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KINEMATIC ANALYSIS AND TERTIARY EVOLUTION OF THE PINDOS-VOURINOS OPHIOLITES (EPIRUS-WESTERN MACEDONIA, GREECE)

D.MOUNTRAKIS, A.KILIAS, N.ZOUROS*

ABSTRACT

The Pindos and Vourinos ophiolites are continuous at depth below the Meso-Hellenic Trough and represent fragments of the destroyed oceanic lithosphere of the Neo-Tethys. Kinematic analysis of the structures was carried out using shear criteria and kinematic indicators, in order to distinguish the successive events that affected both Pindos and Vourinos ophiolites. Field data, mainly striated faults, were computed using numerical methodologies (quantitative analysis) in an attempt to define the strain ellipsoid for each tectonic event.

Stretching lineations observed in the amphibolites of the Pindos metamorphic sole as well as in the Vourinos ophiolite and the underlying carbonates, are remnants of the initial emplacement of the ophiolites, but they are not associated with the significant kinematic indicators for the sense of the emplacement movement. Tertiary evolution started in Late Eocene times with a compressional event (maximum stress σ_1 axes ENE-WSW) which caused detachment, folding, thrusting and imbrication of the Pindos flysch before the emplacement of the ophiolite over the flysch. This was followed by an important extensional event (minimum σ_3 axes ENE-WSW) in Early Oligocene times, which caused a semi-ductile to brittle deformation in the area i.e. major extensional features in both ophiolites and flysch the emplacement of the ophiolites over the Pindos flysch and certainly the formation of the Meso-Hellenic Trough. Two younger successive compressional events, with the maximum stress axes trending E-W and N-S respectively, took place during the Middle-Late Miocene (the second probably evolutionary to the first). Some very important strike-slip and reverse faults are attributed to both events.

INTRODUCTION

Ophiolites and associated Mesozoic pelagic sediments occur on both sides of the Meso-Hellenic Trough in Northern Greece, known as Pindos and Vourinos-Kastoria ophiolites. The Pindos ophiolites are continuous at depth below the Meso-Hellenic Trough molassic sediments with the Vourinos and Kastoria ophiolites together forming a single ophiolitic mass (Smith 1979) of the Subpelagonian zone. The subpelagonian ophiolites represent fragments of the Neo-Tethyan oceanic

* Dept. of Geology and Phys. Geography, School of Geology, Aristotle University of Thessaloniki, 540 06, Hellas.

lithosphere which were emplaced on the western margin of the Pelagonian zone during Late Jurassic-Early Cretaceous times (Smith et al. 1979, Mountrakis 1983, 1986) and subsequently in the Tertiary, part of the Subpelagonian ophiolites emplaced over the Pindos flysch, forming the Pindos ophiolite (Brunn 1956, Aubouin 1959).

Although several studies have been carried out on the emplacement problem and origin of these ophiolites (Vergely, 1976, 1984, Mountrakis 1982, 1983, Kemp & McCaig 1984, Jones & Robertson 1991), some critical points concerning the post-Jurassic geological evolution remain uncertain, particularly the emplacement of the ophiolites on the Pindos flysch.

In this paper we present new field data on the Tertiary kinematics of both the Pindos and Vourinos ophiolites, based on the study of shear criteria and kinematic indicators, approaching the above mentioned problem of the emplacement of the ophiolites on the flysch.

The area of the present study is located in Western Macedonia and Eastern Epirus, including Mt. Vourinos and the Smolikas-Lyngos mountain range (fig. 1).

