007 (from high resolution D-GPS field measurements), after the construction of the dams (period 2002-2007), it has been estimated that: only 39% of the delta and the adjacent coastlines has been accreted while 61% has been eroded. In other words, there was a surplus of erosion by 22% and the delta began to retreat. This was due to *the great reduction (by almost 80%) of the river's sediment load reaching to the sea. Thus, up to 2002, or so, the balance accretion – erosion in the whole delta coastline was positive, whereas after 2002 the erosion and retreat predominates in the delta's coastline.*

The prevention of sediments and fresh water flooding in the delta area, has also affected the crops production in the fields in the vicinity of the delta as well as the fish output in the lakes and lagoons of the coastal zone.

Key words: *Nestos Delta, coastal erosion, Aegean Sea, North Greece.*

1. Introduction

The coastal zone is a transitory zone between land and sea and between fresh and salt water. It is a zone where the life is flourishing and man uses it for food production, for fishing, for recreation, for sea transportation and industrial activities. Due to these human activities, the coastal zone receives high environmental pressure from man. It should be mentioned that approximately half of the world's population are living or working in a narrow zone of a 100 km from the world coastlines. In Greece, a country with a total coastline development nearly 16000 km long and over 3000 smaller and bigger islands, about 70% of the population and more than 80% of the industrial activities in the country, are concentrated in the coastal zone. Therefore the importance of the coastal zone for the survival and the prosperity of the Greek people is vital and is subjected to high environmental pressure. The coastal zone of Nestos delta and the adjacent coastlines is an example of such a system receiving high environmental pressure by man and is discussed in detail in the following paragraphs.

2. Physical Geography of the Area

2.1 Geology

The sedimentary basin of river Nestos delta constitutes part of the broader quaternary basin of Prinos that includes the Nestos delta and the sea between Thassos island and the main land around Kavala bay. The Prinos-Nestos basin is also part of the broader tectonic basin of south Rhodope Range. The bedrock of the basin consists, therefore, of Rhodope mass rocks (gneisses, schists, amphibolites, marbles, etc) (Fig. 1). Due to continuous subsidence of the basin, the thickness of its deposits ranges approximatelly from 2.5 to 6.0 km (Psilovikos, et al, 1988). The initial faulting and subsidence of South Rhodope is located in the Lower to Middle Miocene (Lalechos et al., 1977; Pollak, 1979; Proedrou, 1979). The deeper layers of the basin's deposits consist of conglomerates and sandstones deposited in a pre-delta environment. During the Upper Miocene, a period of intense evaporation, and the deposition of evaporates and clastic sediments, in alternative layers, followed. Later, during Pliocene and Pleistocene, sedimentation turned again to clastic materials with the deposition of sandstones, mudstones and claystones, in a marine-deltaic environment (Lalechos et al., 1977, 2000; Stournaras, 1984). The Quaternary and recent deposits of the Nestos basin delta are not more than one to two hundred meters thick and consist of gravels, sands, silts and clays in a lensial and alternating (cyclothem) pattern, deposited principally in a deltaic environment. The modern soils of the coastal zone consist of sands, silts and clays in various proportions.

The relief of the coastal zone under discussion is low to almost level. The beach consists of coarse to fine sand and its width varies from 10 m up to 50 m in some places. The beach sands are extended seawards forming a zone of 300 to 400 m of shallow waters, (less than 10 m deep), surrounding the coastline. This shallow waters zone is extended up to 900 m, in some places, e.g. at ammodis Akra (Cape Akroneri) and at the river Nestos mouth. This means that at least some of the sediments extracted from coastal erosion and/or discharged by the river Nestos waters are deposited nearshore.

