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Structure and history of Hellenides

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ABSTRACT

This study is based on some new field observations made on the group of the Eastern Hellenic regions. Our observations have led us to adopt a simplified view of the paleogeography of the Greek mainland before the Alpine orogenesis. The subsequent varied tectonic units originate mainly from the following paleogeographic areas:

- A carbonate Arabo-African shelf margin which displays several lateral transitions, ridges and basins. On the Greek mainland this margin is represented by the Preapulian, Ionian, Gavrovo-Tripolis, Parnassos zones, the Olympus platform and probably the Kavala and Thassos marble.
- A transition zone from the shelf units to the Tethys ophiolites (Pindos Zone, Styra, Argolis and Hydra, Eretrias new unit).
- Tethys ophiolites, which might represent either an "ocean" fault zone or subduction of the lithosphere along a weak area.
- A Hercynian continental mass (Serbomacedonian).

This group is currently completed by the presence of a large tectonic mélange connected to the ophiolite overthrust.

Key words: Hellenides, structural geology, ophiolites emplacement, actualism

Estructura e historia de las Helénides

RESUMEN

Recientes trabajos de campo nos permiten llegar a una nueva lectura del conjunto de datos así como a la nueva interpretación que resulta de los mismos Distinguimos por ende, para el conjunto de las Hellenidas, cinco unidades paleo-geográficas mayores, escalonadas entre Paleo África y Europa, quiénes, mediantes fases tectónicas superpuestas - y no paralelas, ni tampoco de igual desplazamiento, conformaron el edifico actual:

- *Una plataforma carbonatada arabo-africana, incluyendo variaciones laterales y longitudinales.*
- *Una zona de transición entre la plataforma carbonatada y las ofiolitas tethysianas.*
- *Una zona de ''mezcla colorada'' tectónica*
- *Las ofiolitas tethysianas, material mantélico de tipo oceánico.*
- *La masa continental herciniana .*

Palabras clave: Helénides, geologia estructural, ofiolitas, actualismo

VERSIÓN ABREVIADA EN CASTELLANO

Introducción y Resultados

Eubea. Es una isla que bordea el este la península de Ática. En el sur de la isla, de acuerdo con nuestras observaciones, las formaciones metamórficas se dividen en tres unidades cabalgando la una sobre la otra *con una vergencia general hacia el NNE (Figura 3). En su base, la unidad fosilífera Almyropotamos, consiste fundamentalmente por mármoles de edad Mesozoica y coronada por un metaflysch Paleoceno. Sobre ella un nivel de espesor variable rocas verdes, marca el contacto con los mármoles y cuarcitas de Styra que se sitúan sobre los niveles anteriores y que son también de edad Mesozoica al menos en parte. Sin embargo, el contacto principal esta plegado, lo que produce repeticiones que se han interpretado en el pasado, como unidades independientes.*

La Eubea central es una región compleja, para la que proponemos una nueva interpretación: se distinguen dos unidades principales. En la base, la unidad de Eretria, anquimetamórfica, fuertemente plegada y casi sistemáticamente invertida, incluye un Paleozoico superior fosilífero, que pasa a un Mesozoico también fosilífero en el que la parte superior de la serie estratigráfica podría ser cretácico inferior, sin que esto se haya confirmado con precisión. Por encima, la unidad Eubea media que incluye una serie sedimentaria carbonatada del Noriano al Jurásico superior, con radiolaritas del Kimméridgiense, coronado por masas de rocas ultrabásicas cabalgantes. El conjunto está cubierto por una transgresión Albense-Cenomanense, seguida del resto del Cretácico Superior (calizas laminares) y un flysch Paleoceno. Todo ello cubierto por otra unidad cabalgante, pero del mismo origen paleogeográfico. Estos cabalgamientos tienen todavía una vergencia hacia el NNE.

Entre estas dos unidades principales y resaltando su contacto tectónico, hay una gran masa de milonitas, de hasta cientos de metros de espesor en algunos puntos, constituida por rocas ultrabásicas milonitizadas con bloques de rocas de todas las procedencias (calizas del tipo "Pindo", calizas con rudistas), seguidas de una impresionante masa de dolomías totalmente fracturadas (krakéritas). Esta milonita es una característica importante de las Hellenides, totalmente ignorada y englobada a menudo bajo el nombre de "Pizarras-Corneanas".

Argos (Peloponeso). En esta región se ha revisado la cartografía geológica. De hecho en ella se representa el "flysch'' terciario, quizás el verdadero flysh, pero la mayor parte de las veces se trata en realidad de la formación milonítica, similar a la observada en la Eubea central. De hecho, se han distinguido: en la base una unidad de plataforma carbonatada fosilífera Mesozoica que esta cabalgada por una unidad perteneciente a la zona del Pindo que tiene las características de un talud continental existente entre el Triásico y el Cretácico (calizas con ammonites, radiolaritas, calizas laminares, etc.); por encima encontramos de nuevo las enormes masas de milonitas, seguidas por las rocas ultrabásicas cabalgantes. Los contactos entre estas unidades están plegados muchas veces, de modo que todo parece muy fragmentado.

Norte del Pindo. Hemos descubierto en esa zona rocas ultra básicas cabalgantes, una transgresión bien datada de calizas del Campaniense-Maestrichiense (Figura 4); karstificadas y que incluyen coladas de lava doleríticas que se aprecian incluso en las cavidades del karst. El conjunto está coronado por la base de la transgresión ''surco meso-helénica" (Auvertien).

Pindo Central. Se sitúa en plena zona de Pindo. Hemos descubierto en el flysch Paleoceno del Pindo, masas de rocas ultrabásicas sobre las que se aprecia una transgresión supra cretácica idéntica a la del Norte del Pindo (Figura 5). Esta es una evidencia irrefutable (en este caso la vergencia de los cabalgamientos es al Oeste-Suroeste) que la zona del Pindo se encuentra en esa época en el este de la plataforma carbonatada del Parnaso.

Ubicación de las rocas verdes en la Grecia oriental

Hemos revisado los datos de J. H. Brunn. Por lo tanto, en la base de Vourinos hemos confirmado y afincado el corte de la base del macizo ofiolítico (Figuras 6 y 7). Hemos encontrado una plataforma carbonatada de edad Noriano, que se va deshaciendo hacia la parte superior por la inyección de coladas de lavas doleríticas estratiformes cada vez más frecuentes. El conjunto pasa a calcoesquistos sobre los que a su vez se apoyan radiolaritas y lavas almohadilladas. Por último, sobre un nivel de anfibolitas y de corneanas (metamorfismo térmico) descansan masas de peridotitas. En este caso, el contacto no es tectónico sino térmico (efusivo). Los cabalgamientos de las rocas ultrabásicas también incluyen a los niveles de su sustrato. Lo mismo se observa en la región de Vermion y cerca Siatista (Macedonia occidental). Otro hecho importante es la existencia, en las masas de peridotita cabalgantes de una "melange" tectónica compuesta fundamentalmente por ofiolitas y rocas volcánicas. Este es el resultado de la fricción mecánica en la base de las masas cabalgantes y no se debe confundir con la enorme milonita descrita anteriormente.

