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POST EMPLACEMENT TECTONICS AND KINEMATIC ANALYSIS OF THE ALBANIAN OPHIOLITES

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ABSTRACT

The Albanian ophiolites, which represent fragments of the destroyed Neo-Tethyan lithosphere, occupy the Mirdita zone and its boundary with the Krasta-Cukali zone, which are the northern extension respectively of the Subpelagonian and Pindos zones of Greece. New field data, concerning structural features of the ophiolites and based on shear criteria and kinematic indicators, were used in the kinematic analysis in order to distinguish different tectonic events, particularly in the post-emplacement tectonic history of the Albanian ophiolites. Numerical methods have also been used in the palaeo-stress analysis in order to define the position of the main axes of the stress elipsoid during these tectonic events.

Although the structures of the initial emplacement are poorly preserved in the ophiolites, a well defined stretching lineation, trending NW-SE was observed in the metamorphic sole. This represents an early tectonic event (D_0), possibly related to the emplacement mechanism but without a clear connection with kinematic indicators for the sense of emplacement movement. An important compressional event (D_1), with horizontal σ_1 axes in the ENE-WSW direction, caused an intensive imbrication of the Krasta-Cukali zone in the Late Eocene, before the tectonic emplacement of the ophiolites over the Krasta-Cukali flysch. An extensional tectonic event (D_2) affected the ophiolites in the Tertiary times with tensional axis σ_3 trending E-W to ENE-WSW. It prodused extensional shear structures in semi-ductile to brittle conditions in the ophiolites and the tectonic emplacement of the latter over the Krasta-Cukali flysch with sense of movement towards WSW, in the Early Oligocene after flysch imbrication. The D_3-tectonic event of the ophiolites was compressional with maximum σ_1-axes horizontal trending ENE-WSW. It took place in the Middle-Late Miocene and produced mainly sinistral strike-slip faults (NW-SE) and conjurate thrust and back-thrust structures (NNW-SSE). The orientation of the main axes of the strain elipsoid changed later in the Late Miocene during an evolutionary compressional D_4-tectonic event, with σ_1-axis almost horizontal in the N-S direction, which caused further imbrication in both ophiolites and Krasta-Cukali sediments.

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INTRODUCTION

Since all plate tectonic models proposed for the evolution of the Eastern Mediterranean are related to the location of Tethys, the role of the ophiolites representing remnants of the Tethyan oceanic crust has been particularly emphasized.

The ophiolitic outcrops in the Balkan peninsula for the most authors are distributed along two main ophiolitic sutures: The internal (IRO) along the Axios zone in Greece and Vardar zone in Yugoslavia, and the external (ERO) along the Subpelagonian and Pindos zones in Greece extending norhtwards to the Mirdita zone in Albania and in between the Serbe and Golija zones in Yugoslavia. Hence, there is a clear connection between Subpelagonian zone in Greece and the Mirdita zone, which is the main ophiolitic zone in Albania located between the Internal and External Albanides zones (fig. 1). More precisely, the Albanian ophiolites occupy the Mirdita zone and its boundary with the Krasta-Cukali zone (Shallo et al. 1985, Kodra 1987, 1988), which is the northern extension of the Pindos zone in Greece.

Thus, the geological setting of the ERO ophiolitic suture and surrounding units are similar in Greece and Albania and hence ophiolite investigation in both countries contributes to the geodynamic interpretation of the Eastern Mediterranean region. Although several studies have been carried out on the emplacement problem and origine of the ERO ophiolites (Vergely 1976, 1984, Smith et al 1979, Shallo et al. 1987, Kodra and Bushati 1991, Karamata 1980, Mountrakis 1982, 1983, Jones and Robertson 1991, Qirinxhi A. 1991, and others) the post-emplacement deformations of the ophiolites have not been sufficiently investigated to date. We believe that many structural features which have been attributed to the initial emplacement of the ophiolites in fact took place later during the structural evolution of the continental margins.

In this paper we present new field data on the post-emplacement tectonics of the Albanian ophiolites, based on the study of shear criteria and kinematic indicators.