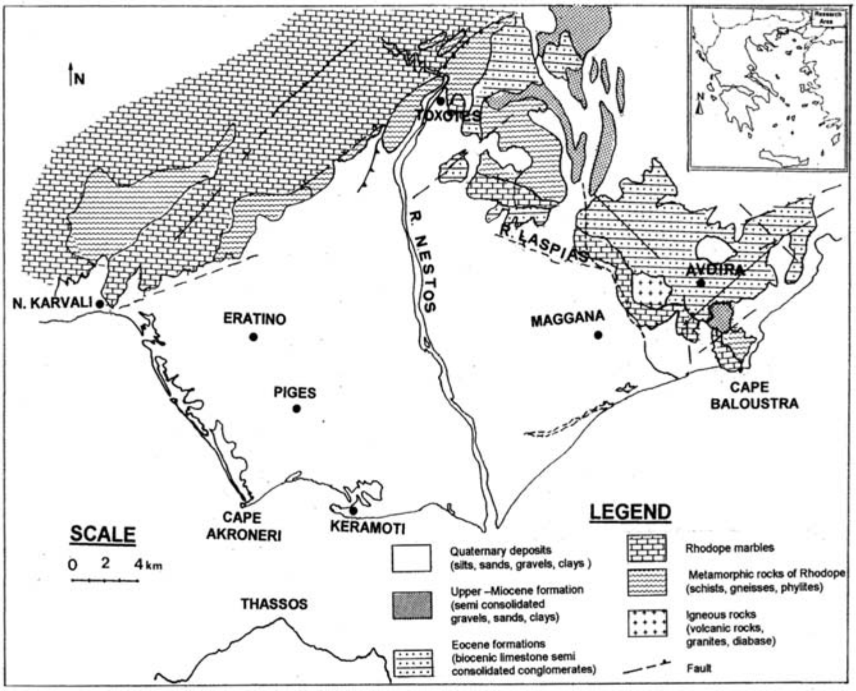

Fig. 1: Simplified geological map of the Nestos (Mesta) river modern delta.

2.2 Evolution of Delta

At the end of Wurm glacial period, some 18.000 years ago, when the melting of ice sheets covering the earth surface started, a rise of the sea level has been initiated worldwide. It has been suggested that the total rise of the sea level since that time is around 120 to 130 m. The sea level increase was faster at the begging (nearly 1cm/yr) and very slow the last 5000 years (about 0.2 mm/yr). The last hundred years the rate of sea level rise increased again due to rise of global temperature. During that sea level ascent most of the coastal lowlands around the world have been inundated. This rise has also happened in north Aegean coasts. The sea flooded the initial Nestos river delta (palaeodelta), which is now under the sea between Thassos island and Kavala coast, and modified greatly the flow regime of the river. The river course inclination decreased and the river started to flood the plain area adjacent to it, to bifurcate and to from new distributaries, wetlands and ultimately a new delta (Perissoratis, 1990) (Fig. 1).

It should be mentioned that the catchment area of river Nestos is around 5752 km^2, from which 3437 km^2 are inside Bulgaria and the rest 2315 km^2 inside Greece. The average total physical runoff from the Rila mountain up to the Nestos/Mesta estuary is $2076x10^6$ m^3 and the average physical discharge is about 66.4 m^3/s, based on data of the hydrological years 1965–66 to 1989–90 (Mimidis et al., 2007).

The mean annual sediment yield before the construction of the dams was $2x10^6$ tn/yr (or $1,08x10^6$ m^3/yr), after the construction the dams in the river course (2002 onwards) it is $0,33x10^6$ tn/yr. *This means that after the construction of the dams the sediment load reaching at the sea was reduced by about 80%* (Hrisanthou et al., 2002; Beacmed-e final report, Sub-program 3.3 «GESA», 2008). The River's modern delta area is almost 440 km^2 and the delta shoreline is 51 km long. The river course was diverted and confined by artificial levees during fifties due to flooding control operations. This de-

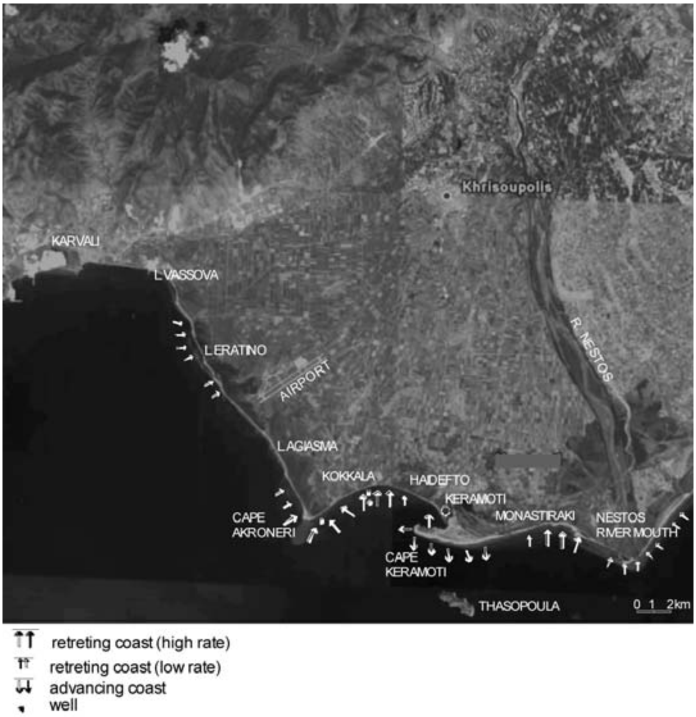

Fig. 2: Sites of coastline changes (erosion-accretion) along the west section of the Nestos' River Delta.

