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THE ATHENIAN AKROPOLIS KLIPPE: RELICS OF EARLY TERTIARY LARGE SCALE NAPPE EMPLACEMENT

P.GAITANAKIS*, V.J.DIETRICH**

ABSTRACT

A structural and petrograpghic reinvestigation of the contact zones between the Cenomanian limestones, which cover the tops of the Piraeus and Athens hills, and the underlying Athens schists has been undertaken.

The results favour the allochthonous hypothesis for these limestones as "klippes" for the following reasons: the flysch-type Athens schists are younger (Maestrichtian to Eocene) than the overlying limestones; typical shear deformation is present in the lower part of limestones (Riedel-systems); the contact zone is comprises Upper Jurassic Radiolarian cherts cherts, slates and diabase (Akropolis hill) as well as serpentinite, ophicalcite and talc-chlorite schists (Piraeus hills). All rocks exhibit sc-, cataclastic and boudinage structures; Very complex folding, shearing and cataclastic phenomena can be observed within the flysch. Cataclastic deformation is certainly the most dominant feature in the more incompetent silty and sandy layers. Ductile deformation is weak in the slates. the major deformational phase. An overburden of a 2 to 5 kilometer rock pile on top of the Akropolis klippes is feasible according to illite crystallinity.

The time of emplacement of the Cenomanian limestones over the Pelagonian tectonic units is given by the minimum ages of the Athens schists. Overthrusting must have occurred during the Upper Eocene orogenic phase as result of continental collision.

1. INTRODUCTION

The Akropolis hill of Athens is one of the most famous classical sites in Greece. With a height of 158 m, it represents one of eight similar hills in the central part of Athens: Akropolis and the adjacent Paulus hill, Philopappou, Lycabetos, Katsipodi, Arditos, Strefi and Sicelia. The tops of all these hills are made up of several tens of meters of thick-bedded Cenomanian limestones overlying the "Athens schists formation". They are comprised of a 200 to 250 m thick flysch-type formation consisting of shales,

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* IGME, 70 Messoghion Str., Athens 11527. Greece.

** Institute for Mineralogy and Petrography, Swiss Federal Institute of Technology (ETH), CH-8092 Zurich, Switzerland.

siltstones, sandstones, sericite-chlorite schists and slightly recrystallized arenaceous limestones, from Upper Cretaceous to Lower Tertiary in age with *Globotruncana cf. lapparenti* and *cf. helvetica*, *Orbitulina*, *Cuneolina*, and *Siderolites* sp., *Globigerina* sp. (MARINOS et al., 1971 and 1974). In the upper part, the amount of sandstone and fine grained polygenic conglomerates increase. The fossil record indicates Lower Tertiary age: *Laffitteina* sp., Orbitoididae, Miliolidae, Melobesioidae.

The position of the Upper Cretaceous massive limestones on top of the "Athens schists formation" with a similar age led to various tectonic interpretations, of which only two contrasting ones will be given here (for further discussion see DOUNAS and GAITANAKIS, 1981 and ANDRONOPOULOS and KOUKIS, 1988):

1) The Cenomanion limestones of the Athens hills are autochthonous and overly transgressively the slightly older schists.

The autochthonous interpretation has been proposed on the recognition of the Upper Jurassic slate-chert formation at the base of the Cenomanian limestones (TATARIS, 1967 and 1972). ANDRONOPOULOS and KOUKIS (1988) showed in the cross sections through the Akropolis hill a normal stratigraphic sequence from the Athens schists at the bottom to the Cenomanian limestones at the top.

2) The limestones are erosional relics ("klippes") of a large nappe or thrust steets emplaced onto the younger flysch-type sediments.