GEOLOGICAL FRAMEWORK OF THE PINDOS - VOURINOS OPHIOLITES

The Vourinos ophiolitic complex consists of serpentinized harzburgites and dunites, mafic and ultramafic cumulates, diorites, sheeted dikes and rare pillow lavas as well as amphibolites and metamorphic sediments parts of the sole (Moores 1969, Rassios et al. 1983). On the ophiolites lie Late Jurassic calpionellid limestones (Mavridis et al. 1977). An ophiolitic melange is observed in several places of the Vourinos ophiolites particularly along their contact with the carbonate rocks of triassic-jurassic age. The Vourinos ophiolite complex covers an area of about 200 Km^2 and its northern continuation is the Kastoria ophiolite which is an isolated ophiolitic outcrop. Both Vourinos and Kastoria ophiolites were emplaced on the western Pelagonian margin with a movement towards ENE as has been suggested by the structural analysis of folding (Mountrakis 1983, Vergely 1984, Roberts et al. 1988) although a different sense of movement towards SW and origin of the Axios oceanic areas has also been suggested (Zimmerman 1972, Vergely 1976). Recently, Jones and Robertson (1991) explained both Vourinos and Pindos ophiolites as an accreting couple emplaced over a flexural margin on the Pelagonian zone during an eastward subduction of the remnant Pindos ocean.

The Pindos ophiolite complex covers an area of about 2.000 Km^2 and consists of several tectonic units with the following rocks (Brunn 1956, Terry 1974, Kemp & McCaig 1985, Kostopoulos 1989, Rassios 1991, Jones & Robertson 1991): a) upper mantle peridotites, partly serpentinized, including mainly harzburgites, dunites, pyroxenites, gabbros and ultramafic cumulate rocks b) the metamorphic sole, composed of amphibolites, schists, meta-cherts, marbles and other meta-sediments c) mafic cumulates and basic volcanic rocks; gabbro, sheeted dikes, cumulates, massive lavas, pillow lavas and basic breccias d) deep sea sediments and turbidites; pelagic limestones, fine grained sandstones, calcarenites and micro breccias, shales, siltstones, green and red ribbon and nodular radiolarites e) Late Cretaceous neritic limestones f) a tectono-sedimentary melange comprising blocks of all the above mentioned lithologies as well as shales, sandstones and conglomerates of the underlying Tertiary flysch of the Pindos zone.

The tectonic melange tectonically lies under the Pindos ophiolite body and can be observed in many places along the tectonic contact between ophiolites and the flysch; i.e. Katara pass, Greveniti-Vovousa road, Laista village, (Zouros & Mountrakis 1990). It has a "chaotic" structure and recalls a "wild-flysch" formation. The matrix of the melange consists mainly of grey shales and sandstones in most cases completely sheared. Detached blocks of the ophiolites and the associated sediments such as thin bedded pelagic limestones, radiolarian cherts, but even Late Cretaceous neritic limestones with dimensions from centimetres up to several hundred meters, are observed within the matrix. The blocks are strongly tectonized and fault bounded. This tectonic melange is referred to as the "Perivoli Complex" by Kemp & McCaig (1985), or "Anilion Complex" by Lorsong (1977) and "Avdella melange" by Jones & Robertson (1991). It is also observed along the Upper Penios Valley (Papanikolaou et al. 1988). The tectonic melange is lithologically comparable with an analogous melange widespread in Albania (Mirdita zone) associated with the ophiolites (Shallo 1990).