prived the wetlands in the delta area of flooding waters, sediments and nutrients. The modern (diverted) river course axis has an almost N-S direction and is almost in the middle of its delta, dividing it into two nearly equivalent parts, the east part and the west part. Due to the river levees (embankments) the area outside the levees is poorly drained and thus many small and big swamps and marches are formed during the rainy season, especially near the shore. Most of them usually dry up during summer. There are also many dunes in the coastal zone, behind the shoreline. Unfortunately many of the earth features are nowadays destroyed either by sea erosion and retreat of the shoreline inland or by human activities like agriculture, construction of settlements, etc. The Nestos river delta is classified as an *arcuate delta* according to Shepard's (1963) classification (Stournaras, 1984; Psilavikos, 1988).

Figure 2, illustrates the coastline change trends (erosion-accretion) along the west section of the Nestos' river delta that resulted from macroscopic observations and traditional field measurements, conducted by Democritus University of Thrace, in the last decade.

2.3 Climate.

The climate of the broader area is of Mediterranean type: marine, humid with warm summer and rainy winters. It is classified as Cfa or Cfb in the Koppen classification and as Csa along the coastal zone or $C_2s_2b'_2a'$ in the Thornthwaite one (Flokas, 1997). The colder month of the year in the area is January with a mean temperature 4.8 °C and the warmest is July with a mean temperature 23.6 °C. The mean annual rainfall in the plain area is 546.5 mm (data from Chrysoupolis meteological station). In the North Aegean sea, north winds are prevailing but in Autumn and Spring, south winds are more frequent than the north ones. In winder, the north winds are alternated to south and vice versa. In general, the north winds in the area are of NE direction and the south winds are of SW direction. In summer time, Trade winds, characteristic of the North Aegean region, called *Etesians* locally, are blown. They are north to north-east winds, quite strong (5-8 Beauforts), blown from May up to October and are strongest during July-August. They usually cease in middle September each year (Greek Waters Pilot, 1991).

2.4 Sea climate

The surface sea currents in N. Aegean are affected by the Elispontos straits current (Canakkale bogazi) which fans out in N. Aegean and meats the northwards sea current flowing along the Asia Minor coasts. They both turns to the west side of N. Aegean reaching south of Thasos island, where they turn to SW and S at Athos peninsula. They are affected much by the local winds. Thus, the main alongshore current in North Aegean coasts is from the east to the west. This current changes direction and speed locally, near the coast, responding to the direction of the coastline, the geomorphology of sea bottom near the coast, the direction of the blowing wind, etc. For example, in the straits between Thasos island and the mainland (Cape Akroneri and Nestos mouth), when strong S and SE winds are blown, sea water moves to NW along the east coasts of Athos peninsula to Strymonikos bay and it turns to east at Kavala bay, passing from Thasos Straits as an eastwards current. In contrary, with N and NE winds the alongshore current is westwards. Sometimes two simultaneous and opposite sea currents are observed along Thasos straits; one to the westwards nearshore and another to the eastwards offshore, or vice versa, depending upon the direction and the speed of the winds. The speed (the celerity) of these currents reach sometimes up to 1,5 knot = 0,772 m/s=2,78 km/h. (Greek Pilot 1991)

The waves height, with strong south winds, can reach up to 2-3 m, and the tide (high water level near the coast) up to 0,40 m, u.m.s.l.; whereas with north winds the waves nearshore are lower and the sea level up to 0,50 m lower than the mean sea level (m.s.l.).

3. Wetlands of the Nestos River Delta

In the coastal area of the Nestos river delta there are some very important wetlands (small lakes, lagoons, marches, bogs, etc). The whole Nestos delta is under the Ramsar convention and is a highly protected area, for its ecological interest (see Natura 2000). Most of the wetlands of the coastal zone are of lagoon type, connected directly to the sea. Around the lagoons there are many marshes, bogs, swamps, etc. They extend during the rainy season landwards and shrink or dry up during the dry season (summer).