GEOLOGICAL FRAMEWORK OF THE ALBANIAN OPHIOLITES

The Albanian ophiolites cover an area of about 4000 km^2 in the Mirdita zone and they are in tectonic contact with Triassic-Jurassic carbonates along the eastern and western Mirdita boundaries. The Eastern ophiolites, situated in the eastern part of Mirdita zone, consist from the base to the top, of the ultrabasic series (harzburgites, dunites, pyroxenites, wherlites), the gabro-plagiogranitic series, the dyke swarm series, the pillow basalts and andesitic - dacitic volcanics. The Western ophiolites consist of ultramafic tectonites (mainly harzburgite - lherzolites), ultramafic cumulates, troctolites, gabros and the basaltic pillow lavas. Radiolarian cherts of Kimmerigian - Tithonian age and flysch sediments of Tithonian-Berriasian age cover both Eastern and Western ophiolites (Shallo et al. 1987). Homogeneous and heterogeneous ophiolitic melanges are located together with the flysch-sediments on the ophiolites (Melo and Kote 1973, Shallo et al. 1980, 1985, Kodra 1987, 1988, Shallo 1990).

The age of the Albanian ophiolites can be inferred from the earliest age of their sedimentary cover, which consists of Kimmeridgian radiolarian cherts and Tithonian-Berriasian flysch, as well as from the correlation with the Late Liassic-Malm pelagic carbonates at the top of the carbonate platform. Additional absolute datings of phlogopitites in ultrabasic rocks indicate an age of 188 ± 6 million years. From these data a Middle-Late Jurassic age is inferred (Shallo et al. 1985, 1987).

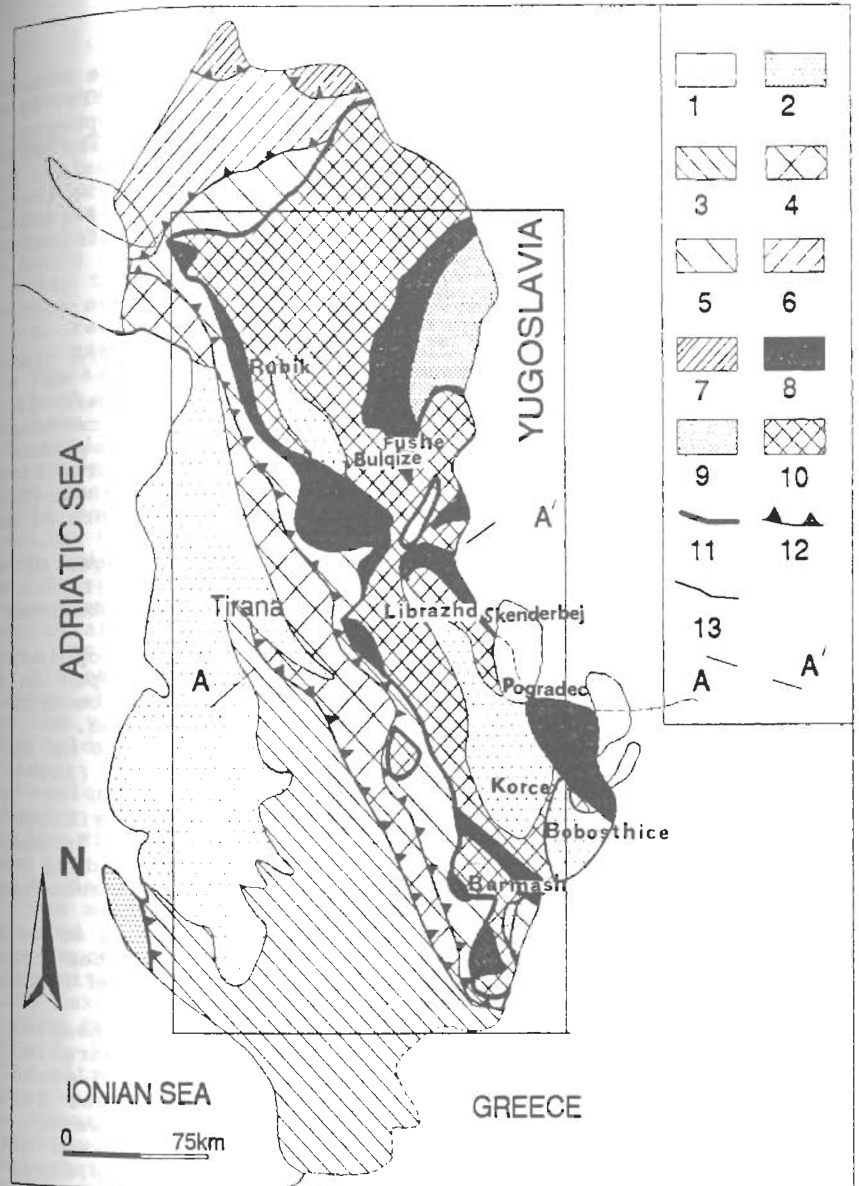

Figure 1. Geological sketch map of Albania (After the Geological and Tectonic map of Albania, scale 1:200.000, 1983, 1985). 1. Molasse sediments, 2. Sazani zone, 3. Ionian zone, 4. Kruja zone, 5. Krasta-Cukali zone, 6. Zone of the Albanian Alps, 7. Gashi zone, 8. Triassic-Jurassic carbonates of the Internal Albanides, 9. Palaeozoic basement of Korab zone, 10. Mirdita zone (Ophiolites and Jurassic-Late Cretaceous sediments), 11. Tectonic contact of the ophiolites, 12. Thrust, 13. Sedimentary contact, A-A' Cross section.phlogopitites in ultrabasic rocks indicate an age of 188 ± 6 million years. From these data a Middle-Late Jurassic age is inferred (Shallo et al. 1985, 1987).