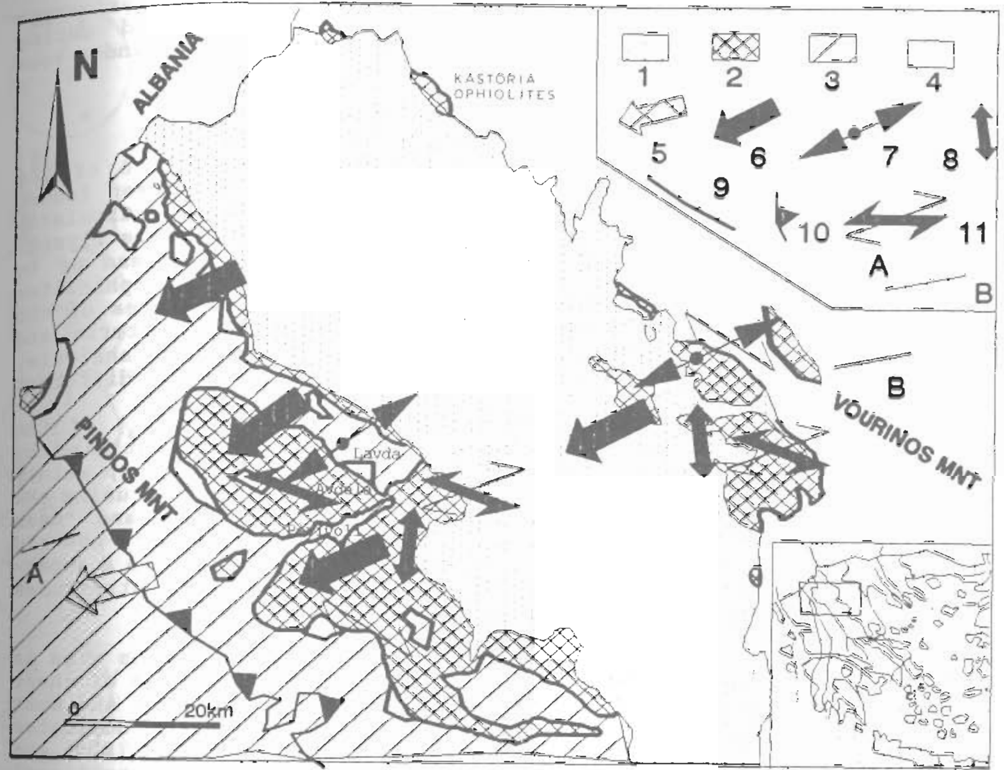

Figure 1. Sketch map showing the Tertiary kinematic evolution of the Pindos-Vourinos ophiolites 1) Molassic sediments of Meso-Hellenic trough, 2) ophiolites, 3) External Hellenides, 4) Pelagonian-Subpelagonian zones, 5-8) main movements during the tectonic events (5 in Late Eocene, 6 in Early Oligocene, 7-8 in Middle-Late Miocene), 9) tectonic contact, 10) thrust of Pindos nappe, 11) strike-slip movements and A-B) cross-section (fig.3).

In the eastern side of the Pindos ophiolitic body molassic-type sediments, of the Meso-Hellenic Trough were deposited during Oligocene-Early Miocene times over the ophiolites and the Pindos zone sediments.

GEOMETRY AND KINEMATIC ANALYSIS OF THE STRUCTURES

Since no clear evidence of the initial emplacement of the ophiolites onto the pelagonian continental margin have been found, we focus our investigation on the Tertiary tectonics, particularly approaching the emplacement of the ophiolites on the Pindos flysch. Field observations in both Vourinos and Pindos areas lead us to distinguish successive tectonic events that affected the ophiolites in Tertiary. Hence, we present below the tectonic features of the ophiolites, particularly the microstructures, shear criteria and kinematic indicators which have been used in the kinematic analysis, in order to understand the sense of movement during the different tectonic events.

To define the position of the main axes (σ_1, σ_2, σ_3) of the stress ellipsoid for each different tectonic event identified by tectonic analysis, we used quantitative analysis. The data, mainly striations from fault planes and shear zones, were computed using the method of "right-diedrons" (Angelier and Mechler 1977) and "mean stress tensor" (Carey and Brunier 1974, Angelier 1979) with the aid of the computer program "Fault" (Caputo 1989). For each site a separate computation was made for the different categories of structures (reverse, normal and strike-slip faults).

a) Vourinos area.

A key point for the kinematic analysis of the Vourinos area is a stretching lineation which is identified on the S-planes of shear structures in the ophiolites and seems to be the dominant and most important tectonic structure in the area. This lineation dominates in the western part of Vourinos ophiolites, trends ENE-WSW (80°) and constantly dips towards W. It is connected with typical extensional features inside the ophiolite body (photo 1a), suggesting that it was caused by a major extensional tectonic event. Micro-structures and other kinematic indicators in the shear structures were processed using quantitative analysis show direction of that extensional deformation ENE-WSE and sense of movement that is towards WSW (fig. 1). It is notable that similar extensional stretching lineation with an almost similar direction has also been observed in the Kranea windows under the Pelagonian nappe a few kilometres SE of the Vourinos area as well as in the Olympos-Ossa area (Kilias et al. 1991a, b). Beautiful pictures of such features are observed in the ultramafic cumulates along the roadcut near the village of Pilori (photo 1a). These fabrics show semi-ductile conditions of that extensional deformation.