Conclusiones

Hemos dicho que vamos a respetar el principio de actualismo. En la naturaleza actual, las principales regiones geográficas (llamadas, a veces con exceso, '"placas") son grandes y atraviesan continentes y zonas climáticas. Partimos del principio de que en el pasado las órdenes de magnitud fueron similares. Ahora en las Hellenides y de acuerdo con nuestros datos más recientes, distinguimos varias zonas atribuidas a categorías paleogeográficas comparables: la formación de una plataforma carbonatada mesozoica e infra-terciaria (zonas preapulianas de Gavrovo, Parnaso Almyropotamos y Eubea, unidades mesozoicas profunda de los mármoles de la Ática, la unidad de Olimpos, la unidad de Drama en la Macedonia oriental, los mármoles de las islas de Tasos y Limnos etc.); formaciones atribuibles a un talud continental (Pindo, Styra en Eubea, varias unidades en Argos, Ethia, Creta etc.); acumulaciones de milonitas y rocas verdes trituradas y olistostromas del tipo "melange" sensu Ganser (Eubea central, Argolidas, envuelta tectónica del Olimpo) y las zonas carbonatas fracturadas (krakérites de la región entre Atenas y Corinto, Eubea , Argos); ciertos olistostromas antiguos (Cretácico medio?) en la Argolida, Beocia Vourinos ...); ofiolitas masivas cabalgadas junto con su sustrato que han marcado el avance tectónico (Norte del Pindo, Vermion, Vourinos Eubea, etc, etc); algunos fragmentos de la plataforma continental con series desde el Paleozoico superior al Jurásico sin discordancia Hercínica visible (Eubea, Quíos, Argos ...). Por último, las unidades pertenecen al continente euroasiático, con o sin discordancia Hercínica (Sidironeron-Kerdillia en Grecia, Sredna Gora en Bulgaria).

Se plantea la cuestión del origen de las ofiolitas del Tetis. Son, sin duda, los representantes del Tetis Alpino. Sin embargo, creemos que representa una gran "grieta" (megarift) en lugar de un océano en sentido estricto. En efecto, tras los grandes avances de la geología marina, se tiende a equiparar a todas las rocas ultramáficas con los restos de un océano. Pero el principio actualismo requiere, que en la noción del océano se incluya también su dimensión. Y ahora, incluso si el Rift de África oriental se puede interpretar como un océano en formación, no podemos pensar lo mismo para los fondos ultrabásicos del Mar Negro y del Caspio.

Por lo tanto, proponemos la siguiente evolución estructural para las Hellénides: una plataforma de carbonato paleo-africana compuesta por varios surcos epidérmicos, y está limitada por el lado del Tetis por un talud continental (zona del Pindo y asociados); los sucesivos y discontinuos empujes tectónicos conducen a la superposición tectónica de sus distintos elementos; las rocas ultrabásicas del Tetis son empujadas sobre esta plataforma en fases sucesivas del Jurásico superior y hasta el Eoceno; los elementos del continente euroasiático siguen el mismo proceso y llegan cabalgantes sobre la plataforma carbonatada Africana del Olimpo.

Todos estos contactos tectónicos están plegados y replegados en diversos sentidos. El aspecto actual de fragmentación no es debido a la hipotética ''microplaca'' que surgen como un "Deus ex machina" en los modelos que se ofrecen hoy en día, sino a esta tectónica de múltiples fases extremadamente complejas, que afecta a las grandes regiones geográficas similares a las actuales.

Introduction

This study is based on some new field observations made from the internal zones of the Hellenic chains. It concerns southern Euboea, Central Euboea, Argolis (east Peloponnesus), Pindos zone (we will see it is a zone of ''internal'' affinities), the ophiolitic zones of Vourinos and Vermion, and finally the oriental Macedonia (regions of Drama and Kavala) (Fig. 1). The observations which have been made are absolutely new, and when put together lead us to a new, synthetic interpretation of the internal Hellenide structure as well as the alpine orogenesis, completely different from those which have previously been formulated. We will start with the description of the field observations, region by region, we will then give our conclusions with the new, synthetic interpretation.

Euboea

The Euboea Island lies along the north-eastern Attic flank (Fig. 1), and for the last century its geologic structure and the age of the geological formations, in part metamorphic, has been under discussion. The first geological interpretations were given by Neumayr (1880) and Teller (1880). Then Deprat's thesis (1904), which was wrongly criticized, presented the first modern monography on the Euboean geology. We will first examine the southern area, then the central one.

Southern Euboea

Southern Euboea, where the pre-Miocene formations are metamorphic, belongs to the ''Attica-Cyclades

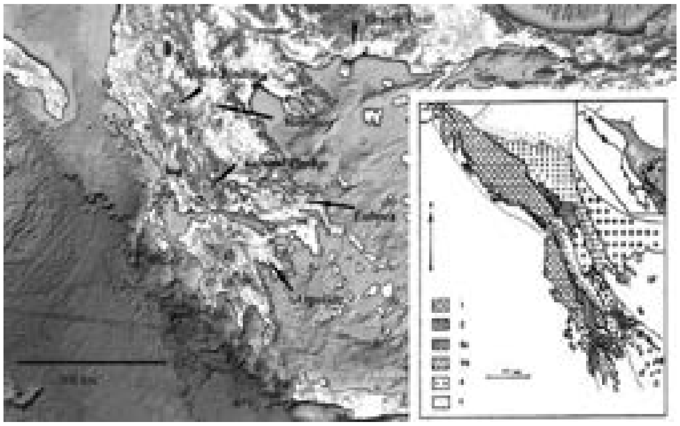

Figure 1. Position of the different locations and main geological zones: 1 and 3a - African shelf units, 2 and 3b - Transition units, 4 - metamorhic units, mesozoïc *pro parte,* 5 - Tertiairy, molassic beds. After Argyriadis, 1974.

Figura 1. *Localización de las zonas principales de este artículo. 1: Isla de Eubea, 2: Argos 3: Norte de Pindo, 4: Pindo central, 5: Vourinos.*

Massif''. The age and structure of the formations has been a topic of discussion since the end of the 19th century. A prediction by Teller (1880) based on a lithostratigraphic observation, confirms the correlation between these formations and the non-metamorphic ones of central Euboea, and attributes them to the Cretaceous. Different authors (Deprat 1904, Paraskevopoulos 1963, Chenevart and Katsikatsios 1967, Guernet 1971) have attributed a Paleozoic age to the metamorphic formations of southern Euboea. Others authors (Negris 1928, Kober 1929, Blumenthal 1931, Argyriadis 1967, 1978, Argyriadis *et al.,* 2010) have observed, as well as the metamorphic formations close to Attica, a tectonic window under a pile of more and less metamorphic overthrusts. The first two authors described some triassic algae in the Attica Hymettus marble, the latter describes the *Megalodontidae* in the marble of the Marathon zone which corresponds to the Almyropotamos zone in front of it. He proposed (1967) for the southern Euboea *stricto sensu,* the existence of four formations or metamorphic units, starting from the base:

- The Almyropotamos unit consisting of Mesozoic marble.
- The Tsakaioi unit consisting of schist and amphibolites, including large bodies of serpentine.
- The Styra unit consisting of thin plate marble, cipoline, white and pink quartzites and amphibolitic schist.
- The Okhi unit consisting of large amphibolitic bodies, glaucophane schist and manganese microquartzite.