Regarding the structural position and origin of the Albanian ophiolites the following views have recently been put forward: 1) The ophiolites are autochthonous in the present position, representing fragments of a palaeo-ocean west of the Korab zone (Shallo et al. 1987, Kodra and Bushati 1991), they have emplaced in the western part of the Korab zone and are found in a normal fault tectonic contact with the pelagic carbonate sequence. 2) They are totally allochthonous coming from Axios - Vardar zone as interpreted by Qirinxhi et al (1991).

REMARKS ON THE EMPLACEMENT PROBLEM

Despite intensive research along the contact between the Midrita ophiolites and Triassic-Jurassic carbonates in order to find structures associated with the initial emplacement, there is no evidence for this Late Jurassic tectonic event. The carbonates posibly represent the continental margin sedimentary sequence on which the ophiolites were emplaced. Hence, the microstructures within the ophiolites along the contact might show significant indications of the emplacement mechanism. However no kinematic indicators of such a movement have been observed.

The only microstructure related to the initial stages of the ophiolite structural evolution is a stretching lineation (L_1) in the amphibolites of the metamorphic sole. This lineation is observed in the following localities of the metamorphic sole:

a) East of Skenderbej village, along the contact between ophiolites and Triassic limestones, a penetrative schistosity developed in the amphibolites of the sole. On these S-planes dipping 60° towards NE a clear stretching lineation trending NW-SE has been found.

b) In Central Albania, near the town of Bulqize (about 30 km NE of Tirana) a similar stretching lineation trending NNW-SSE (350°) is also observed in the amphibolites of the metamorphic sole.

c) In Southern Albania, 6 Km south of Korce, near the village of Boboshtice, there is a large outcrop of metamorphic rocks including amphibolites and metasediments. A stretching lineation trending NW-SE (300°) was observed on the S-planes dipping NE. Microfolds associated with these structures have also been observed (photo 1).

d) Further to the south near the village of Barmash, about 40 km SSW of Korce, similar stretching lineation in the amphibolites trends 340°, almost parallel to the contact between ophiolites and Triassic carbonates.

In all cases the orientation of the stretching lineation L_1 remains constant NW-SE and in two areas (a,d) it trends parallel to the ophiolite and carbonate contact. Hence this lineation could be related to the emplacement of the ophiolites since it was formed during the metamorphic process of the metamorphic sole. However, the latter, including metabasites of the ophiolitic complex and metasediments of its associated oceanic sequence, has been explained in Greek ophiolites as the result of an intraoceanic subduction in Jurassic times (Kemp and McCaig 1985, Jones and Robertson 1991). Thus, the possible relation between the formation of the stretching lineation during the intraoceanic subduction and the date and mechanism of the emplacement of the Albanian ophiolites onto the continental margin remains uncertain.

On the other hand no shear criteria or kinematic indicators related to this lineation have been observed. Probably the younger structures belonging to the posterior (Tertiary) tectonic events affected those of Jurassic-Cretaceous age and destroyed them.

It is clear that further investigation of the possible relation between intraoceanic subduction and emplacement of the ophiolites onto the continental margin is needed in order to understand the emplacement mechanism and direction of movement.

TERTIARY STRUCTURES: GEOMETRY AND KINEMATIC ANALYSIS

We present the tectonic features of the Albanian ophiolites and particularly the shear criteria and significant kinematic indicators along with foot-and-hanging wall microstructures and striations of the fault surfaces, which have been used in the kinematic analysis, in order to understand the sence of movement during the different tectonic events (fig. 2).

a. Tectonic features at the western front of the ophiolites. First tectonic event - D_1.

