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GEOLOGICAL OBSERVATIONS AND A POSSIBLE SUBDUCTION ZONE ALONG THE "SITHONIA - DOIRANI" BELT, NORHERN GREECE

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A B S T R A C T

Geological observations on both sides of and along the Axios-Serbo-Macedonian geotectonic boundary provide sufficient evidence for the existence of a subduction zone in this area. Evolution of such a zone from Permian to Tertiary can account for the structural symmetry, greenschist-facies metamorphism, granodiorite emplacement and geochemistry..

Σ Υ Ν Ο Ψ Η

Γεωλογικές παρατηρήσεις εκατέρωθεν του γεωτεκτονικού ορίου της ζώνης Αξιού και της Σερβομακεδονικής μάζας, παρέχουν σαφείς ενδείξεις για την ύπαρξη μιας ζώνης βύθισης κατά μήκος του ορίου αυτού. Η ανάπτυξη αυτής της ζώνης από το Πέρμιο μέχρι το Τριτογενές ερμηνεύεται από την τεκτονική συμμετρία, την πρασινοσχιστολιθική φάση μεταμόρφωσης, την τοποθέτηση γρανοδιοριτικών σωμάτων και την γεωχημεία.

INTRODUCTION

The present study is the result of extensive research in the area of Sithonia during the past decade. Although consensus on the setting of this complex belt has been reached, discrepancies are not missing. In this work we propose a possible evolutionary scheme for the western margin of the Serbo-Macedonian massif in the framework of plate tectonics taking into account both resembling and differing interpretations.

Our attempt to consider the petrology and structure of the "Sithonia -

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Doirani" belt in the context of plate margin processes was faced with some critical problems, the most important of which are outlined below. Primarily, the ophiolite complexes are allochthonous, dismembered and display variable thickness (2-10 km; J. Filbrandt, pers. comm., 1984). Other difficulties comprise the very old age of the basement rocks (Palaeozoic to Precambrian) and the overlying sediments of the autochthonous Svoula Fm (Permo-Triassic) as well as the absence of younger sedimentary lithologies (e.g., Tertiary) and the poorly studied granodioritic bodies, whose age is greatly unknown.

The area of study occupies a NW-SE trending belt which extends from Sithonia northwards to lake Doirani, 18 km distant from Thessaloniki (fig. 1). It coincides with the well-known geotectonic boundary between the Axios zone and the Serbo-Macedonian massif. Greece's major subdivision into Internal and External

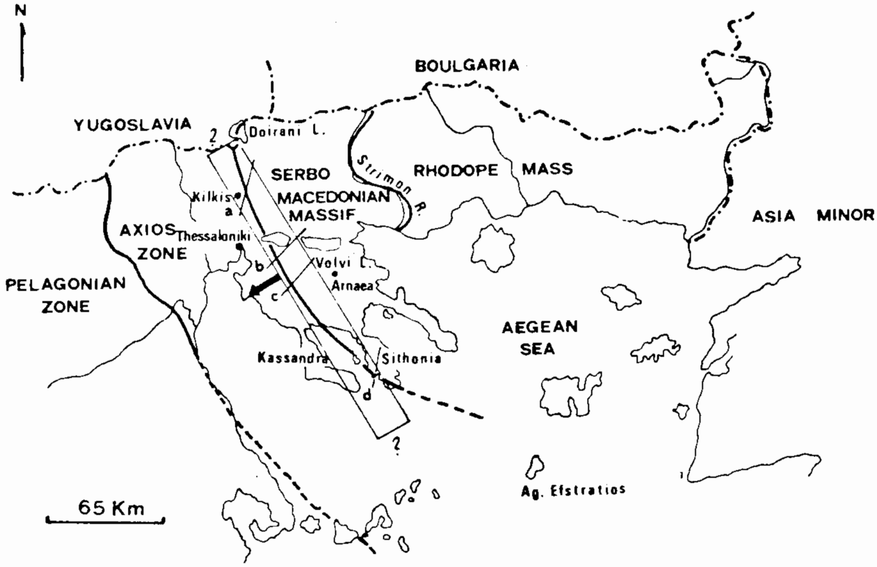


Fig. 1. Geotectonic map of the Internal Hellenides showing the position of the possible Mid-Jurassic subduction zone along the "Sithonia-Doirani" belt. Lines a,b,c and d correspond to the cross-sections of fig. 2.