Since then, many authors who were concerned about these regions have reviewed this classification, enlarging and refining the details (Katsikatsos, 1971, 1991a, 1991b, Katsikatsos *et al.,* 1986, Gautier and Brun, 1986, Lensky *et al.,* 1997). Meanwhile, the petrography and stratigraphy of these formations are more detailed.

Almyropotamos marble, in which one of us (IA) found some Upper Cretaceous Rudistids which were shown to the French Geological Society during a field trip in Greece (1976), (see Durand-Delga and Argyriadis, 2012) is overlapped by a metaflysh, the base containing some Nummulites (Dubois and Bignot, 1979), the Tsakaioi, Styra and Okhi are ''blue schist'' units, the tectonic overlapping has been recognised by all the authors. Some new field observations provided a new structural and paleogeographical interpretation. In fact the Okhi formation is far from ''crowning'' the unit sequence, it has been found under the Styra formation and in fact is a whole with the Tsakaioi formation (Argyriadis *et al.,* 2010).

This fact, which has just been confirmed, has been *locus typicus* evidenced, as Mount Okhi. This mountain in fact looks as if it is seated above a very thick marble series (the Styra marble). Its upper crest is constituted by two characteristic crests made of amphibolites, whereas its flanks are constituted by Styra quartzite and marble. The whole is characterized by a southern inclination.

But the impression that the amphibolites are overlying the marble and cipoline is a simple optical error: two geological sections through the mountain show this very clearly: the Styra formation is a large, steep south-oriented pericline which covers and envelopes a tectonically composite strand of amphibolites, serpentine and metalava, the same as that which can be observed northwards in the Tsakaioi region; under this formation, some fragments of quartzite, marble and metaradiolarites are dragged in a sort of tectonic sole; underneath and at the end, the Almyropotamos flysch and Mesozoic carbonatic series can be observed. Some other observations can be added in confirmation of what has been just been described (Fig. 2).

The Styra marble cover is not so massive as was supposed by some authors, it is relatively discontinous, and the underlying Almyropotamos can be observed in many different places, such as for example to the north of Styra village where a Rudistid marble outcrop has been cut by the national road to Karystos, showing its position under the Styra overthrust. The Stouronissi small island, which is situated just in front to the west, is made up of Almyropotamos marble, darker and well layered,

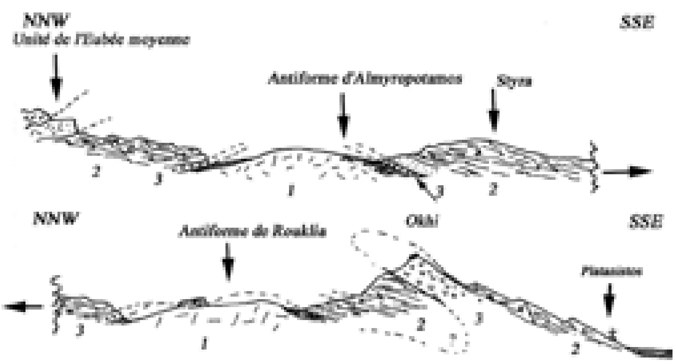

Figure 2. Structure of southern Euboea. 1: Almyropotamos, mesozoïc marble and metaflysch; 2: Styra, cipolines, silexites, quartzites, metaradiolarites; 3: ophiolitic rocks (amphibolites and serpentines)
Figura 2. *Estructura del sur de Euboea. 1: Almyropotamos, marmol y metaflysch mesozoicos; 2: Styra, cipolines, silexitas, cuarcitas, metaradiolaritas; 3: rocas ofiolíticas (anfibolitas y serpentinitas).*

which corresponds to some lower levels in the series: there it is possible to find some *Ellipsactinia* and *Nerinea* sections, at the end of the small bay in the northern area. Similarly, in the western part of the bigger island of the Petalioi group, NW of Karystos, the Almyropotamos marble seems to be reversed on its own flysch, and covered on its eastern part by the Styra overthrust.

This contact of Styra over Almyropotamos is systematically bordered by the amphibolite strand and the discontinuous band of the sepertinised ultra-basic rocks: this is evidenced in Tsakaioi as in the Okhi section just described, in the northern border of the karstic Dystos lake, where the Almyropotamos marble is separated from the Styra Unit – represented by the Koskinon quartzites – form a thin layer of amphibolites and green rocks, often laminated to reach a thickness of some metres, but always present.

This main contact is violently folded following at least two axes, one in the direction of N 85° and the other one in a NW-SE direction. The intersection of this folded contact and of its topographic structure which is very valley-shaped, gives the aspect of its increased structural complexity in the field.

Two remarks must be made before concluding this section on southern Euboea. The first concerns the methodology of the structural analysis: many authors base their stratigraphy and then their structural interpretation on the metamorphic facies of these formations, mainly on blue schist metamorphism. We think this is a mistake of structural interpretation: the metamorphic zone cannot constitute a stratigraphy but it can on contrary – and this is the general situation – be oblique and transverse respect to the original superposition of the sedimentary layers. In other words, the same paleogeographic zone can be in some places metamorphically characterized by some "blue schist", and in other places anchimetamorphic or non metamorphic. The second remark concerns the metamorphism: in southern Euboea there are not one but several metamorphisms which coexist and are overlayered. We can find some blue schist formations, green schist in other formations, and an evident and more recent thermal metamorphism is also present, probably due to the same granitic intrusion which is at the origin of the Laurium mineralizations in Attica and is here responsible for the small mineralizations (sulphurs, a little gold and silver) near Kafirevs Cape (Cavo Doro) at the SE extremity of the island.