The latter tectonic situation is not restricted to the central part of Athens (NIEDERMAYER, 1971: Die Geologische Karte von Athen 1:10 000; GAITANAKIS, 1982: Geological map of Greece 1:50'000, Athinai-Piraeus sheet, IGME, KATSIKATSOS, 1986: Athinai-Elefsis sheet, IGME); it is also present in the hills of Piraeus and in the neighbourhood of Kalamaki southeast of the city of Athens (KATSIKATSOS, 1986). In addition, small klippes of Upper Cretaceous limestones have been found on top of a very similar flysch in the northern part of the Island of Aegina across the Saronic gulf (DIETRICH et al., 1991).

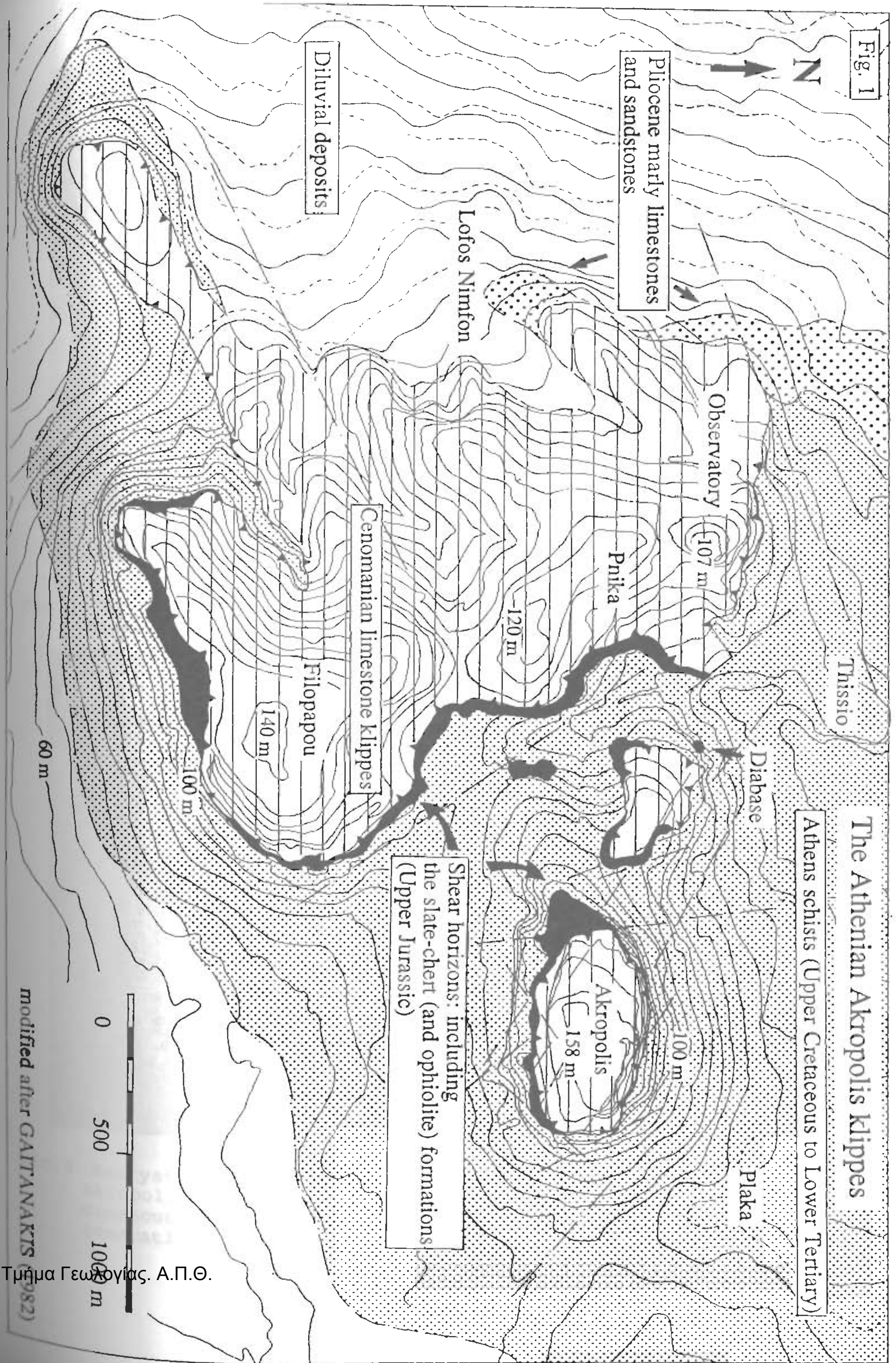
The hypothesis of an allochthonous origin for the Akropolis Cenomanian limestones, which has been already been suggested by KOBER (1929), KIESLINGER (1933), RENZ (1940) and DOUNAS and GAITANAKIS (1981), is also favoured by the authors. A structural and petrographic reinvestigation of several critical locations, e.g. the contact zones between the different tectonic units in the hillsides of Piraeus and underneath the Akropolis (Fig.1), has been undertaken. Two columnar sections (Fig. 2) are given to compare the tectonic correlation between the Pireus and Athens klippes.