Σχ. 1. Γεωτεκτονικός χάρτης των εσωτερικών Ελληνίδων. Απεικονίζεται η θέση της μεσο-ιουρασικής ηλικίας ζώνης βύθισης. Οι γραμμές a,b,c και d αντιστοιχούν στις τομές του σχ. 2.

Hellenides was initiated by Renz (1910). Kossmat (1924) and Osswald (1938) introduced the term Axios (or Vardar) zone to distinguish the Sithonia granodiorite, the Svoula series and the Vertiskos gneisses from the younger sedimentary formations to the west (see figs. 1 and 2). Kober (1932) assigned the name Rhodope mass to that terrane lying east of Strimon River; the latter is considered as a major structural line along which the Rhodope mass thrust under the Serbo-Macedonian massif during late Tertiary times. Brunn (1959) used the term Internal Hellenides for the Pelagonian and Axios zones.

Kockel et al. (1971) discriminated between the Serbo-Macedonian massif and the Axios zone invoking that the former consists of "crystalline" rocks metamorphosed in the almandine-amphibolite facies. The common presence of migmatites in the Serbo-Macedonian basement confirms the existence of high metamorphic grades (Chatzidimitriadis and Papastavrou, 1975). The age of the latest metamorphic episode that affected the "crystalline" Serbo-Macedonian rocks has been radiometrically determined (Rb-Sr in pegmatites) to be Hercynian (Kockel et al. 1971). Hercynian ptygmatic folds (similar to those of the metamorphic sialic basement of western and central Europe) have also been reported from the Serbo-Macedonian basement (Chatzidimitriadis and Papastavrou, 1975). The above suggest that the Serbo-Macedonian massif (and the Rhodope mass as well) possibly represent the southernmost extension of the Eurasian plate (in agreement with the Dixon-Robertson model of the plate tectonics evolution of the eastern Mediterranean area; J. Dixon, pers. comm., 1984). Kauffmann et al. (1976) introduced the term "Circum Rhodope Belt" to separate the Svoula sediments from the high-grade metamorphic rocks of the Vertiskos series.

GEOLOGY - PETROGRAPHY - STRUCTURE

The area of study stretches across the geotectonic boundary between the Axios and Serbo-Macedonian zones, the rock types of which must, therefore, be described. To assist the reader four representative geological cross-sections have been constructed (figs. 2a,b,c and d).

The metamorphic basement of the Serbo-Macedonian massif consists of gneisses and schists that belong to the Vertiskos and Kerdillia series. Within the gneisses thin, and rarely thick, intercalations of amphibolites and thicker ones of marbles are observed. The parentage of these rocks is still a matter of debate; Chatzidimitriadis and Papastavrou (1975) described both "ortho-" and "para-" rocks while Dimitriadis (1974) and Kasoli (1981) only "ortho-" ones. The above lithologies are cut by numerous aplite, pegmatite and quartz veins, and lesser diabase dykes. Gabbro-peridotite thrust slices of possibly small thickness are also observed within the sequence. The gneisses of the Serbo-Macedonian massif extend both to the west and east, towards the Pelagonian and Rhodope zones respectively. This is supported by drill-hole data kindly provided by the State Electricity Corporation.

Overlying the metamorphic basement of the Serbo-Macedonian massif is the autochthonous Svoula Fm, a thick sedimentary unit characteristic of the Internal Hellenides. Its deeper members are argillaceous (graphite-bearing phylli-