Central Euboea

The central Euboea area is "classically" considered as a sedimentary succession consisting of Upper Paleozoic and Mesozoic, bearing oceanic ophiolites which are overlayered with an angular discordance by a sequence starting with some transgressive Cenomanian Rudistids limestone followed by thin bedded Campanian – Maastrichtian limestone where they progressively pass to a Paleocene flysch. This series is strongly tectonized, with some tectonic and overthrusted covers, and is probably overthrusted on the southern Euboea metamorphic ensemble. Our research in this area was able to evidence and demonstrate a reality which is infinitely more complex. This research which was carried out (2005) with Daniel Vachard and Jérémie Gaillot, then with Mohamed Midoun (see Argyriadis *et al.,* 2010) and finally with Silvia Forti, led to the first evidence that the "Seta" Paleozoic series, known since Renz and Reichel (1946) is violently folded following different axes, and is often intensely reversed. We were then able to observe two major facts:

- The fossiliferous Paleozoic Seta series passes normally and progressively to the Eretria Olympus Mesozoic semi-metamorphic limestone. This limestone is present under the Paleozoic Seta schist, in other words the whole constitutes a widely extended and reversed geological unit. The same Paleozoic schist overlies the Meozoic limestone in stratigraphic conformity, and is then followed by the Dirfys limestone: the Olympus limestone which is apparently the same as the Dirfys, passing like a "tunnel" under the Paleozoic schist.
- The relationships between this new unit (Olympus – Seta – Dirfys) with the Euboea ophiolitic unit are

of tectonic origin: a spectacular mylonitic zone constitutes the overthrust contact of the second unit above the first one.

These facts have been confirmed by a more detailed investigation. Currently, the conclusive remarks can be the following:

– In Central Euboea two geological units are present (Argyriadis *et al.,* 2010), they correspond to two different paleogeographic zones: one unit which is still called the "Middle Euboea unit", and a newly evidenced unit which will be from now on be called the "Eretria unit".
– The middle Euboean unit consisting, just to remember, of a Meozoic limestone series starting from the Upper Trias (Rhaetian) to the Upper Jurassic (Kimmeridgian), passing to a reduced series made of calcshist and red radiolaritic pelites, overlayered by a by ophiolitic mass (peridotites, lherzolites, gabbros, alkaline volcanic rocks); the whole is covered by a discordant transgressive series which starts from some Cenomanian limestone and which continues in the Upper Cretaceous evolving into a thin plate of *Globotruncana* limestone reaching the Upper Campanian and even the Lower Maastrichtian, passing to a Paleocene flysch.
– The (new) Eretrian unit is made up of a series of anchimetamorphic schist and grauwackes, where we have long known about (Renz and Reichel, 1945, Guernet 1971, Argyriadis 1978) some Upper Carboniferous limestone with fusuline interbeddings (at Panaghia spring) but also some Upper Permian fossiliferous limestone layers; these are covered by different "hard grounds" and successively by some white quartzite which are identical to the alpine Werfenian ones (Lower Trias), then a series which is composed of green and purple tufs, some acid volcanic rocks (Quartz-keratophyres) as well as alkaline (spilites) passing to some pink or purple ballstone layers similar to the Anisian ones of the eastern alps; everything is surmounted by a limestone series which in Olympus is composed of some red radiolarites interbeddings, but is mainly constituted of black limestone in thin laminations and some more massive white limestone, evolving then into a grey limestone series with many characteristic silexite interbeddings. Mohamed Midoun found some fossiliferous layers in the white limestone (Crinoids, Lamellibranchiates, Brachiopods) where, from a macroscopic point of view, it may be possible to recognize some *Plagiostoma* or *Halobia* which are associated to the Crinoids and that should confirm to an Upper Triassic age; the existing geological map indicates many rhetian microfossils in the Olympus formations, but this map does not take into consideration any distinction between the Olympus formations and the overthrusted mylonitic units, so we cannot be sure about the real significance of these fossils. Then, the sadly missed Maurice Lys found some "foraminifera phantoms with Lower Cretaceous affinities" withinin the silexite limestone; I found (IA) some sections of big decimetric Lamellibranchiates within the Dirfys limestone which are some Lias *Lithiotis sp.* At present we do not know the stratigraphic upper limit of this series. A consequent number of samples are at present under more detailed investigation.
– The Middle Euboean Unit is overlapped to the Eretrian unit through a high style overthrust. The contact is characterized by an impressive mylonitic zone where it is possible to also observe some green rocks (serpentines, gabbros) fragments with some dislocations and alterations, some thin layered limestone and some "Pindos" type radiolarites, some dolomites and limestone which constitute very large breccia masses. This contact is itself violently folded, following some axes in the average E-W direction and with an inclination (''Vergenz'' sensu Stille) to the NNE direction, and this is remarkable for the Hellenides where the principal currently known alpine folding axes follow the NW-SE direction with an inclination to the SW direction. In the area of Kambia village, a mass of Upper Trias dolomites is violently reduced into mylonitic breccia. In this breccia mass, Silvia Forti found some limestone fragments, including well identifiable Rudistid debris, and this gives the possibility of attributing these tectonic formations, at least *pro parte*, to an Upper Cretaceous age.
– The Eretrian Unit is violently folded following different axes: one axis following the N110° direction, which characterizes some decametric isoclinal in the Olympus and very packed folds where the axis is nearly horizontal (vertical folds); one axis following the same direction seems to characterize, in the Dirfys and towards the Aegean Sea, some hectometric to kilometric recumbent folds, with a NE inclination; this folding seems to be responsible for the regional reversal of the whole unit; in the northern part of the Olympus it is possible to observe some metric folds with a inclination to 60° to the ENE) affecting the silexites marble; finally, it has been possible to observe some recumbent (horizontal) decametric folds in the Paleozoic series with a NW-SE axis plunging towards the SW direction.

– The overthrusted Middle Euboean Unit is around the Eretrian unit following a very complicated plane due to the folding which is posterior to the overthrusting, and closes in the SE area with some peridotite and limestone outcrops; this unit is extended to the whole Kymi region and is overthrusted over the southern Euboea metamorphic formations, in the Ochtonia region.

Argolis

Geological maps of this area are confused as they present an extended Late Cretaceous flysch formation of "sediments of passage from Eastern Greece zone to the Pindos zone". In fact, there are limited occurrences of flysch formation. However the majority of occurrences are a formation that we will refer to as "melange". It is a thick mylonite zone with intense deformation that includes radiolarites, remnants of serpentine, blocks of limestone, usually of Late Cretaceous period and mainly clastic sediments with ophiolite origin. This clastic material is characterized by the presence of rounded lithoclasts which are strongly oriented and cleaved. Here are some examples:

– In the Tolo region, the geological map shows a flysch formation placed tectonically over Late Cretaceous limestone or under Triassic limestone. In fact, mylonite is overthrust recrystallized limestone, probably of Triassic age. This can be seen on the road towards the port of Tolo. This mass includes blocks of underlying limestone, sandstone with ophiolite origin, fragmented radiolarite and pillow lavas and blocks of black limestone. Moving north-westwards to the waste site of Tolo, at the pass of Seitan-bahce site, we see the tectonic contact between the mylonite and subjacent limestone. Limestone is karstified before upthrust and ophiolitic material seems to be depressed inside karstic cavities. The same mylonite can be seen under the ancient castle of Asini.
– In the area of Pyrgiotika village, flysch formation exists but it is under the mylonite with the contact between these two formations being intensely folded. To the east of the village we observe remnants of serpentine inside the mylonite, covered by white and purple calcschists with *Globotruncana sp.* Nearby, there is a tectonic remnant of white limestone and radiolarite always inside the mylonite.
– In the area of Marathea village, peaks of Goumouria and Aetovigla are chiselled out in thick bedded limestone in the base of which Lower Triasic lava exists. Despite what the geological map shows, this limestone is not over the flysch formation, but below it. Moreover, this formation is not flysch but mylonite, which is overthrust onto the Triassic limestone. This overthrust can be seen clearly near the church of Ag. Georgios, which is has it foundation on limestone tectonic remnants inside the mylonite.
– In Argos city, Aspida hill consists of highly altered ophiolite with transgressive bioclastic limestone, probably of the Late Cretaceous. Flysch is totally absent and Larrisa hill consists of radiolarite and thin plated, pink limestone of the Pindos Zone, covered by thick bedded limestone, probably Cretaceous (near the Panagias Monastery).
– Westwards of Argos City, in the area of the Ag. Triada church, there is an extended appearance of highly altered ophiolite which contains old, pedogenetic surfaces covered by lateritic crusts and angeritic dolomites of continental or lacustrine origin. On the surface limestone seems to lie in stratigraphic conformity with hornstone intercalations containing ostracodes.
– In the Akova site, limestone of the eastern front of the Loutses Mountain is below tectonically fragmented ophiolite, which in turn is below intensely folded sandstone of ophiolitic origin.

Constructively in Argolis area, three paleogeographic areas are present: a carbonate shelf belonging to the Paleo-African margin, a continental slope (the Pindos Zone) which now forms tectonic slices, and the ophiolitic complex of eastern Greece tectonically placed at the top of the succession. The original fingerprint of this research is the recognition of the broad mylonite, just like in Euboea.

Northern Pindos

A Late Cretaceous transgression over an ophiolitic complex has been described (Argyriadis 2004, 2007). In this region, the ophiolitic complex has been tectonically placed over the Pindos Zone (Philippson 1890, Reinhardt 1911, Kober 1931, 1952, Renz 1940, Brunn 1956). Inside the ophiolitic complex there is limestone of Triassic, Jurassic, Upper Cretaceous, and even the Eocene epoch, embedded or intercalated. An array of limestone outcrops is observed to the east of the Katara site. From south to north we find Tragopetra and Petra Portas, anonymous outcrops and Megali Petra. Commonly attributed between these outcrops is the Late Cretaceous epoch. Although Brunn (1956), firstly had interpreted these outcrops as tectonically placed, today it has been proved (Argyriadis 2004) that they are transgression remnants.

The most reachable outcrop is Tragopetra, beside the National Road 6, about 2 km east of the Katara Pass (Fig. 3). Here, the origin of ophiolite is peridotite and gabbros which fluctuates to doleritic lavas. It is fully serpentinized and has strong tectonic deformation. The columnar section of the specific site is (microfauna determinations by G. Tronchetti, Marseille):

- Ophiolitic lava at the bottom, the top of the ophiolitic complex of northern Pindos (1).
- Transgressive conglomerate (2) consisting of ophiolitic rounded shingles mainly peridotite and gabbros and sometimes radiolarite. Conglomerate fills concavities on ophiolite surface. Thickness range from 10 to 100 cm.
- A thin layer (about 10 cm thick) of red coloured limestone.
- White coloured bedded limestone (3) up to 7-8 m thick. At the bottom containing ophiolitic pebbles the same as the previous ones. In the last two calcareous horizons *Globotruncana linneiana, Gl. bulloïdes, Gl. arca, Contusotruncana fornicata, as well as Rugoglobigerina sp., Heterohelix striata, Pseudotextularia sp., Plassoglobulina sp., Calcisphaerulidae* are found of Late Campanian age.
- Miscellaneous conglomerate (4) up to 1-2 m thick, containing ophiolitic, quartzite, crystallic rock and limestone pebbles.
- Pink coloured limestone (5), up to 2-3 m thick, with cleavages and lenticular intercalations of conglomerate. It has the same microfauna with layers (3).
- White coloured, thick bedded limestone (6) up to 30 m thick. Only small orbicular foraminifera have been found without key fossils.
- Pink coloured, thin bedded limestone (7), up to a few metres thick, with lenticular intercalations of conglomerate the same as the previous. It has the same *Globotruncana* microfossils but even more, *Globotruncanella havanensis*, of Early Maastrichtian age. The limestone series ends upwards in a karstic surface with big concavities.
- Effusions of doleritic lavas (8), completely different from the previous one of ophiolite, also fully altered. Locally lava penetrates and discharges inside the concavities of subjacent karst. The thickness is estimated at 50 m.
- Superimposed red carbonate schist (9), filling the concavities of subjacent doleritic lava, up to 1-2 m thick.
- Conglomerate (10), of Auversian age over a previous lava formation, in stratigraphic unconformity. It is also miscellaneous but different from the previous one, consisting of big boulders (up to 20 cm diameter) of rock crystal. It is the base of the MesoHellenic Trench.

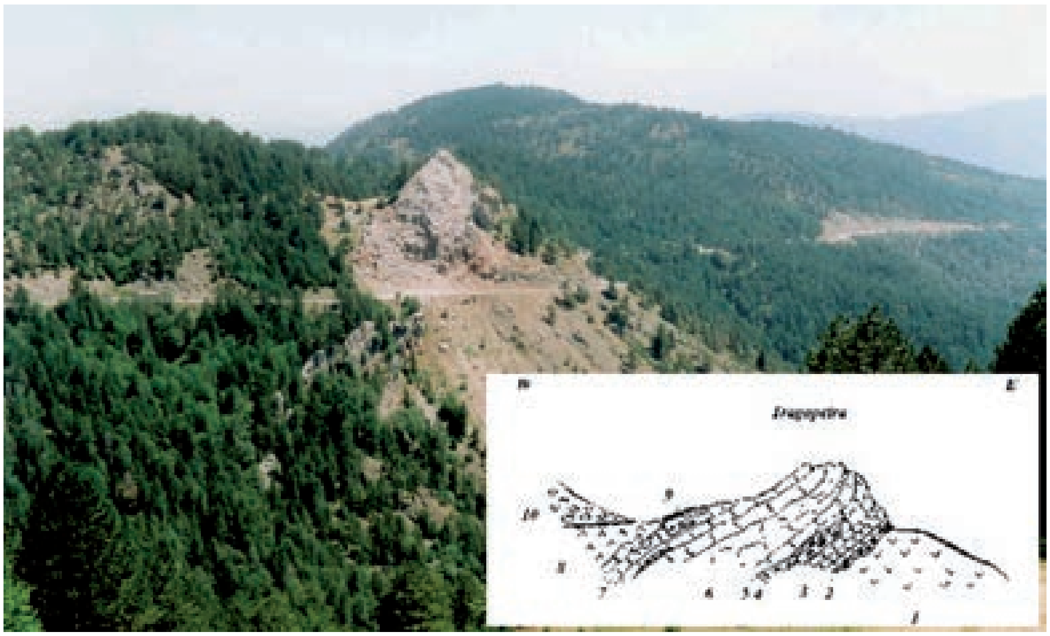

Figure 3. Tragopetra, photo and geological section.
Figura 3. *Tragopetra, fotogeografía y sección geológica.*

About a kilometre north of Tragopetra, at the "Tzina" site an array of outcrops begins, trending north. For details, see Argyriadis *et al.* (2010).