2. THE PIRAEUS KLIPPES

In the Piraeus hills (Karavas, Korydallos, Kaniaris), the contacts exhibit typical thrust tectonic criteria: the lower parts of the Cenomanian limestones are effected by brittle deformation and contain numerous generations of calcite veins. The older generations are partly sheared. The contact zone is comprised of chrysotile and lizardite mesh-serpentinite as pseudomorphs after lherzolite and harzburgite (Fig.3), ophicalcite and talc-chlorite schists. These low-grade metamorphic ultramafics represent ideal shear-matrix between the limestones on top and the underlying

Fig. 1

The Athenian Akropolis klippes



modified after GAITANAKIS (1982)

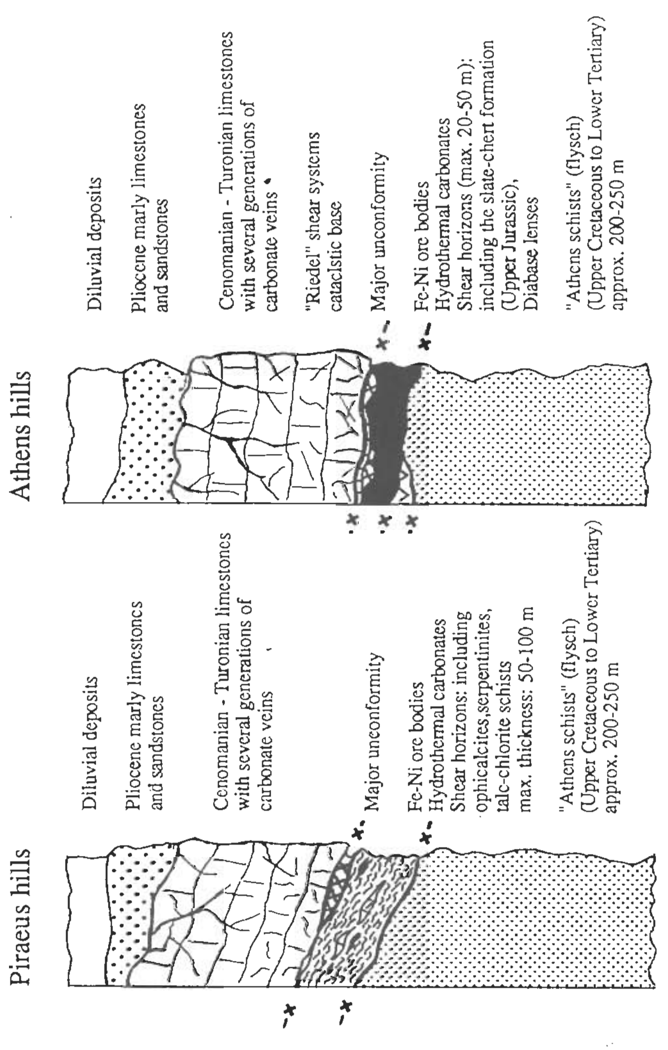


Fig.2 Columnar sections, demonstrating the tectonic correlation between the Piraeus and Athens hills, modified after GAITANAKIS (1982); not to scale.