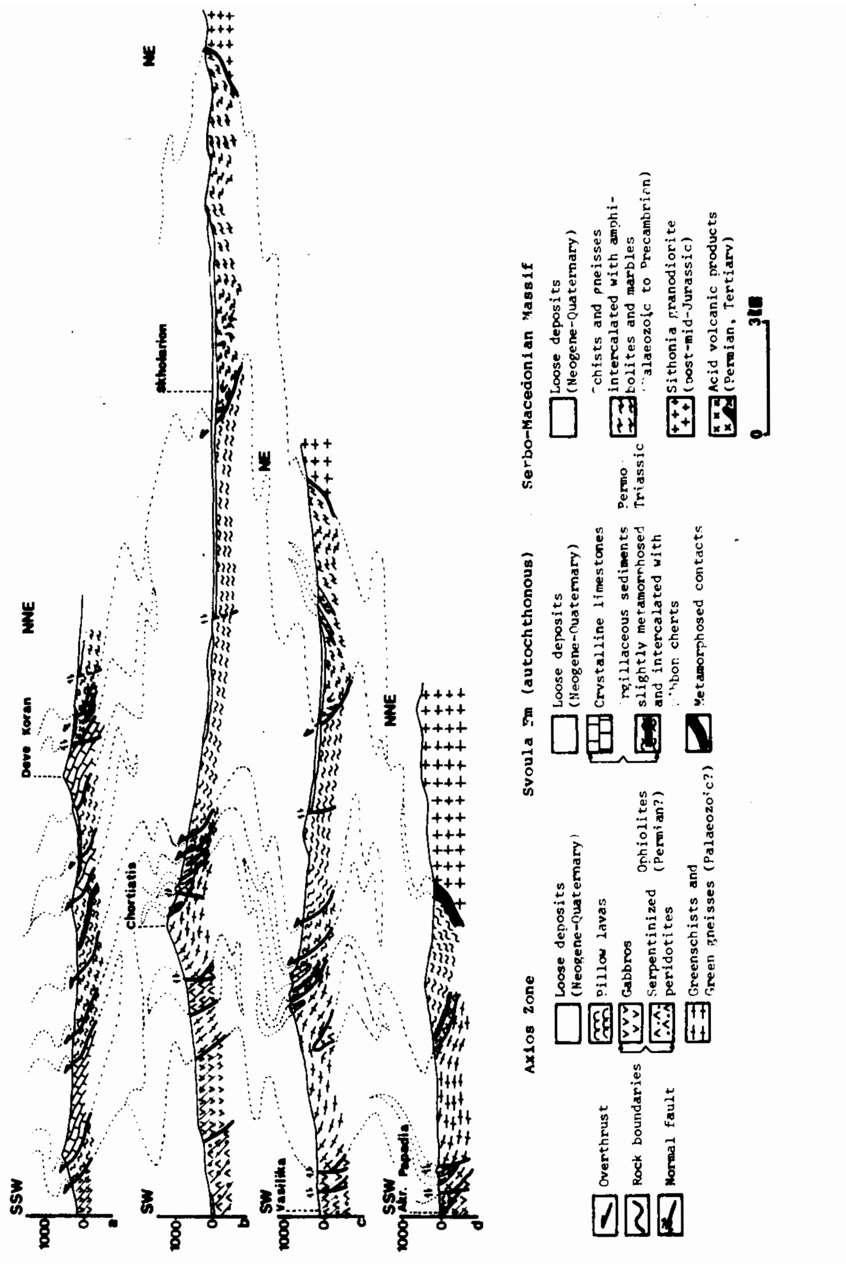


Fig. 2. Geological sections across the "Sithonia-Doirani" Belt. For location see fig. 1.

Σχ. 2. Γεωλογικές τομές εγκάρσια στη λωρίδα "Σιθωνίας-Δοϊράνης".

tes, metapsammites and shales intercalated with coarse-grained sandstones and conglomerates) grading upwards to carbonate cover (crystalline limestones). Also observed within the Svoula series are black ribbon cherts as well as thrust slices of Serbo-Macedonian gneisses and green gneisses of the Axios zone. From the above it becomes obvious that sedimentation was taking place under variable conditions, manifested therselves, on the one hand, by deposition of coarse-grained sandstones and conglomerates and on the other by deep-sea clays and cherts (Chatzidimitriadis, 1980).

Dating of the Svoula Fm was based on fossils (Heterastriidae) found in limestones at its western margin suggesting a Carnian-Norian age. As for the lower argillaceous members we propose a Permian age (see also Chatzidimitriadis; 1980; Papastavrou and Chatzidimitriadis, 1980/81). A Permo-Triassic age to the unit has also been assigned by Papadopoulos (1982).