Central Pindos

Something similar can be observed at Vardousia Mountain, in the area of Artotina, about 6 km south of the village. In Arenta Mountain (1604 m), at a site, called "Melana Litharia", a serpentinized ophiolitic mass, covered northwards by transgressive limestone with *Globotruncana,* is tectonically placed between flysch formations.

This ophiolitic mass is constituted of serpentines, gabbros, pillow lavas, radiolarite, etc. Transgressive limestone, up to 25 m thick, becomes thinly bedded upwards and pink coloured ending up as pink-violet calcschists. This formation is intensively deformed and is under and simultaneously over a flysch formation. It is simply the case of tectonic insertion defined up and down by tectonic unconformities (Fig. 4). The subjacent flysch formation contains clastic material of ophiolitic origin. This indicates that the Pindos Zone and the Tethys ophiolites were in direct adjacency, and origin of Pindos is ultra-Parnassos. We should remember that the carbonic sedimentation goes up to the Eocene and the flysch begins afterwards in the Parnassos unit.

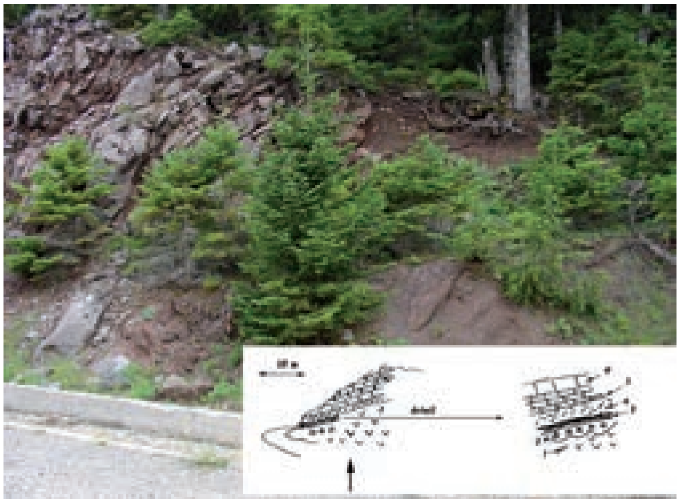

Figure 4. An outcrop of serpentine in "Melana Litharia" 300 m south from the previous outcrop. 1: serpentine, 2: breccias up to 20 cm thick, with limestone and ophiolite fragments, 3: Crust up to 5 cm thick of altered volcanic matrix 4: Altered volcanic rock up to 1 m thick, 5: thin plate limestone with *Globotruncana arca*, 6: white limestone with *Gl. arca* and *Gl.cf calcarata.*
Figura 4. *Afloramiento de serpentinita en "Melana Litharia" a 300 m al sur del afloramiento anterior. 1: Serpentinita, 2 Brechas de hasta 20 cm de espesor, con fragmentos de caliza y ofiolita, 3 Corteza de hasta 5 cm de espesor de matriz volcánica alterada 4: Rocas volcánicas alteradas de hasta 1 m de espesor, 5: Caliza laminar con* Globotruncana arca *6: caliza blanca con* Gl. arca *y* Gl.cf calcarata.

Ophiolites and emplacement

Finally it is possible to discuss the origin and building mechanisms of the ophiolites. This question is very important as the ophiolitic rock masses very often belong to the most important folded chains of our planet. This fact, which has long been recognised, was first interpreted as the result of magmatic (upper mantle) material intrusions through the crust (Suess 1902, Daly 1906, Haug 1921, Bowen 1927, Dubertret 1953). It is evident that it also concerns the alpine-mediterranean chains from which the Hellenides occupy a very particular place, as from the beginning they have been considered as "classic" theoretical examples. Of course, the intrusion theory about the ophiolitic masses also prevailed (Ami Boué, 1832, 1834, Becke 1878, Davi 1950, Deprat 1903, 1904, Hammer 1923, Hiessleitner 1951-52, Kossmat 1924, 1937, Lacroix 1898, Nopsca 1928, Petrascheck 1942, Philippson 1890, 1895, Steinmann 1926, Voreadis 1932, Wenck 1949). It is important to know that very early on many authors noticed that the ophiolitic masses were overthrusted (Reinhard 1911, Kober 1914, 1929, 1952, Renz 1940, Steinmann 1926) as some other authors stated that such masses were at the origin of some thermal-contact metamorphic phenomena (Deprat 1904, Lacroix 1895, Sossman, 1938). Finally, the underwater origin of the ophiolites has been long been stated, due to their association with some jasps and radiolarites (Brunn 1950, 1952, 1956, Hess 1938, Lemoine 1955, Paraskevopoulos 1948, Routhier 1945, 1946, 1954, Vuagnat 1952). What is the real situation?

For many years, J.H. Brunn formulated the theory of mantelic material effusion on the pre-orogenic platform (Brunn, 1950, 1952, 1956), then later, the differential crystallization of this magmatic ultra-alkaline material leading to the ophiolitic "mounts" as we can currently observe. This author mainly based his studies on the Vourinos ophiolites, such as those of Vermion and of northern Pindos, where and in the opinion of the same author, the ophiolites constitute some high style overthusts.

Since then, research in deep oceans has started and the evidence of the Atlantic Mid-Ocean Ridge and the discovery of the subduction zones as well as the establishment of the theory of plate tectonics. One of the results of this research was the formulation of "global plate tectonics". Of course, the ophiolites of the folded chains have been placed in this model, and their emplacement has been interpreted as the result of an overthrust of oceanic sea floors above the folded, or even metamorphosed formations of the so called chains (cf. Boccaletti *et al.,* 1971, Bortolotti *et al.,* 1969, Dewey *et al.,* 1973, Jackson *et al.,* 1975, Jones *et al.,* 1990, Moores 1969, Smith 1971, Vergely 1977, Zimmermann 1969...). Of course as with any up-to-date phenomenon, the interpretation has been processed a little bit too quickly, and as often happens, critical analysis of the possible mechanisms – mechanisms that followed "global plate tectonics" that should act always and everywhere – was only occupied by a simple word, "obduction" (Coleman, 1971). Many field surveys have given us the opportunity to control the facts in the places where they have been stated.