However this tectonic event was also responsible for the large scale normal faults trending NW-SE in the area, in brittle conditions. Data from striated slicensides of these faults, mainly dipping towards SW, were computed and show that tensional axes σ_3 were almost horizontal, trending ENE-WSW while the compressional axes σ_1 were vertical (fig 2). This direction of the σ_3 coincides with the above mentioned extensional direction of the semi-ductile conditions belonging to the same event.

A notable lineation trending WNW-ESE (110°) was also observed on the S_1-schistosity planes in the eastern part of the Vourinos ophiolite, near the contact with the underlying marginal neritic limestones. The S_1-schistosity planes dip towards SSW (180°-220°/35°) and affect serpentinites, tuffs, dolerites, pelagic sediments of the

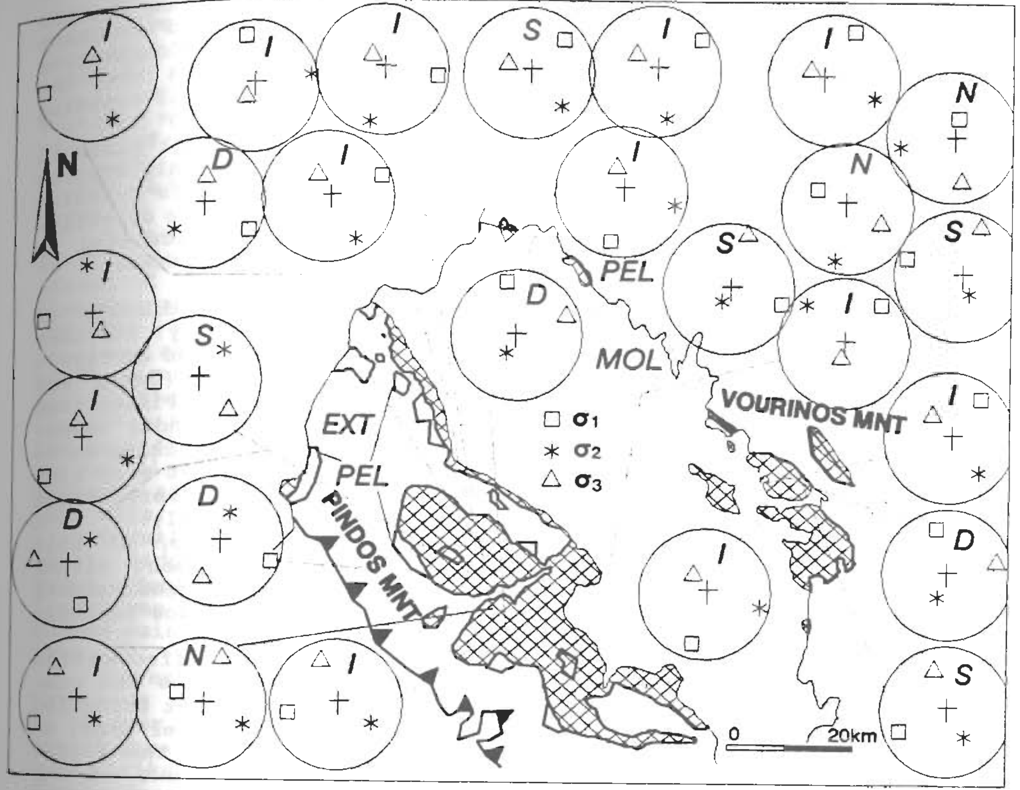

Figure 2. Diagrams with the results of strain analysis showing the position of the main axes (σ_1>σ_2>σ_3). Projection of the lower hemisphere I: reverse faults, D: dextral strike-slip faults, N: normal faults, S: sinistral strike-slip faults.

melange unit, and the underlying neritic Jurassic carbonates. Despite these indications of a possible relation of this lineation to the initial emplacement of the ophiolites, there is no clear evidence of kinematic indicators for the sense of the movement of the ophiolites over the carbonates. On the other hand this lineation along the contact between ophiolite and marginal carbonates has a WNW-ESE (110°) direction, similar to the WSW-ENE (80°) of the stretching lineation of the above mentioned extensional event and hence possibly a result of the same event. Thus the extensional event with the stretching lineation remains the most certain structure of the Vourinos ophiolite.