The ten major wetlands have a very rich biodiversity and are of high ecological ans scientific interest. 570 species and subspecies of plants, 25 species of mammals, 43 species of fishes, 12 species of amphibians, 30 species of reptiles and 277 species of birds have been registered, so far, as living or nesting in the Nestos delta area (Panagiotopoulou, 2000).

The deforestation of much of the delta area and the extension of agricultural fields up to the river external levees, together with the intensive use of fertilizers and pesticides for crops, contribute greatly to deterioration of the soils and the waters in area.

The building of big dams on the Nestos river course and its tributaries; the confinement of many water courses (creeks, torrents, etc) on the plain area of delta, for avoiding flooding; the construction of a net of drainage canals; the over-pumping of the groundwater aquifers, etc., deprive sediments, nutrients and fresh water of delta plain, helping the reduction of soil productivity, the intrusion of sea water inland and the salinization of the groundwater aquifers and soils in the coastal zone. For example, the salinization of the groundwater on the coastal zone due to sea water intrusion has been extended up to 5 km inland nowadays. All these human and natural interventions on the delta area affect directly all the organisms living in the area. In addition they influence the crop production in the fields and the fish output in the lakes and the lagoons of the area. Due to overpumping of the groundwater aquifers, and lowering the groundwater table, the rate of intrusion of seawater inland, has been increased lately and the ground water in many places of the coastal zone, turned to brackish. Pumping and irrigating with brackish water leads to *salinization* of the soils and to a serious brought down of the crops output. (Diamantis, 1994, 1999; Delimani, 2000; Delimani et al., 2002, Xeidakis and Delimani, 2003).

4. Erosion / Accretion Phenomena in the west part of Nestos River Delta

4.1 General

The length of the coastline of the west part of river Nestos Delta (the Kavala- Chrisoupoli part) from Nea Karvali village, to the west, up to the river mouth to the east, is around 35 km long. This part constitutes the biggest and more extended part of the Nestos delta where the main channel of the river and its tributaries were developed. Along the coastal zone of this part of the delta many lagoons, sand bars, spits, barrier islands, washover fans, etc. were developed. Some of these geoforms still exist.

After the diversion and entrenchment of the river Nestos course to the east, in its modern site, in late '50s, most the river channels and courses crossing the west part of delta were dried up and deprived this part of the river's delta of water and sediments. As a result, erosion of the coastal landforms started with varied intensity in places.

Along the coastline, under discussion, one can meet:

- stretches with high erosion rates, like at the Acroneri Cape/spit, the inner coastline of Keramoti bay (Kokala -Piges coast), the Monastiraki coastline, etc,
- stretches with high accretion rates like at Keramoti peninsula/spit, and
- stretches at equilibrium or low rate of change like at the barrier/spit west of Akroneri Cape and a short stretch of the coastline southeast of Keramoti peninsula.

4.2 Shoreline Evolution Monitoring

In order to quantify the shoreline evolution in the wider region of Nestos river delta, archive QuickBird (2002) high resolution, satellite images as well as available aerial photographs (year 1945), were geo-referenced from which the instantaneous shorelines were extracted. Moreover high resolution D-GPS measurements where conducted (2006, 2007) in order to extract a coastline which approximates the high water line (HWL) the day of measurements ("wet sand"). In addition, ground control points were installed in selected locations, to facilitate frequent field measurements for shoreline seasonal variability determination. The accuracy of the instantaneous shorelines, extracted automatically using ARC GIS from the satellite images, is checked on sections where the change from land to water is sharp (shore protection structures, ports, etc). It is estimated that the accuracy of determining the instantaneous shoreline is of the order of 2 to 3 pixels or else 1.2 to 1.8 m for the extracted shoreline from pan-sharpened Quick Bird Satellite Images (Pixel Dimension 0.6 m in each band, R-G-B-IR) (Beacmed-e final report, Sub-program 2.1 «OPTIMAL», 2008). The main "hot spots" regarding large values of erosion or accretion in the neighbour of river Nestos delta are illustrated in Figure 3.