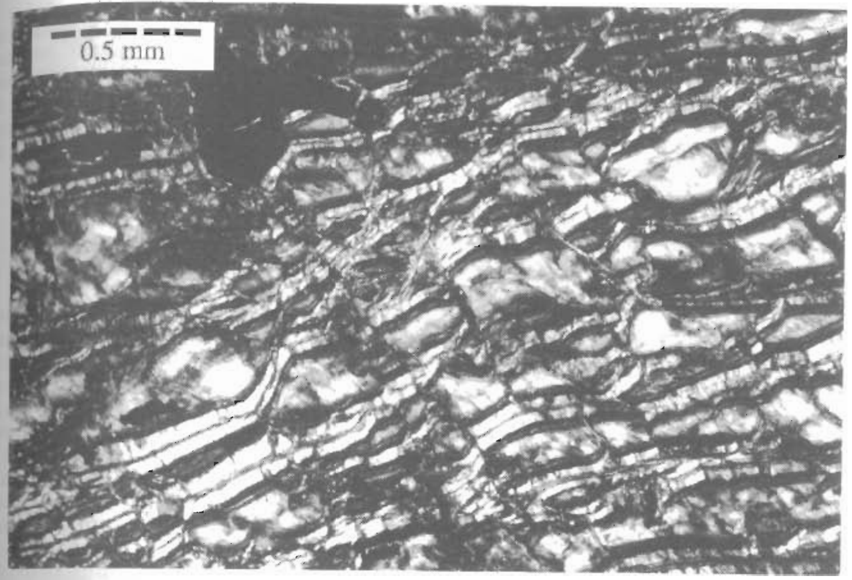


Fig.3 **Chrysotile/lizardite mesh-serpentinite as pseudomorphs after harzburgite(roadcut north of Korydallos).**

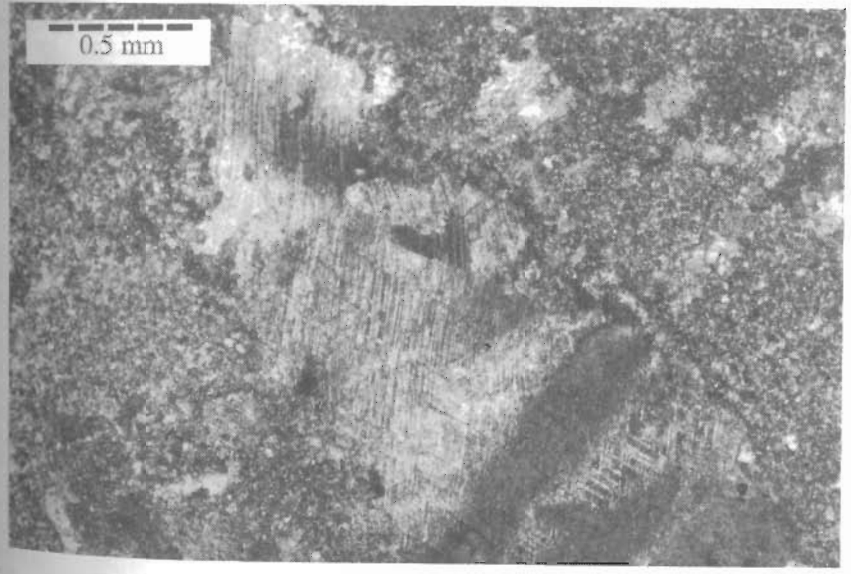


Fig.4 **Recrystallized Cenomanian limestone from the base of the Akropolis hill. Several generations of calcite-filled veins crosscut the limestones. The calcite grains in the older vein generations show twinning and kinking.**

flysch and are often associated with iron-nickel ore bodies (Karavas). These mineralizations are the result of hydrothermal leaching, fluid migration and deposition within a major overthrust horizon containing large amounts of ophiolitic relics. This contradicts the assumption that this ophiolitic material represents large erosional blocks from oceanic crust, deposited by gravity sliding into a wild-flysch type slope/trench environment.