Vourinos

The study of the relationships between the Vourinos ophiolites and their basement is particularly significant at their southern borderline, in a very clear section which has been shown in the Aliakmon valley (Brunn 1956, Brunn *et al.,* 2001, Brunn *et al.* 2004, Argyriadis 2010, Argyriadis *et al.* 2010). The geological frame is the following:

- In the southern area, the Vounassa mountain, where northern border is made up of marble with an age which has been determined by some conodonts as Norian (Mavridis *et al.,* 1977). This marble dips deeply (N70°), on the eastern side of Aliakmon.
- At the summit of this marble it starts to contain some doleritic basalt interbeddings, with layers which are absolutely parallel to the marble stratification, whereas is some places, we can observe some dykes and microdykes through interbedded lava layers.
- Progressively, the marble layers are thinner and thinner, to be replaced by some calcshists, with centimetric alternances of lava and metatuff horizons. This horizon follows the river bed. An interesting but difficult of interpretation is the presence of the tufites, in some places some conglomerates lenses with peridotite pebbles and more rarely radiolarites.
- At the top of this series, the calcshists turn progressively into radiolarites, as the lava turns into "pillow-lava".
- Above, it is possible to observe some anphibolites (1 to 2 metres) in normal contact (not tectonic)

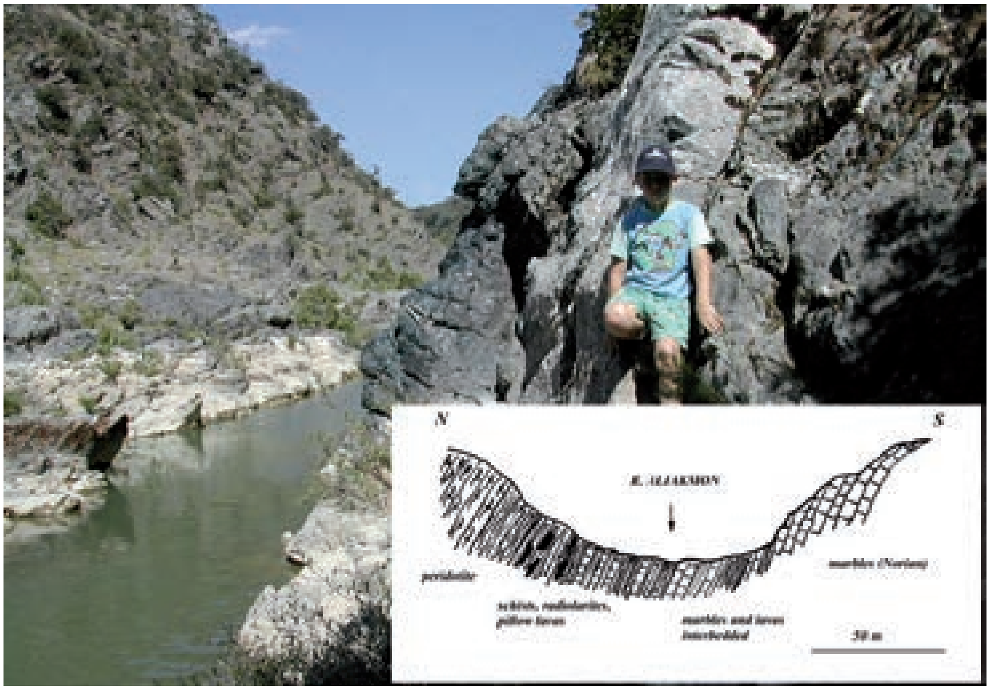

Figure 5. The Aliakmon river, photo and geological section. Lavas interbedded with Norian marble.
Figura 5. *Río Aliakmon, foto hacia el Este y corte geológico. El río tiene aproximadamente unos 20 m de ancho. Lavas intercaladas en mármoles norianos.*

with their basement, passing finally, always in normal contact, to the peridotite mass on top.

This remarkable section of the Aliakmon valley, slightly to the west of the Zabordas monastery, previously described by J.H. Brunn (1956), allows us to make the following important statements:

– First, the contact between the peridotites and the basement formations is absolutely normal, with no traces of any tectonic discontinuity.
– This contact is not tectonic and has the characteristics of a thermal contact (the presence of amphibolites with large hornblende crystals, hornfels and sometimes garnets.
– But the most important statement concerns the basement evolution: we can clearly observe that the arrival of the peridotites has been preceded by a progressive and systematic transition of a continental carbonatic platform, towards a marine environment more and more influenced by the volcanic and magmatic activities, which is a continuous transition from the initial dislocation of the platform until the emplacement of the ultra-alkaline rocks.

Vermion and extensions

The case described above is not local. In the northern part of the previous emplacement, at the western limits of Vermion mountain, and at the eastern side of the Ptolemaïs lignite basin, it is possible to make some similar observations. The known Aghios Dimitrios fold, uphill with respect to the village which has the same name, is made up of serpentine and marble. A closer observation shows us that it is an opened synform towards the south-west direction: the folded marble constitute a kind of hectometric to kilometric pocket, and pass in the upper part (nearly from the centre of the "pocket") to some schists and metatufites with some pillow lava interbedding with a thickness of around 25 metres, on which the serpentinized peridotite normally lies. It is exactly the same case as described above, the Vourinos.

A particular ''melange" under the Vourinos ophiolites

The very important ophiolitic mass of Vourinos (around 10 km thick) has been involved in the paroxysmal tangential tectonic from the Upper Jurassic to the end of the Cretaceous, then to the Upper Eocene. Sometimes it has been removed with a part of its basement, as a whole block (Zabordas, Vermion) but sometimes it reacted differently (differences in the rock density, differences of "competence") as for example in northern Pindos (Smolikas) but also in relation with the northern border of the Vourinos mass (Askion mount, Siatista region…). This differential behaviour resulted in the formation of a mechanic friction zone which can currently be observed in the field by the presence of some extremely crashed formations, consisting mainly of ophiolitic and volcanic material. It is a "melange" but the thickness is reduced in comparison with the thickness which characterizes the huge mylonitic zone described previously, and its significance is also more local. The two different formations, as well as the two phenomena should not be confused: the first has a global importance as it takes part in the fundamental mechanisms of the orogenesis, and the second one is only the local result of a density difference between the rocks which are involved in the orogenic movements.