The Albanian ophiolites in several areas of their western margin have been emplaced over Tertiary flysch sediments of the Krasta-Cukali zone (I.S.P.Gj. - I.Gj.N. 1983, I.S.P.Gj. - I.Gj.N. - F.Gj.-M. 1985, Shallo 1991). The latter forms a nappe thrusting westwards and is composed of Mesozoic pelagic sediments and Tertiary flysch in thrust sheets dipping towards E. This imbrication of the Krasta--Cukali zone was created during a compressional event in the E-W direction before the tectonic emplacement of the ophiolites over the flysch, since the ophiolites are absent from the Krasta sheets. A Late Eocene age for the tectonic event responsible for the imbrication of the Krasta-Cukali flysch has already been suggested since it affected Eocene flysch sediments (Melo et al. 1991, Shallo et al. 1991).

Almost vertical bedding planes in the Krasta sediments are observed at the front of the tectonic slices in the area of river Mat near the village of Plane (Northern Albania). Strongly disharmonic tight folds with NNW-SSE B-axes and axial planes coinciding with the vertical bedding are also the result of this Late Eocene compressional event. These structures have been affected by the posterior compressional tectonic features, which were the result of the Late Miocene events (see below) in the ENE-WSW and N-S directions (fig. 2).

b. Second tectonic event - D_2.

The most impressive structures in all Albanian ophiolites are major and minor extensional tectonic features which are the result of an important post-emplacement extensional tectonic event. North of the city of Pogradeci, the serpentinites of the ophiolitic mass beside Lake Ohrid, present a well developed L_2 stretching lineation trending ENE-WSW on S_1-planes lightly dipping SE. A similar direction of the L_2 lineation was also observed near the village Fushe-Bulqize in the ultramafics along the contact with Triassic limestones as well as in the ophiolites SW of Korce. In all cases the L_2 is associated with minor typical extensional features in the serpentinites i.e. shear structures, elongation of competent ultramafic bodies along the L_2 orientation etc. (photos 2, 3). All these fabrics indicate a semi--ductile deformation in the ophiolites. Kinematic indicators observed in the shear microstructures show a sense of movement towards W or WSW (fig. 2).

Large scale normal faults, trending NNW-SSE and steeply dipping WSW along the contact between ophiolites and Triassic carbonates, observed near the village Fushe-Bulqize and the villages Rajce and Skenderbej (photo 4) are probably connected with this extensional tectonic event, although they show a small but significant sinistral strike-slip component as well. All these normal faults are associated with extensional minor features and the shear criteria show a WSW sense of movement. Shallo (1990) has described the creation of a faulted horst-graben topography for the ophiolites and peripheral