3.THE AKROPOLIS HILLS

3.1 The Cenomanian limestone klippes (Fig.1)

The base of the Akropolis limestone horst is well exposed along its southern slopes between the Propylaen and the Dionysos theater, as well as around the Paulus hill. The limestones are fractured and block faulted by steeply inclined N-S, E-W, and NW-SE trending faults. Cataclastic deformation increases towards the base as expressed by the occurrence of classical Riedel-shear systems (RIEDEL,1929). Several generations of calcite-filled veins crosscut the limestones. The calcite grains in the older vein generations show twinning and kinking (Fig.4).The pink recrystallized carboanate veins resemble those on Moni Island southwest of Aegina, crosscutting Cenomanian Rudist limestone. These fissures are filled with pink micritic Globotruncana limestones of Campanian tp Maastrichtian age (DIETRICH et al., 1991).

3.2 Upper Jurassic slate-chert formation

Behind the Beulé entrance, the contact zone is comprised of several meters of strongly folded (Fig.5, with predominantly N-S fold axes) reddish and greyish cherts, fine-grained siliceous limestones and slates. An Upper Jurassic age for this formation is suggested by the occurrences of Radiolaria and Tintinidae in the slightly recrystallized cherts and biomicritic limestones. Fig. 6 shows the schistosity and state of recrystallisation of the Radiolarians, which unfortunately do not allow a precise age determination.

The slate-chert formation changes its deformational character rapidly within a few tens of meters towards east and west. At the northern foot of the Paulus hill, shearing has increased, and the more cherty competent layers have been transformed into small boudins of a few centimeters in diameter. As the result of displacement and heterogeneity of strain gradients, the schistosity (s-structures) have become uneven and shear banding (c-cisaillement) appeared. The sense of displacement can therefore be determined from the oblique relationship within these s-c band structures (RAMSAY and HUBER, 1987). In the east, close to the Dionysos theater, the same formation appears as a monogenous "brecciated conglomerate". In addition, larger lenses and elongated blocks of the upper Cenomanian limestones are incorporated into the boudinaged and brecciated contact zone. Spilitized diabase lenses also occur in this sheared contact zone, as reported from the northwest corner of the Akropolis by *ANDRONOPOULOS* and KOUKIS(1988).

At the lowermost contact, undeformed carbonate layers and iron-nickel deposits occur, exhibiting under the microscope typical radial and concentric, hydrothermal crystallization fabrics. In many places, these post-deformational hydrothermal sediments,

Fig.5 Slate-chert contact zone behind the Beulé entrance of the Akropolis, which is comprised of several meters of strongly folded reddish and greyish cherts; metamorphic mineral assemblage: quartz, chlorite, sericite, hematite.