All the above mentioned structures of this extensional event have been affected by a younger compressional event, producing in the Vourinos ophiolite reverse faults trending NNW-SSE, mainly dipping towards ENE as well as antithetic ones dipping towards WSW. Kinematic indicators and shear criteria show the sense of movement to be towards ENE. The reverse faults accompanied by kink-bands with axes trending NW-SE. Additionally, some very important sinistral strike-slip faults trending NW-SE have also been caused by this compressional event (photo 2). All these structures show brittle conditions of deformation of this tectonic event and dominate particularly in the eastern part of the Vourinos complex. Computation of data from different sites within the complex, shows that the compressional axes σ_1 of this event were almost horizontal trending ENE-WSW (fig. 2).

Subsequently, a successive compressional event took place in the area and caused reverse faults trending E-W, and mainly dipping to the S. It also caused major dextral strike-slip faults trending WNW-ESE, particularly in the serpentinized peridotites. The direction of compression of this event was N-S (fig. 2) as calculated by computation of the striations on the reverse faults surfaces.

b) Pindos area.

The Pindos ophiolite complex rests over the sediments of Palaeocene-Late Eocene Pindos zone flysch. An Early Tertiary compressional event is reflected in the definite cessation of flysch sedimentation with the closure of the Pindos basin (Jones and Robertson, 1991). This event caused the detachment of the Pindos zone sediments, folding, thrusting and imbrication of the Pindos nappe. Numerous thrust sheets have been formed in the flysch, stacking each-other and trending NW-SE. To the same compressional event were also attributed folds with NW-SE axes (140°-160°), which are very common and increase near the thrust surfaces (Zouros et al. 1991).

The orientation of the principal stress axes σ_1 of this compressional event was ENE-WSW, with sense of movement either towards WSW or towards ENE, as calculated using field measurements of the microstructures on the thrust surfaces of the Pindos tectonic slices.

The imbrication of the Pindos flysch has not affected the Oligocene Molasse of the Meso-Hellenic Trough that dates the compressional tectonic event responsible for the thrust sheet formation to the Late Eocene (Brunn 1956, Aubouin 1959). On the other hand, no ophiolitic material is involved in the imbrication of the Pindos flysch suggesting a post-Eocene age for the emplacement of the ophiolites over the already imbricated Pindos flysch.

The general attitude of the contact between the ophiolites and the flysch seems to be horizontal to slightly dipping eastwards. This can be confirmed by a number of tectonic windows of the Pindos flysch behind the front of the overlying ophiolites. Typical extensional features inside the ophiolite complex and Pindos flysch are observed along their contact. Elongation of competent ultramafic bodies and asymmetric boudins of the oceanic sediments belonging to the whole ophiolite complex, as well as shear-deformed blocks of sandstones and rotated clasts of the Pindos flysch sediments (photo 1b, c, d) are typical extensional fabrics along their contact indicating an extensional semi-ductile deformation in both of them during the emplacement of the ophiolites over the flysch.

Since these extensional structures represent the first common deformation of both ophiolites and flysch, and they have been affected by the subsequent compressional tectonics in Late Tertiary times (see below), we conclude that an important extensional tectonic event was responsible for the emplacement of the ophiolites over the flysch and produced the above mentioned extensional fabrics. It took place in Early Oligocene times since the molasse sediments of Oligocene-Miocene age overlie the Pindos ophiolites.

The main movement direction of the ophiolites was westwards, (ranging from 250° to 290°), as is deduced from striations observed on the contact surface in many sites along the ophiolite front (i.e. villages of Perivoli, Laista, Greveniti-Flaburari road, Katara pass).