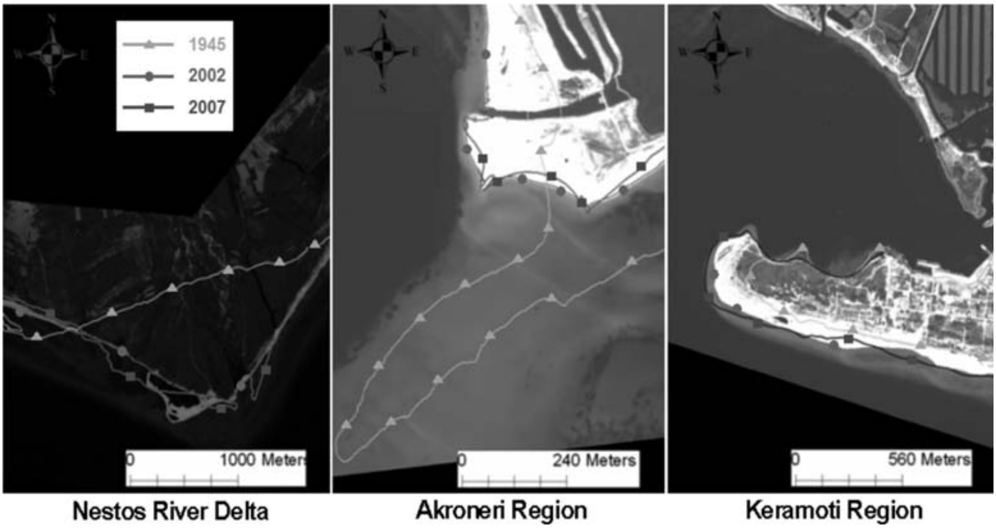

Fig. 3: Shoreline Evolution Monitoring results in Hot Spots of Erosion & Accretion in the Pilot Study Areas.

The shoreline evolution for a short term period (year 2002 to 2007 that corresponds to the period after the construction of dams) and a long term period (year 1945 to 2002, that corresponds to the period before the construction of dams) were determined, from the analysis of the overall extracted shorelines. It is found that the maximum transverse variation (accretion) of the shoreline position between the year 1945 and the year 2002 (before the construction of dams) at the mouth of Nestos river was about 1100 m or about 18 m per year. The maximum transverse erosion of the shoreline position between the year 1945 and the year 2002 (before the construction of dams) at Akroneri, was about 780 m or about 12.5 m per year. An interesting result regarding the evolution of the beaches at the east and west of Nestos river delta (coastal length about 25 km), for the two time periods mention previously is shown in Table 1 and some examples of intense erosion and accretion phenomena from the overall study area are depicted in Figure 4.

Table 1. Comparison of sediment balance in the beaches close to river Nestos mouth (from Akroneri to Dasoxori, about 25 km) before and after the construction of dams.

Area of sediment change	**2002-2007 (after dams)**	**1945-2002 (before dams)**
Total evolution area (m^2)	665531	2608678
Accretion (m^2)	261873	2304096
Erosion (m^2)	403658	304582
Accretion (%)	39	88
Erosion (%)	61	12
Erosion area / Accretion area	1.54	0.13