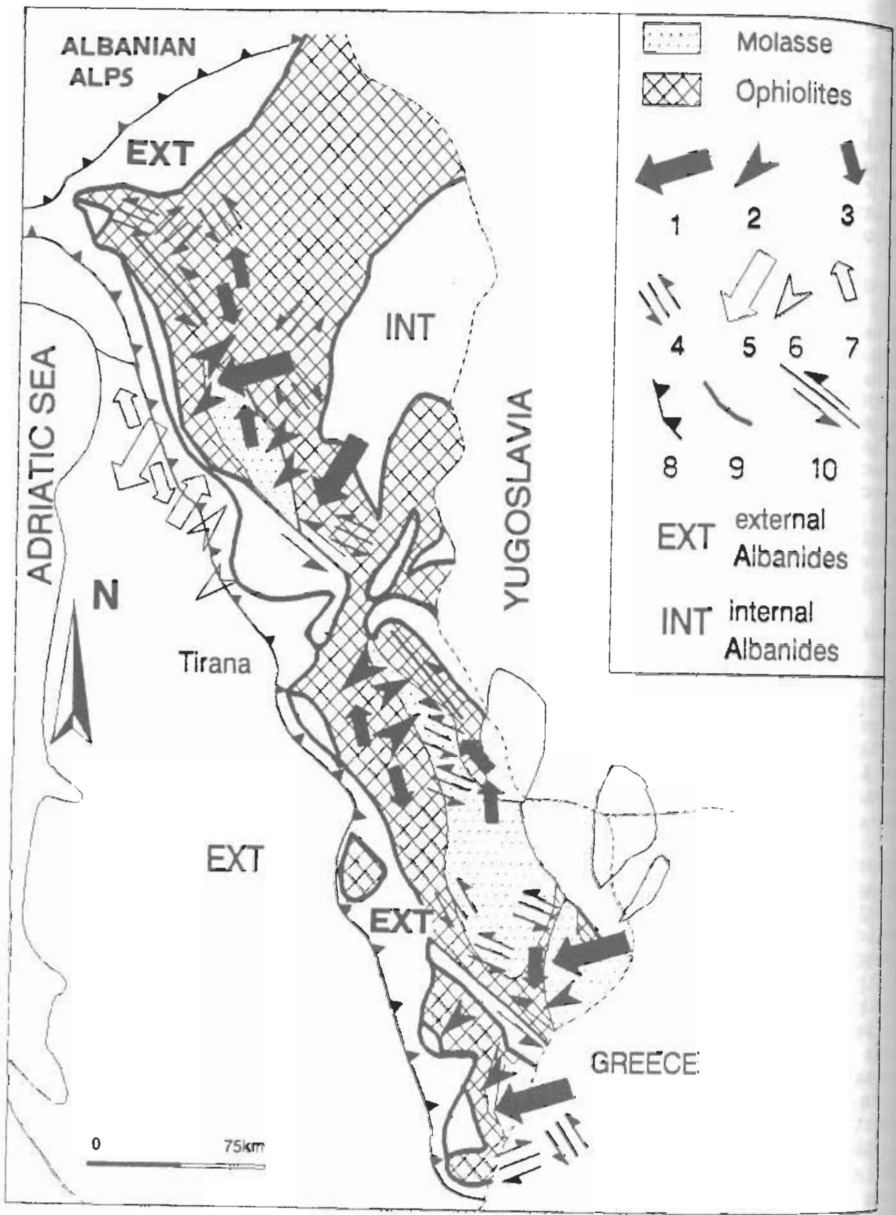

Figure 2. Sketch map showing the Tertiary kinematic evolution of the Albanian ophiolites. 1-3: Main movements during the Tertiary tectonic events in the Albanian ophiolites [1. Early Oligocene (D_2), 2-3. Late Miocene (D_3, D_4)], 4. Strike-slip shear zones, 5-7: Main movements during the compressional tectonic events in the External Albanides [5. Late Eocene (D_1), 6. Late Miocene (D_3), 7. Late Miocene (D_4)], 8. Thrust fault, 9. Tectonic contact of the ophiolites, 10. Major strike-slip faults.

carbonates, taking into consideration the above mentioned normal faults, and suggested a model for the autochthonous fragmentary uplift of the ophiolites during Tithonian age.

c. Third tectonic event - D_3

A younger compressional event later influenced the previous extensional features in the Albanian ophiolites. Large scale and mesoscale sinistral strike-slip faults trending NW-SE and minor ENE-WSW trending dextral strike-slip faults as well as reverse faults trending NNW-SSE and dipping towards ENE or WSW are the result of this compressional event in the general ENE-WSW direction in brittle conditions (fig. 2).

Kinematic indicators and shear criteria observed along the reverse faults and within significant shear zones show the sense of movement mainly towards WSW but in some places towards ENE as well.

In the southwestern part of the ophiolites (SW of Korce), as well as in central Albania (W of Bulqize) and in the area of Rajce-Skenderbei vilages (photos 5, 6), the sinistral strike-slip faults (NW-SE) are the dominant structures and define the external ophiolitic contact with Triassic-Jurassic limestones. In the area West of the village of Barmash (Southern Albania), these strike-slip faults affect both ophiolites, Triassic limestones and the underlying Tertiary flysch of the Krasta zone, suggesting that these faults belong to a tectonic event that took place after the thrust of the Mirdita zone over the Krasta zone in Tertiary times. Microfolds with axes trending NW, observed in the sediments associated with the ophiolites in the Mirdita zone, probably belong to the same compressional event.

Thrust surfaces with sense of shear towards WSW are well exposed between the villages of Rajce and Skenderbei, while in the peridotites along the road between Bulqize and Fushe-Bulqize examples of both types of movement towards ENE and WSW in conjugate low angle reverse faults, trending NNW-SSE, are observed.

Conjugate sinistral strike-slip faults trending NW-SE and dextral strike-slip trending NE-SW caused during this compressional event are observed in the serpentinites of the Pogradeci area. The striations on the slickensides are superimposed on others produced during the previous D_1 extensional event. Additionaly, in the area near the town of Rubik, there is the clearest evidence of a posterior age for the above described compressional event in relation to the D_1 extensional tectonic event. Normal faults with a N-S trend due to the extensional event have been affected by the relatively younger sinistral strike-slip faults, trending NW-SE, of the D_2 compressional event.

Conjugate thrust and back-thrust stuctures are very common, particularly in Central Albania. A very significant back-thrust of the ophiolites over Middle-Late Miocene molassic sediments has been observed near the town of Librazhd, 40 Km WSW of Tirana, along a NNW-SSE reverse fault dipping WSW, which is connected in the same location with dextral strike-slip mesoscale faults trending ENE-WSW. Both of these belong to the ENE-WSW compressional event. Thus, a Late Miocene age is very possible for this compressive event.