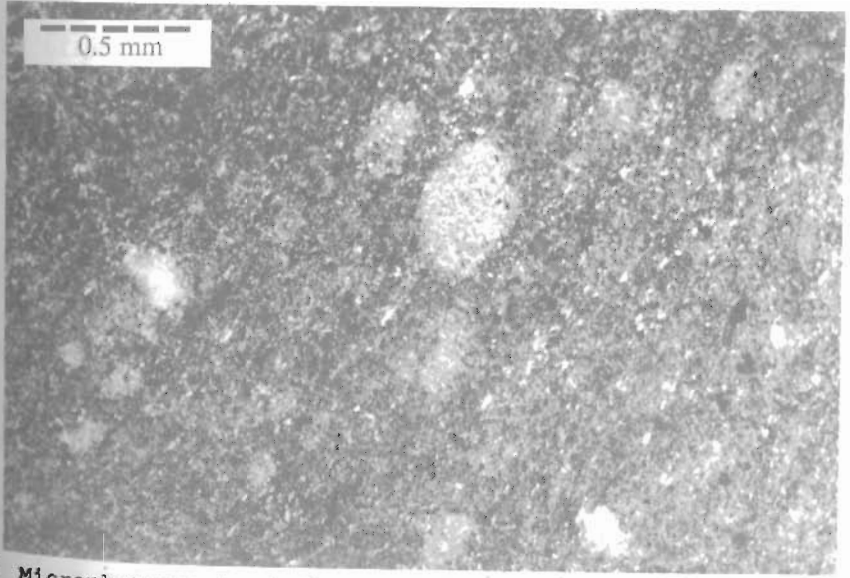


Fig.6 Microphotograph of the Radiolarian cherts (Fig.5), which shows the schistosity and state of recrystallization of the Radiolarians.

well as the limestones, have been affected by suberosional solutions forming the well known holes and caves.

Thus, the horizons including the Radiolarian slate-chert formation, the diabase lenses in the Akropolis hill, and the serpentinites in the Piraeus hills represent the actual thrust contacts.

However, the problem of the thickness of the overlying thrust sheets or nappes, from which we now only see the Athens klippes, needs to be solved. An estimation of temperature and lithostatic pressure can be derived from the metamorphic grade, the deformation fabrics and the cristallinity of the clay minerals in the Athens schists.

3.3 The Upper Cretaceous to Lower Tertiary "Athens schists formation".

Very complex folding, shearing and cataclastic phenomena can be observed within the flysch. Cataclastic deformation is certainly the most dominant feature in the more incompetent silty and sandy layers. Ductile deformation is weak in the slates. Pressure solution phenomena around quartz grains are very weak or absent. This would indicate temperatures below 200°C and pressures between 500 bar and 1.5 kbar during the major deformational phase. The occurrence of chlorite and the cristallinity of illite/sericite transformation suggest temperatures of approx. 200°C, and therefore, a transition from zeolite into lowermost greenschist facies. An overburden of a 2 to 5 kilometer rock pile on top of the Akropolis klippes is quite feasible.

4.PALEODYNAMIC EVOLUTION

The diversity of the different rock types which build up the Piraeus and Akropolis klippes, as well as the complexity of their deformational styles, requires a discussion of the paleotectonic evolution of the whole region, particularly the areas of Attica, Argolis, Aegina and the central Aegean. Between the Upper Jurassic and today, five major orogenic phases can be established.

The time of emplacement of the Upper Cretaceous platform carbonates over the "par-autochthonous" Pelagonian Paleozoic and Mesozoic formations and Upper Cretaceous to Lower Tertiary flysch is still uncertain. This also includes the ophiolite-chert thrust slices and their deformational phases, as well as their paleogeographic reconstruction.

4.1 The eo-Hellenic phase (Jurassic/Cretaceous boundary)

I) There has been a debate over years about time of the Pindus and ophiolite nappe emplacements (for extensive discussion see AUBOIN, 1973; KATSIKATSOS, 1977; BIJU-DUVAL et al., 1978; ROBERTSON and DIXON, 1985; KATSIKATSOS et al., 1986;). JACOBSHAGEN et al. (1978) and BONNEAU (1982) assume a large obduction of Mesozoic Tethyan oceanic lithosphere over the Pelagonian continent from NE to SW starting at the Jurassic/Cretaceous boundary. This movement has been referred to as "**eo-Hellenic phase**".

A subduction process followed by the collison of continental blocks, such as the Serbo-Macedonian and the Pelagonian massives, must have been the major force leading to a closure of a Tethyan oceanic environment (most probably the Varda[illegible] and to obduction of oceanic lithosphere onto continental crust.