Ζώνη Α: Acid tuffs with rhyolite bodies (volcano-sedimentary units) exhibiting moderate schistosity are found to thrust over the Svoula Fm to the east of it (see fig. 2a). We, therefore, suggest that they originally underlay the Svoula sediments and consequently are of, at least, Permian age. These rocks have been affected by younger volcanic activity (Tertiary?), a fact supported by microscopic examination of the tuffs themselves (two generations of minerals) and also by the signature of such an activity left to Mesozoic rocks and by the presence of hydrothermal mineralization in the Vertiskos gneisses.

Along the eastern boundary of the Svoula Fm, and especially at the areas of Sithonia and Arnaea several granitic to granodioritic bodies have intruded (figs. 2b,c and d). The Sithonia granodiorite shows clear, yet weak contact metamorphic phenomena (silicification, epidotization, etc.) against the Svoula sediments and the basement rocks. This observation in conjunction with the distortion caused by the intrusion to the NW-SE trending schistosity of Mid-Jurassic age of the Svoula Fm leave no doubt for a post-Mid-Jurassic time of emplacement of the Sithonia granodiorite (Chatzidimitriadis et al. 1983).

The part of Axios zone contained in the study area (fig. 2) comprises thrust slices of greenschists to green gneisses and ophiolites. The "green rocks" occur in a NW-SE trending belt from Sithonia to Thessaloniki and represent low--grade gneisses which grade into greenschists by lowering the amount of feldspar present in the rock. Apart from feldspar, quartz and mica, their green colour is due to the presence of epidote and chlorite. Their metamorphic age is Lower Cretaceous (113 m.y.; Kockel et al. 1977) while the pre-metamorphic one is possibly Palaeozoic (Chatzidimitriadis and Kilias, 1984). We suggest an "ortho-" origin for these rocks, having been derived most probably from intermediate to acid volcanic rocks (andesites, dacites).

The ophiolites trend almost parallelly to the green gneisses and comprise mainly gabbros and peridotites. The whole complex is cut by numerous pyroxenite and diabase dykes; stockwork magnesite veins predominate at the altered parts of the ultramafic members (dunites altered to serpentinites). The age of the ophiolites remains an open question, however, their subjection to Mid-Jurassic compressional tectonics in connection with the absence of contact metamorphic phenomena against the Svoula sediments implies that they are older than the latter.

West of Strimon River compressional tectonics is clearly responsible for the formation of nappes in the area. The latter are invariably striking NW-SE whereas bedding and schistosity planes are dipping 30 to 40 degrees NE. Two types of folds have been recognized. B_2 folds of Mid-Jurassic age are mainly isoclinal and affected the Permo-Triassic sediments of the Svoula Fm and the Permian volcano-sedimentary units (Kockel et al. 1971; Chatzidimitriadis, 1980; Chatzidimitriadis and Kilias, 1984). Their vergence faces towards the SW implying that the fold-producing forces have originated from the NE. Evidence in support of such an explanation is the observation that thrust slices of gneisses belonging to the Vertiskos series have been tectonically displaced some 20 km southwestwards to Thessaloniki. It is not known, however, how long this movement did it last. B_1 folds of possibly Palaeozoic age are mostly upright and affected the green gneisses; they are far less abundant than the B_2 folds (Chatzidimitriadis and Kilias, 1984).

Apart from the compressional tectonics and the accompanying it phenomena (e.g., thrusts) the area of study is also characterized by variably striking (e.g., N-S, E-W, etc.) normal faults of Tertiary age (Hiessleitner, 1951/52; Chatzidimitriadis and Kelepertzîs, 1983). It is these faults to which the formation of the lakes of Volvi, Lagadas, and Doirani is ascribed. The recent tectonics of the area is due to intermittent reactivation of the above faults, expressed as thermal-water activity at Lagadas and Volvi (frictional heating produced as the walls of the faults slip one each other) as well as seismic activity along a NW-SE trending narrow belt from Skopje (Yugoslavia) through Volvi and Kassandra to Aghios Efstratios (Chatzidimitriadis and Kelepertzis, 1981/82).