Similar thrust and back-thrust structures of this compressional event-D_3 are also observed in the sediments (Cretaceous limestones and Tertiary flych) of the Krasta-Cukali zone (photo 7) at the western front of the ophiolites since it certainly was affected by the D_3-event.

d. Fourth tectonic event - D_4

A successive compressional event affected the ophiolites and caused reverse faults trending E-W to ENE-WSW mainly dipping to the S (photo 8), and sinistral strike-slip faults trending NE-SW. The direction of this compressive deformation has been calculated from field measurements as N-S (fig. 2). The reverse faults trending E-W have affected the previous sinistral strike-slip faults trending

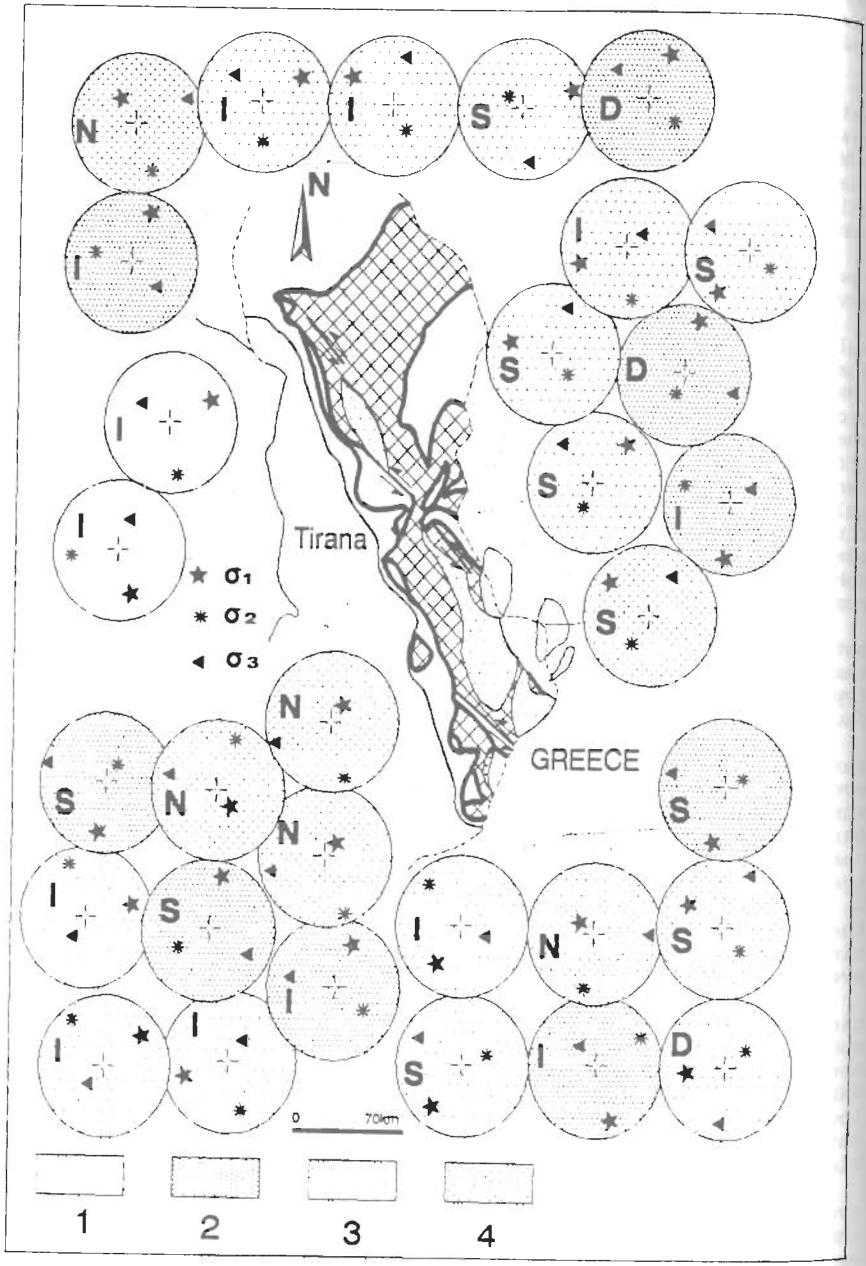

Figure 3. Diagrams with the results of paleo-stress analysis (Lower hemisphere projection). I: reverse faults, D: dextral strike-slip faults, N: Normal faults, S: sinistral strike-slip faults. Tertiary tectonic events of the Albanian ophiolites: 1. D_2 - extensional event (Early Oligocene), 2. D_3 - compressional event (Late Miocene), 3. D_4 - compressional event (Late Miocene), 4. Compressional events of the External Albanides (D_1 - Late Eocene, D_3 Late Miocene, D_4 - Late Miocene).