The emplacement of the ophiolites over the Pindos flysch caused a redeformation of the tectonic mélange along the ophiolitic front, i.e. near the villages of Perivoli and Flaburari. This melange was initially created during the Jurassic subduction-accretion evolution (Jones and Robertson, 1991) but probably redeformed during the Tertiary emplacement of the ophiolite complex over flysch. Detached blocks of serpentinites, basic volcanics, cherts and other oceanic sediments derived from the ophiolite complex are exposed within the flysch sediments along the contact between ophiolite complex and flysch.

In relation to the important extensional tectonic event there is a typical stretching lineation, which is identified on the S-planes of shear structures in both ophiolites and flysch. This is clearly connected with the extensional shear-structures and trends ENE-WSW (70°-80°), similarly to the lineation observed in the Vourinos area, and obviously belongs to that extensional tectonic event. A similar stretching lineation trending E-W is also observed within the amphibolites of the metamorphic sole in the River Loumnitsa near the village of Perivoli, but this could be related to the initial emplacement of the ophiolites onto the continental margin as was already described for the Vourinos area. However no shear criteria are observed in relation to this lineation in the metamorphic sole.

Normal faults within the ophiolite complex trending NNW-SSE and mainly dipping to the ENE are also related to the same extensional event. Tectonic striations of these slickensides and stretching lineations of the shear-structures were computed separately and showed coinciding axes σ_3 almost horizontal in the ENE-WSW direction (fig. 2).

The extensional structures of the Early Oligocene tectonic event have been affected by subsequent compressional structures belonging to younger, Late Tertiary events. Impressive strike-slip structures are of great importance for the structural evolution of the area. The main strike-slip faults generally trend NE-SW to ENE-WSW with dextral displacement, but some sinistral strike-slip faults trending NW-SE are also observed. A very important strike-slip structure could be considered as responsible for the Perivoli corridor, which is a NE-SW trending structure that divide the Pindos ophiolite into two parts although other explanations for this structure have been given as well (Kemp & McCaig 1985).

Associated NW-SE to NNW-SSE trending reverse faults have been observed at several sites with a direction of movement towards SW. Measurements of striations from the fault planes of all these structures computed separately show an ENE-WSW direction of the compression. Strong folding of the ophiolites and the associated pelagic sediments occurred during this compressional event. Red and green radiolarian cherts exhibit tight folds with NW-SE trending axes (150°).

Strike-slip shear zones might be responsible for local tilting of the normal succession, as in the River Lumnitsa area near the village of Perivoli, where the contact between peridotites and amphibolites is rotated to the vertical due to an E-W trending strike-slip zone. The shear sense can be confirmed in these sites by field observation of the rotation of the foliation (Boudier et al. 1988). A sinistral strike-slip fault, trending NW-SE (300°) is the contact between the amphibolites of the metamorphic sole and the underlying basic volcanics (dolerites) that fits well with the above criterion.

However the above described structures are confused in some places with some younger fault structures having almost similar trends but different orientations of the maximum stress axis. More precisely, these structures comprise WNW-ESE to WSW-ENE trending conjugate reverse faults as well as NW-SE trending strike-slip faults that show a dextral displacement and NE-SW trending sinistral ones. Dextral and sinistral faults intersect each other in some cases and seem to have been activated at the same time (photo 3, 4). Data selected from striated fault planes were processed separately in order to define the maximum stress axes. The compressional axes are oriented towards N-S and hence these structures either represent a subsequent compressional deformation in changing the axis of maximum stress from ENE-WSW to N-S, or belong to a completely new compressional event which took place later. These structures produced further internal imbrication of the ophiolite body. Minor reverse faults affect the metamorphic sole, cutting the vertical planes of S_1 schistosity of the amphibolites and hence these structures of the imbrication have to be later than the mechanism which made the S_1-planes vertical.

There are many sites where the superposition of the relatively younger N-S compressional structures on the relatively older ENE-WSW ones can be seen. For example, north of the village Avdela two superimposed sets of tectonic striations have been observed along the slickenside of a major fault zone in serpentinites. Another site is in the Aoos valley, north of the Aoos dam, where a NE-SW trending dextral strike-slip fault has been reactivated as a reverse fault.