Subduction occured in the Argolis peninsula during the Upper Jurassic from northwest towards south, forming the ophiolite-chert mélange (e.g. the Potami formation: BAUMGARTNER, 1985; GAITANAKIS and PHOTIADES, 1989) and subsequently the obducted Lower Cretaceous detrital thrust sheets (HUSS et al.,1988). Along this Upper Jurassic plate margin, an island arc system was built up, as indicated by the occurrence of boninitic lavas. These volcanics occur as components of the detrital Upper Jurassic Dhimaina formation in the Argolis and in the ophiolitic relics on Methana and Aegina island (DIETRICH et al., 1987).

The generation of an Upper Jurassic to Lower Cretaceous arc-trench environment along the Pelagonian margin, forming ophiolitic thrust sheets and mélange supports a more complex geodynamic model than the simple large scale eo-Hellenic obduction hypothesis. This phase cannot be held responsible for an initial emplacement of the Akropolis platform carbonates, since both, the overlying and underlying formations are stratigraphically much younger.

During the early Cretaceous, the Argolis Jurassic thrust sheets, as well as the Pelagonian platform with its Mesozoic cover, became deeply eroded partly under subsequently subaerial conditions and formed hard grounds.

Subsidence during the Middle to Upper Cretaceous produced neritic and pelagic limestones, which were followed by Upper Cretaceous to Lower Tertiary flysch sequences. These flysch trenchs and basins were fed by quartz and mica-rich detritus from the Pelagonian crystalline basement, as well as from the Upper Jurassic ophiolite thrust sheets.

4.2 Subduction (supra-subduction) during Turonian-Campanian

II) According to the deformation phases and metamorphism in the Aegina overthrust series ((DIETRICH et al.,1987; DIETRICH et al.,1991) a **second tectonic phase** can be inferred during the Upper Cretaceous with a time span of 10 to 15 ma fron Turonian to Campanian time. There, deformed and weakly metamorphosed Middle to Upper Turonian limestones and marls are overlain by undeformed and unmetamorphosed Globotruncana limestones of Campanian to Maastrichtian age (75 - 68 ma).

This tectonic event has not yet been well established, but indications have also been found within the ophiolitic mélange in the Argolis peninsula (PHOTIADES, 1989; DOSTAL et al., 1991; BAUMGARTNER, pers. communication) and in parts of the Pelagonian nappes, where Upper Cretaceous neritic limestones are conformably overlain by Uppermost Cretaceous to Eocene flysch (HYNES et al., 1972).

BONNEAU (1982) and ROBERTSON and DIXON (1985) conclude in their geodynamic models of the Eastern Mediterranean, that during the Upper Cretaceous, the intra-oceanic arcs started to collapse by northward directed motions of the Apulian, Ionian and Menderes-Taurian microcontinents. These processes may be described as subduction of oceanic crust combined with supra-subduction in the opposite direction of the fore-arc and arc environments.

This Upper Cretaceous event has not been detected in the Athens schists and in their Mesozoic basement. These tectonic phases were most probably not effective further north within the Internal Hellenides.

The transition of stratigraphic ages within the Athens flysch into Maastrictian and lower Tertiary however, suggests a Tertiary age of emplacement of the Akropolis Cenomian platform carbonates.

4.3 Collisional phase during Upper Eocene

III) Northward directed subduction of the Pindus oceanic lithosphere along the southern Pelagonian-Argolian continental margin and subsequent collision of the southern microcontinents with the Hellenic orogen and its Eurasian continental plate in the hinterland ignited the **major tectonic phase** during Upper Eocene time.

Indications of large scale nappe emplacements over distances of 50 to 150 km are given by the existance of unmetamorphosed and undeformed relics of Upper Cretaceous neritic limestones on top of the Piraeus and Athens area, as well as on Aegina island and as far as on the central Aegean Islands. It can be assumed that the neritic and pelagic Upper Cretaceous limestones were deposited further north on top of the large ophiolitic nappes, which were emplaced during the eo-Hellenic phase. Relics of this situation can be seen in the par-autochthonous nappes in central and northern Evvia.