NW-SE in the area of Rubic.

A very interesting structural feature has been observed near the village of Boboshtice, south of Korce, in the metamorphic sole. Two parallel fault surfaces trending NW-SE and dipping NE (70°), very close to each other (2-3 m) contain tectonic striations and other shear criteria showing both dextral and sinistral sense of movement caused by two different compressional events in ENE-WSW direction the D_3 and in N-S the D_4 event.

Important compressional features of this D_4 tectonic event are also observed at the western front of the ophiolites, affecting the Krasta-Cukali sediments. Thus, low angle reverse faults dipping northwards and open folds with B-axes trending E-W affected the previous Krasta-Cukali thrust sheets, which have been caused during the First - D_1 event in Late Eocene times.

PALAEO-STRESS ANALYSIS (fig.3)

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).

Analysis of the collected data (fig. 3) allows us to distinguish the following successive tectonic events which affected both the Albanian ophiolites and Krasta-Cukali sediments in the Tertiary and confirms the field observations on the superimposed microstructures suggesting succesive deformations.

Thus, elaboration of the tectonic measurements on the compressive features associated with the imbrication of the Krasta-Cukali zone gave a horizontal σ_1 axis in the ENE-WSW direction during a D_1 compressional event in Late Eocene times (fig. 3).

The posterior extensional tectonic event (D_2) is the first post-emplacement event in all the Albanian ophiolites. Computation of measurements of striations along the slickensides of N-S to NNW-SSE trending normal faults, some of which include a significant sinistral strike-slip component, show that tensional axes σ_3 were almost horizontal during this event, trending ENE-WSW. The compressional axes σ_1 were in most cases sub-vertical and only rarely dipped towards NNW at an angle of 30° to 35° for the faults with the strike-slip component. The intermediate axes (σ_2) during the same event were generaly horizontal trending NNW-SSE and sub-vertical in the cases of strike-slip component.

The younger compressional tectonic event (D_3) caused reverse and strike-slip faults in the ophiolites. The maximum (σ_1) axes remained constantly sub-horizontal during this event, trending ENE-WSW. For the reverse faults the σ_3 were sub-vertical and the σ_2 trended NNW-SSE, dipping towards NNW or SSE. For the strike-slip faults, sinistral and dextral, of the same compressional event the σ_3 remained sub-horizontal trending NNW-SSE, and the σ_2 became vertical.

The orientation of the main axes of the strain elipsoid changed later during a successive compressional event (D_4) in both ophiolites and Krasta-Cukali sediments involving compression in the N-S direction. The σ_1 were almost horizontal in the N-S general direction, ranging from 350° to 25°. Reverse faults show that the σ_2 trended E-W and the σ_3 were sub-vertical while for the strike-slip faults the σ_3 trended E-W to ESE-WNW and the σ_2 were sub-vertical.

TECTONIC EVOLUTION OF THE ALBANIAN OPHIOLITES.

The evolution of the Albanian ophiolites comprises successive tectonic events which were responsible for their emplacement, thrusting and definitive deformation. A widespread regional geodynamic event caused the oceanic detachment in the Neo-Tethys ocean during the Mid-Jurassic that is responsible for the metamorphic sole in the ophiolites (Kemp & McCaig 1984, Jones & Robertson 1991). In an evolutionary stage the ophiolites were obducted onto the carbonate sequence of the continental margin by an emplacement mechanism which remains uncertain despite the intensive studies during last twenty years both in Greece and Albania (Vergely 1976, 1984, Smith et al 1979, Mountrakis 1982, 1983, Shallo et al. 1985, Shallo 1990, Jones & Robertson 1991). The stretching lineation L_1 trending NW-SE observed in the metamorphic sole in several parts of the Albanian ophiolites is probably a remnant of the initial tectonic event D_0, but no significant kinematic indicators for the sense of movement have been found. Thus, additional data are needed in order to understand the emplacement mechanism and direction of movement.

However, in the Tertiary, successive tectonic events deformed both ophiolites and surrounding geological units. Using critical observations on superimposed sets of tectonic striations along slickensides of the faults affecting each other, we suggest the following succession of the Tertiary events. An important compressional tectonic event D_1 with a horizontal σ_1 axis in the ENE-WSW direction took place in the Krasta-Cukali zone before the tectonic emplacement of the ophiolites over the Krasta-Cucali flysch and produced folding, thrusting and imbrication of the latter. The sense of movement was towards WSW (fig. 4). The age of that event has been defined as Late Eocene.