TECTONIC EVOLUTION OF THE PINDOS-VOURINOS OPHIOLITES AND RELATED ZONES

Various successive tectonic events, responsible for the emplacement, folding, thrusting and imbrication of the Pindos and Vourinos ophiolites arise from our structural analysis.

Initially a regional compressional event caused the oceanic detachment and thrusting responsible for the metamorphic sole in the ophiolites (Kemp & McCaig 1985, Jones & Robertson 1991). Spray & Roddick (1980) propose a Mid-Jurassic age for the metamorphism by 40Ar/39Ar datings. In an evolutionary stage the ophiolites were obducted onto the western pelagonian continental margin, by an emplacement mechanism which, despite intensive studies during the last twenty years, remains uncertain, because no clear evidence of shear criteria and kinematic indicators have been found and the previous studies suggested the initial ophiolite emplacement have taken into account the dip of the ophiolite sheets or the structural analysis of folding (Vergely 1976, 1984, Smith et al. 1979, Mountrakis 1982, 1983).

In general the structures produced by these early tectonic events have been poorly preserved and have proved unidentifiable as younger structures have affected all the previous ones.

The stretching lineation observed in the amphibolites of the Pindos metamorphic sole and the lineation observed in both the Vourinos ophiolite and the underlying neritic carbonates are probably remnants of the initial emplacement structures, but they are not associated with significant kinematic indicators for the sense of movement. Thus, additional data are needed to define the precise conditions of the emplacement.

The transgressive Late Jurassic Calpionellid limestone over the Vourinos ophiolite (Mavrides et al. 1977) give a Late Jurassic (pre-Kimmeridgian) age for the initial ophiolite emplacement onto the western Pelagonian margin.

The Tertiary evolution in the Hellenides started in the Late Eocene with an important compressional tectonic event which caused

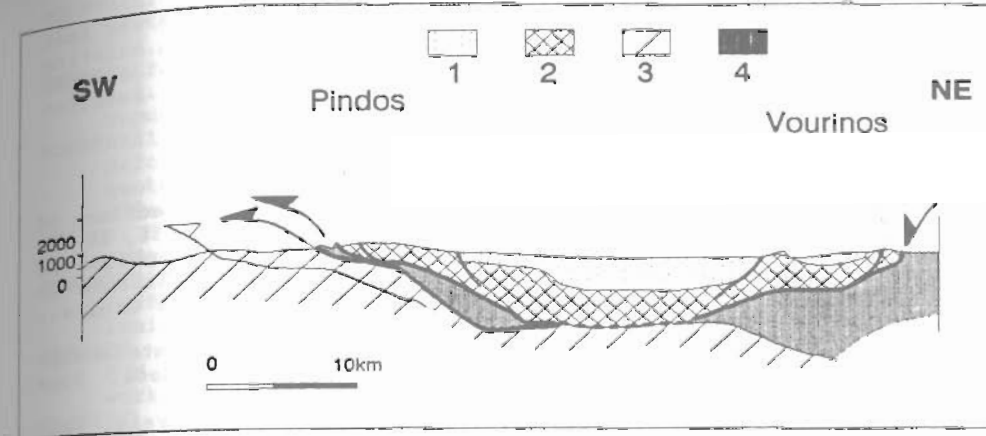

Figure 3. Schematic cross-section showing the Tertiary emplacement of the ophiolites over the Pindos flysch 1: molasse sediments, 2: ophiolites, 3: External Hellenides, 4: Pelagonian - Subpelagonian carbonates of Triassic-Jurassic age.

the final closure of the Pindos ocean, folding, thrusting and imbrication. The absence of ophiolite material in the imbrication of the Pindos flysch indicates that the emplacement of the ophiolites over the flysch is a later event.

Subsequently an important extensional event took place during the Early Oligocene and produced large scale normal faulting trending NNW - SSE in brittle conditions and other major extensional features, typical of semi-ductile conditions, which are very common within both ophiolites and Pindos flysch. The initial formation of the Meso-Hellenic Trough in NNW-SSE direction probably was connected with that faulting. Since the sediments of the Meso-Hellenic Trough overlie both Pindos and Vourinos ophiolites, the emplacement of the trailing edge of the ophiolites on the Pindos flysch took place during this extensional tectonic event in Early Oligocene times, slipping towards West (fig. 3). A similar age for this very important extensional event has also been suggested for both Northwestern Thessaly and the Olympos-Ossa areas (Kilias et al. 1991a, b).