EVIDENCE FOR SUBDUCTION AND TIME EVOLUTION OF THE "SITHONIA-DOIRANI" BELT

The most important geological, petrological and structural evidence in support of the existence of a subduction zone in the area of study can be summarized as follows:

1. The sedimentary lithologies of the Svoula Fm have been transgressively deposited on the floor of a Permo-Triassic geosyncline. When considering this phe-

nomenon in the context of plate tectonics, and taking into account their regional extent, the best alternative is the floor of an ocean basin, or, stated in another way, the existence of an oceanic plate.

2. The presence of ribbon cherts within the Svoula Fm implies a deepening of the ocean floor during the Mid- to Upper-Triassic.

3. The Mid-Jurassic folding which affected the Svoula Fm and the underlying it rocks is intimately associated with a possible NW-SE striking subduction zone.

4. The ophiolite nappes occur in a belt elongate in a NW-SE direction and represent detached remnants of oceanic lithosphere and upper mantle that have been subjected to the compressional tectonics of Mid-Jurassic.

5. Formation of the Axios zone greenschists and green gneisses during the Lower Cretaceous metamorphic episode is an evolutionary consequence of the Mid-Jurassic subduction of the postulated oceanic plate.

6. The anatectic to palingenetic post-Mid-Jurassic granodioritic magma of Sithonia is clearly related to subduction in the area. It should also be noted here that apart from basaltic material, thrust slices of acid gneisses as well as acid tuffs and rhyolites of Permian age would have followed the sinking slab on its way to the mantle.

7. Chemical analyses of tuffs and rhyolites (Tertiary?) occuring in a NW-SE trending belt from Kilkis to Doirani (i.e., parallel to the Axios-Serbo-Macedonian boundary) revealed high K_2O values, a case well-documented from subduction -zone environments (see Table 1).

8. The pillow lavas of the West Sithonia area are of Upper Jurassic age (Kockel et al. 1977). According to Teranidis (1984) these lavas were formed through subduction of oceanic and partly continental lithosphere. They are geochemically related to the gabbros and dunites of the Vavdos-Basilika Series, because the trace elements analysed Th, Ta and La showed ratios of Th/Ta > 10-20 and Th/La > 0,2. Pilow - lavas formed at mid-ocean ridges are characterized bei (trace elements) ratios of Th/Ta 0,75-1,60 and Th/La 0,03-0,14. It is believed that this is an additional evidence for subduction in the study area.

9. Finally, the intense thermal-water and seismic activities discussed previously are positive indications of the existence of a subduction zone in the area.

The chronological evolution of events described above is partly based upon speculations. For example, the Mid-Jurassic folding of the Svoula sediments is also taken as the time of subduction (geosynclinal maturity; see fig. 3b). The postulated oceanic plate was born east of Sithonia and subsequently moved and subducted towards the SW along constant NW-SE strike (fig. 1). The angle of subduction is considered to have been steep as suggested by the presence of cherts within the Svoula Fm. Further evidence in support of our interpretation comprises the southwestwards displaced nappes of Vertiskos gneisses as well as the southwesterly facing fold-vergence of the Permo-Triassic formations.

Figure 3c depicts the final stages of our model from Cretaceous to Tertiary. Lower Cretaceous metamorphism resulted in the formation of the greenschists and green gneisses of the Axios zone (fig. 3c, no 5). Pre-Mid-Cretaceous is also the emplacement of the Sithonia granodiorite (fig. 3c, no 8). During the Tertiary, high-K acid volcanism (tuffs and rhyolites) affected the Permian volcanic rocks. Nowadays, active faults and earthquakes are the only "reminders" of the postulated Mid-Jurassic subduction zone in the area.