An extensional D_2 tectonic event with tensional axis σ_3 trending E-W to ENE-WSW produced extensional shear structures and a L_2 stretching lineation in semi-ductile conditions in the depth and

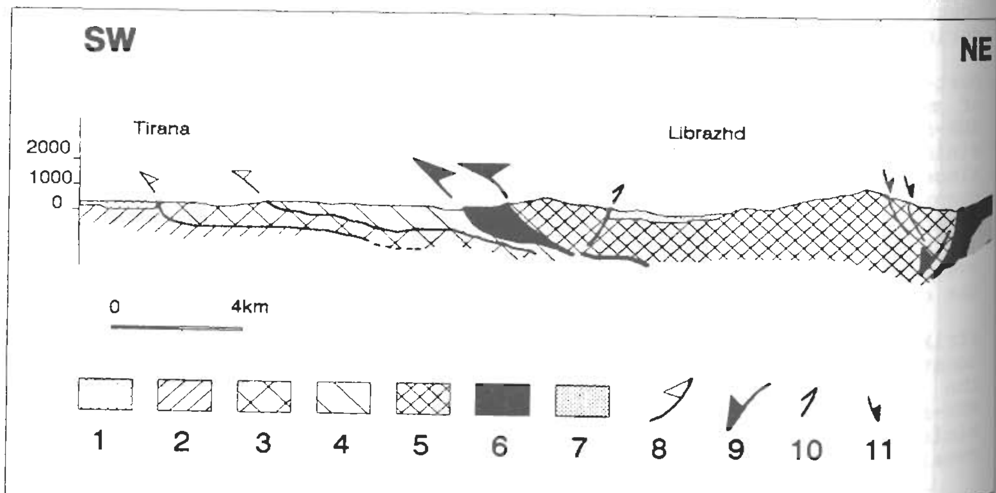

Figure 4. Simplified cross section through Central Albania. 1. Molasse sediments, 2. Ionian zone, 3. Kruja zone, 4. Krasta-Cukali zone, 5. Mirdita zone (Ophiolites and associated sediments), 6. Triassic-Jurassic carbonates of internal Albanides, 7. Palaeozoic basement of Korab zone, 8. Major thrust in the external Albanides, 9. Sense of ophiolite movement over the external Albanides, 10. Reverse faults during the Miocene compressional event, 11. Normal faults.

large scale structures i.e. normal faults trending NNW-SSE in pure brittle conditions in the upper horizons. The sense of movement was towards WSW. Since this deformation was the first for the ophiolites in Tertiary times it must be the tectonic event which was responsible for their emplacement over the Krusta-Cukali flysch in Early Oligocene times immediately after the flysch imbrication. Similar tectonic conditions are inferred in Greece for the emplacement of the ophiolites over the Pindos flysch and the initial formation of the Mesohellenic Trough during this extensional tectonic event in Early Oligocene times (Mountrakis et al., in press).

The D_3-tectonic event was compressive, with maximum σ1 axes horizontal trending in the ENE-WSW direction. We suggest a Late Miocene age for this event, since very significant back-thrusts of the ophiolites over mollasic sediments observed near the town of Librazhd, belong to that compressive event (fig. 4). However the dominant structures of this event are sinistral strike-slip faults in the NW-SE direction.

The orientation of the main axes of the strain elipsoid changed later during an evolutionaly compressive D_4-tectonic event with a maximum σ1-axis almost horizontal in the N-S direction. This also took place in the Late Miocene and caused reverse and strike-slip faults in the ophiolites and similar structures, additional folding and further imbrication in the Krasta-Cukali zone.

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CAPTIONS OF THE PHOTOS

Photo 1. Microfolds in the metamorphic sole in the area of Boboshtice village, South of Korce.

Photo 2-3-4. Structural features of the extensive D_2 - tectonicevent. 2) Extensional shear structures in serpentinite bodies near the village Fushe-Bulqize showing the sense of movement towards WSW. 3) Antithetic small scale extentional structure showing a movement towards ENE east of Bulqize town. 4) Large scale normal faults along the contact of the eastern Ophiolites and the Triassic-Jurassic carboates near the village Skenderbej.

Photo 5-6-7. Structural features of the compressional D_3 - tectonic event. 5) Sinistral strike-slip meso-scale fault, trending NW-SE, with kinematic indicators (Skenderbej village). 6) Small scale dextral fault trending NE-SW (Skenderbej village). 7) Back-thrust surface showing a movement towards ENE in the Upper Cretaceous limstones of Krasta-Cukali zone (Mat river).

Photo 8. Imbricate fan of a reverse fault with a northward movement due to the fourth D_4 compressional tectonic event in the serpentinite near Pogradeci.

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