Compressional deformation of the ophiolite bodies took place later, during a younger tectonic event with the maximum axes trending ENE-WSW. This event produced strike-slip and reverse faults (with thrust westwards and back-thrust movements), folding and imbrication within the ophiolites. Additionally during this event, the Triassic-Jurassic carbonates thrust on the molassic sediments at the eastern margin in the Meso-Hellenic Trough, near Kastoria (Mountrakis 1983), the Pindos slices thrust on the Early Miocene sediments of the Epirus-Acarnania synform and took their arcuate shape in the Politzes Mountains and finally the folding and imbrication of the Gavrovo and Ionian zones took place as well. The age of the youngest sediments of both the Epirus-Acarnania synform and the Meso-Hellenic Trough involved in the compressional process, suggest a Middle-Late Miocene age for this compressional event.

A subsequent compressional event with the maximum stress axes trending N-S produced reverse conjugate low angle faults and strike-slip faults, and caused further imbrication and folding of all the above mentioned tectonic units.

The change in the direction of maximum stress axes of the last event, arising from structural analysis, fit well with the existing palaeomagnetic results for Western Greece suggesting a 60° counterclockwise rotation of the stress pattern due to clockwise rotation of the structures (Kissel et al. 1985).

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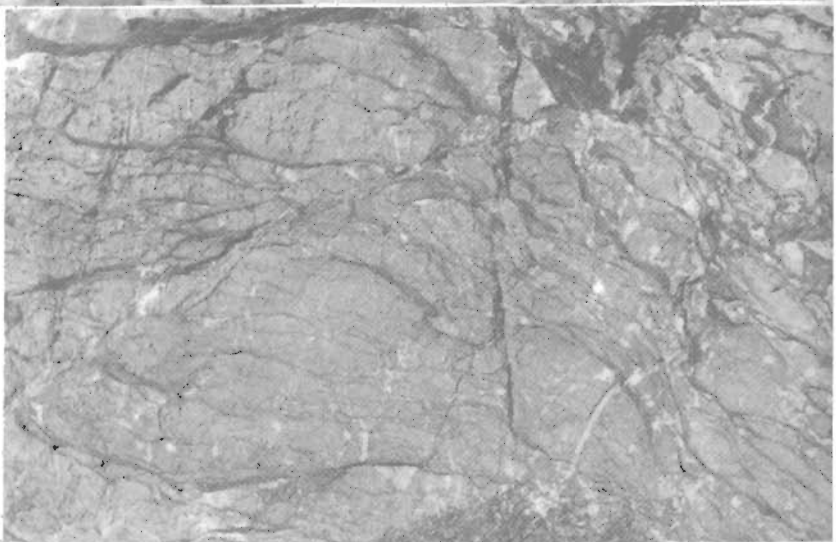
Captions of the photos

Photo 1. Semi-ductile deformation of the Early Oligocene extensional tectonic event. (a) Vourinos ophiolite. Elongation of ultramafic bodies and asymmetric boudins near the Village of Perivoli. (b) and (c) emplacement of the Pindos ophiolite complex over Tertiary Pindos flysch, associated with typical extensional fabrics, asymmetric boudins and rottated clasts, showing sense of movement westwards. Village of Perivoli.

Photo 2. Sinistral strike-slip fault trending NW-SE, associated with folds, due to the Middle-Late Miocene compressional event, Vourinos ophiolite, Agios Nikolaos valley.

Photo 3. Strike-slip faults intersecting each-other during the last compressive event, N-S trending. Oceanic sediments associated with the Pindos ophiolite, village of Perivoli.

Photo 4. A reverse fault trending E-W, associated with shear criteria, of the last compressive tectonic event (N-S direction) in the Pindos ophiolite, village of Avdela.



4