Conclusion

Thanks to the observations that are reporeted in this paper, it has been possible to build a new interpretation of the alpine history and structure of the internal Hellenides. First of all, we will make a general observation on which all our conclusions are founded: the basic principle without which Geology would not be a science in contemporaneous terms, it is the principle of *actualism or uniformitarism* formulated by James Hutton (1795) and Charles Lyell (1830/33) and already stated by Strabon (1,3,10 C54). On the basis of this principle, we can observe that in the present world, the great geographic units (continental platforms, folded areas, rifts, oceans,..) have some common characteristics but can admit some variations and differences in the sedimentation details, in what concerns the exact age of the different tectonic and/or stratigraphic events. What can make the distinction are the general tendencies in their position and evolution. This is the reason why we should apply the same criteria in the distinction between the great paleogeographic units, without falling into the trap which consists of defining new units (or microplates as is the up-to date terminology) every time we observe a local or regional deviation compared to arbitrarily stated strict laws. At present what we can observe in the field:

– Mesozoic and infratertiary carbonate platform outcrops (Preapulian Gavrovo, Parnasse, Almyropotamos (in Euboea) areas, deep units of Hymette and Pentelique in Attica, Olympos marble, Kavala marble in eastern Macedonia (Drama unit, Argyriadis and Fourquin, 1987), Thasos and Limnos marble).

- Some outcrops correspond to a continental slope where the depth and sedimentation change in function of (paleo)areas (Pindos, Styra in Euboea, Hymette and Pentelique envelope in Attica, more or less dislocated "shreds" in Argolide, the Ethia series in Crete).
- Whole areas which present a "melange" (Argyriadis *et al.,* 2010), consisting of: crashed and mylotinised ophiolites with olivine phantoms, dislocated gabbros, pillow lava, decametric klippes of Pindos type, ophiolitic olisthostroms (Central Euboea, Argolide, Olympus tectonic cover), totally crashed and mylonitised dolomites or exploded carbonates (the region between Athens and Corinthos, Corinthie, Argolide) region south of Dirfys (Euboea).
- Some "melanges" vary from precedent, more restricted in extension and intensity of deformation (essentially under the Vourinos ophiolites).
- Some ancient olisthostroms (of middle Cretaceous?) consisting of rounded ophiolitic pebbles, (Kakoplevri between Kalambaka and Grevena, Vateroni in front of Vourinos, Asini in Argolide), the last two are in part participating in the great "melange".
- Some ultrabasites which constitute an "ophiolitic complex" according to J.H. Brunn (1956) ("subpelagonian" zone of the authors, Orthrys, Vourinos, Smolikas in northern Pindos, Kotziakas, then Vardar, ophiolites of Dadia and Therma in Thrace). These "tethysian" formations are transgressed by the Tithonic (Theopetra close to Trikala, Vermion) to Middle Cretaceous (Vourinos in Krappa, "sub-pelagonian" area, middle Euboea, Argolide), also sometimes by the upper Cretaceous (Upper Campanian to Maastichtian, septentrional Pindos and central Pindos in Artotina klippes). These tethysian ophiolites may well belong to the alpine Tethys, without presuming its exact origin: we think it was a megarift (a "tethysian crack", Argyriadis 1974, Argyriadis *et al.,* 1980) rather than an ocean *stricto sensu*. The nature is complicated, and it is not because we are currently focussing on the study of the oceans that any ultrabasic rock is an undiscussable index of the presence of a past ocean. Rifts that exist as the "outcrop" presence of mantelic material are not necessarily the evidence of an "ocean ridge process". The examples of the Black and Caspian sea floors are explicit from this point of view. The interpretation of the presence of ophiolites upwelling through a rift can be simply explained by their normal position on the Vourinos basement as in middle Euboea, and in the Kaz Dag region of occidental Anatolia. As the rift opens, warm, mantelic material rises up, and can recover the edges following a scheme which is close to what has been proposed by J.H. Brunn (1956).
- Some continental platform fragment formations are from an Upper Paleozoic without any hercynian discordance, as already proved, then a Trias of south-alpine type (Werfenian quartzites, Anisian massive nodular limestones, Carnian thin layered radiolarites – Ladinian, massive Norian limestones – Rhetian) then carbonatic Lias and Jurassic ("sub-pelagonian" area of French authors on Euboea, Chios, Argolide,..). It is with possibly the peri- hercynian platform. The stratigraphic record of this platform is not always complete, it can be crossed by a mantelic material upwelling (Vounassa under Vourinos such as the Askion mountains). These fragments are mostly overthrusted with ophiolites.
- Some outcrops belong to eurasiatic building, with or without hercynian discordance (in the Hellenides, essentially the Serbo-Macedonian mountain range and those of Sidironeron-Kerdyllia, central and oriental Macedonia) such as the Sredna Gora unit in the Rhodope of Bulgaria.

On this basis we can formulate the following proposal concerning the main structural lines:

The African paleoplatform (or Arabo-African) constitutes the "external" Hellenides margin. Its present prolongation is far under the most internal overthrusted areas, under the tethysian ophiolites but also under the real continental eurasiatic units (Olympos window, Godfriaux 1968, Drama unit, Argyriadis and Fourquin 1987)).

The slope which was on the Tethys edge of this platform has been repeatedly overthrusted during these paroxysmal regional phases (austro-alpine phase, Austrian, post-Gosau, Pyrenean and Laramian then ante-auversian phase). The problem with its present exterior position to Parnasse is not only one: the ophiolitic klippes which are present in its Paleocene flysch can definitely prove its ultra-Parnasse origin and its present position is only the typical result of a localized tectonic involution.

The tethysian ultrabasic rocks started to overthrust tectonically over the paleoafrican platform as soon as the Upper Jurassic (Dercourt

1970), before the austro-alpine phase, then by irregular phases until and within the ante-auversian phase. This wide thrust made up of mantelic material, pushed everything before it, extremely eroding and crashing all this material, even its "sole", its owns violent erosion products (olisthostromes) or slope fragments or even the platform. The enormous "melanges" (the terminology, proposed by Gansser (1974), is not satisfactory but there are no other terms) which are characterised by their relevant thickness, the "melange" of different kinds of material and the existence of real ultramylonites must not be confused with the much smaller "melanges" of simple tectonic crash layers under the Vourinos ophiolites. In fact, the tethysian ophiolites have not been displaced by themselves, but most of the time with their close sedimentary basement, the compression cannot make fine petrographic distinctions! Simply, between a sedimentary basement, mostly carbonated (Vourinos, Euboea) and the massive ophiolites, the density and competence of these rocks are not the same, then the peridotites "slumped" over the basement, generating these crashing areas of a violet colour but do not merit the name of "melange" as in the original sense of the term.

The eurasiatic margin followed the same way during the same phases, and covered as far as the Olympus region (Godfriaux, 1968). Anyway, exactly as in Pindos, the base contacts have been folded and refolded at each phase, so that, for example in Thrace, the Dadia ophiolites are currently over the Sidironenron unit, but are also covered by the Alexandroupolis, Vertiskos and Sredna Gora thrusts, similar to a "sandwich" between the eurasiatic units.

We can finally define the fundamental point of the Hellenides interpretation. The large paleogeographical areas with a relatively simple succession have been involved in numerous and extremely violent tectonic phases, with different directions, not always parallel to each other. The result is the present fragmentation, without the need of using microplate models and other kinds of artefacts which have no equivalent in nature. A condition that makes it possible to be able to distinguish what is essential from what is secondary.

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