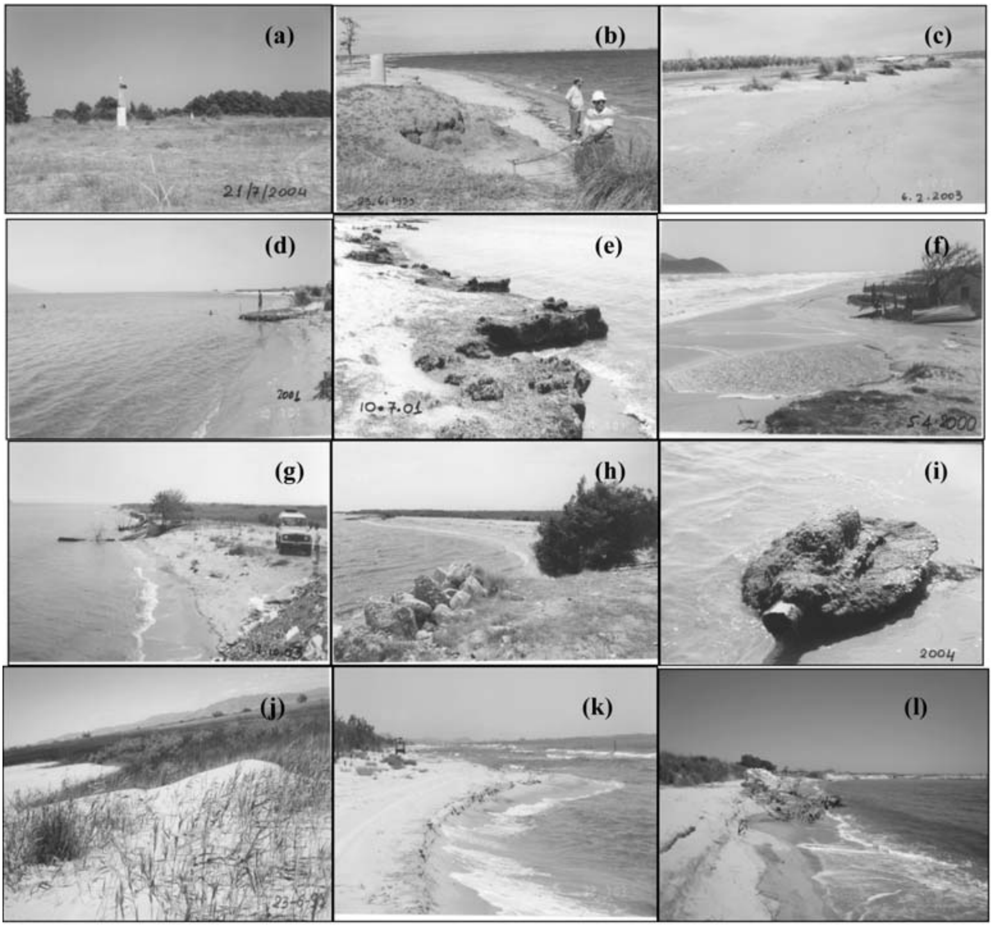

Fig. 4: (a) Lighthouse at Cape of Keramoti (in 1950 was 48m from the west coast) moved to the west (near the coast) in 1981 by 70 m. Today it is some 150m away form the west coast. Coastline under accretion. (b) Agiasma Coast (Kokkala). Topographic post in 1999. Coastline under intense erosion. (c) Agiasma Coast (Kokkala). Topographic post in 2003. It has been completely eroded tranfered into the sea. Coastline under intense erosion. (d) Agiasma Coast (Kokkala). The modern position of two boreholes for irrigation. They both were situated inland some 100 m. (e) Agiasma Coast (Kokkala). Intense retreat of the coast and uncover of the bog surface under the beach sand. (f) Monastiraki Beach. House near the beach. In 1998 it was inhabited and has a small garden in the frond. Between 1998 and 1999 it was destroyed completely. (g) Monastiraki Beach. The same house in 2003. Coastline under erosion. (h) Monastiraki Beach. The place of the house in April 2006. (i) Agiasma baech. Boerehole in the sea due to retreat of the coastline by erosion. (j) Monastraki coast. Sanding of the bog. (k) Dasoxori coast borehole about 40 m offshore. (l) East Monastiraki coast. Intense coastal erosion and destruction of fish pond outlet.

The overall balance of the area of sediment accretion or erosion from the year 1945 up to the year 2002, indicates that accretion is the dominant mechanism, with a total area of accretion about 8 times larger than the erosion are. The large accretion was due to the river Nestos sediment yield. However, this situation has dramatically changed, due to the construction of the big dams along the Nestos river. Therefore for the same beaches and for the short term balance 2002-2007 (after the construction of the dams) it is found that the area of erosion is 1.5 larger in comparison with the area of accretion. This shows that after the construction of dams there is a net deficit in the sediment balance which confirms the initial assumption that the construction of dams upstream of River Nestos Delta and the consequent trapping of the sediments has altered the dynamic sediment balance (Beacmed-e final report, Sub-program 2.1 «OPTIMAL», 2008).

5. Conclusions-Recommendations

The reduction of sediment yield of river Nestos/Mesta because of the two big dams' construction in Greece (Thissavros and Platanovrisi) and one big dam in Bulgaria (Dospat) implies a dramatic decrease (about 80%) of the sediments supplied directly to the river mouth and indirectly to the neighboured coast. This fact has as consequence the alteration of the sediment balance in the delta area, with a dramatic impact on the washout of the river Nestos mouth and erosion of the adjacent coastline.

Although there are many regulations regarding the water management and the obligation of the dam owner to ensure a minimum water discharge to the river for ecological purposes, unfortunately, there is not similar regulation regarding minimum sediment discharge from the artificial reservoirs. Hence, we recommend the necessity of establishing an "ecological minimum sediment discharge downstream of the dam " in the design process of future dams. The advances of modern engineering practice makes possible the achievement of this, environmentally plausible, task.

6. Acknowledgements

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