In Tinos, Mykonos, Paros, Naxos, und Ios, these klippes rest on a highly deformed, polyphase sequence of stacked thrust sheets of Mesozoic and Paleozoic basement rocks, Jurassic to Lower Cretaceous metacherts, marbles and ophiolites with MORB characteristics (DIETRICH and DAVIS, 1986). All these tectonic units have been effected by blue-schist facies, metamorphism of Middle to Upper Eocene (ca. 40 ma according to SEIDL et al., 1982).

4.4 Crustal shortening during Oligocene and Miocene

IV) Continental collision and underplating finally led to crustal shortening during Oligocene and Miocene times. At least two different tectonic styles have to be envisaged, the so-called **"stockwerk-tectonics"**. In the lower and middle crustal units, isoclinal folding and penetrative metamorphism resulted from compression and accompanied crustal shortening. In addition, crustal underplating and shortning led to an enormous thickening of sialic crust and to a drastic increase of the geothermal gradient in the central part of the Hellenic orogen. High-temperature metamorphism, migmatization, intrusion of S-type granites and doming occured during 22 and 13 ma (for review see ALTHERR et al., 1982) in the central and southern Aegean as subsequent result of the continent/continent collision.

Lower "Stockwerk-tectonics" occur in the folded and upthrusted Paleozoic and Mesozoic Pelagonian formations in the Argolis peninsula (HUSS et al., 1988), on Salamis, Methana, Angistri, and on Aegina island (DIETRICH et al.,1991), as well as in the lower tectonic units of the central Aegean islands.

In contrast, the upper crustal tectonic units are mainly effected by detachment mechanisms and gravity sliding. Further emplacements of the allocthonous Akropolis limestones can therefore not be excluded in our opinion. The N-S fold axis in the cherts within the Akropolis thrust zone might be the proof of such E-W directed detachment movements. A maximum thickness of 2 to 5 km of these uppermost crustal nappes can be assumed according to lithostatic overpressure on clay minerals.

4.5 Tensional tectonics during Pliocene-Pleistocene

V) As a rebound of the highly active orogenic period during Oligocene and Miocene times, drastic uplift and erosion occurred.

The central and southern Aegean area, as well as southern parts of Attica were brought to the surface. Molasse-type sandstones and conglomerates full of highly metamorphosed Mesozoic marbles and ophiolites, such as the antigorite-serpentinite containing Pendelikon conglomerates, are the results of the Miocene erosion. Towards the end of Miocene time in the Ionian sea, northward directed subduction started again and individualization of the Hellenic and Pliny-Strabo trenches increased. From the Lower Pliocene on, and continuing today, compressional tectonics are causing crustal thickening with low angle thrusts and overthrusts in the external Hellenic zones (Peloponnesus, Crete and Rhodos). The more internal zone (Argolis, Saronic Golf, Aegina, Attica and the central Aegean area) however, is dominated by tensional tectonics, uplift and subsidence, leading to high angle detachment faults and to horst-graben structures. Active uplift and erosion finally leave only small remnants, such as the Piraeus and Athens hills, of the Tertiary thrust sheets, klippen and nappes.

Most of the material was deposited into the Saronic gulf and adjacent area. The Pliocene transgressional conglomerates, sandstones and green marls are rich in components of neritic and pelagic limestones, flysch, cherts, and lowgrade-metamorphosed ophiolitic material.

EPILOGUE

It is the "Irony of Fate" that Athena chose for her home on earth, the Akropolis, a place that was not autochthonous, but a place that was, like a cloud, from a faraway environment. She built her Akropolis on a base divergent and foreign from the place that she had thought and chosen.

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