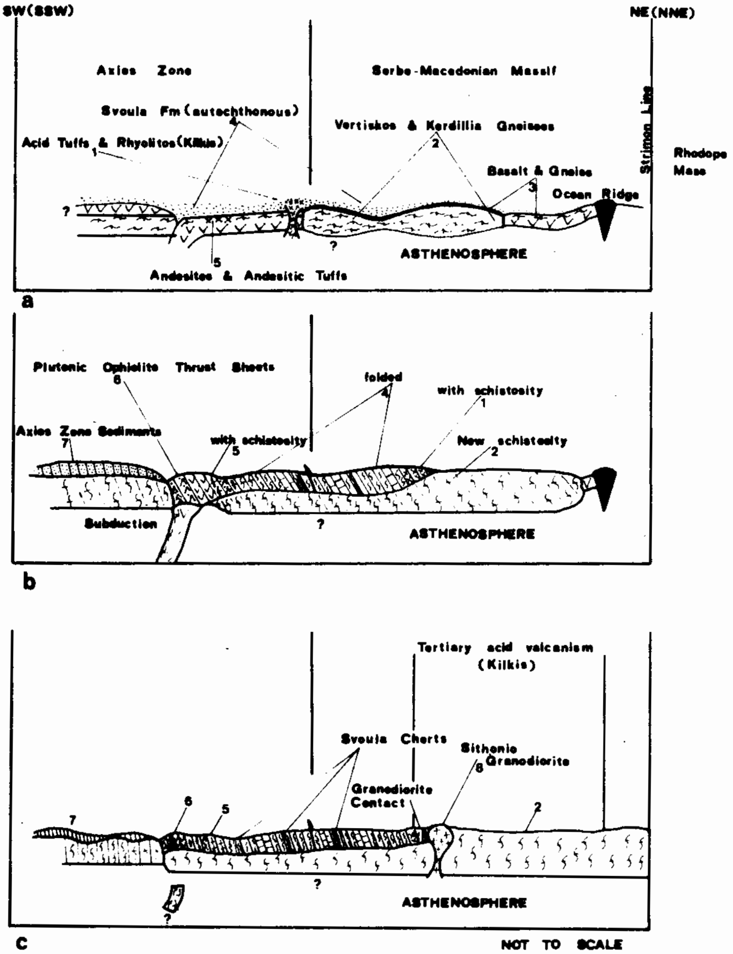
Table 1. Major element analyses of rhyodacites occuring above the "Sithonia-Doirani" subduction zone (After Jung, pers. comm., 1983).

	PIRGOTO	DOIRANI	ZAGLIVERI
SiO_2	65.53	60.33	74.42
Al_2O_3	14.72	18.40	12.56
Fe_2O_3	2.31	2.64	0.91
MgO	0.55	0.59	0.14
CaO	0.25	0.27	0.17
K_2O	9.10	9.53	9.78
Na_2O	2.09	1.17	0.89
P_2O_5	0.07	0.11	0.21

CONCLUSIONS

Geological observations on both sides of and along the Axios-Serbo-Macedonian geotectonic boundary provide sufficient evidence for the existence of a subduction zone in this area (fig. 3). The abnormally high K_2O content in the Tertiary tuffs and rhyolites is consistent with the requirement that subduction related volcanic rocks are enriched in potash. This is also supported by the fact that ridge tholeiites (low-K basalts) yield at subduction zones K-rich basalts (cf. Sonenschejn, 1973). We ascribe the structural symmetry of folds, the presence of ribbon cherts, the greenschist-facies metamorphic episode, the emplacement of the anatectic Sithonia granodiorite and the westward displacement of gneissic nappes to movement and subduction of an oceanic plate towards the SW along constant NW-SE strike.

Jankovic (1977) attributed the genesis of Pb-Zn mineralization in the Bulgarian Rhodope to subduction of a southwards moving oceanic plate. However, his hypothesis cannot account for the various geological problems of our study area and consequently is not acceptable. Boccaletti et al. (1974) considered the Balkanides as an instance of back-arc thrust belt, possibly related to the Hellenides. As for the latter, they proposed the presence in Jurassic-Cretaceous time



3a. Initiation of sea-floor spreading west of Kerdillia Mts; deposition of the Svoula Fm; motion of oceanic and continental lithosphere from NE to SW (Upper Carboniferous-Lower Jurassic).

3b. Subduction along the "Sithonia-Doirani" belt; folding of the Svoula Fm; formation of ophiolite nappes (Mid-Jurassic).

3c. Formation of greenschists and green gneisses by metamorphism of Palaeozoic (?) intermediate to acid volcanic rocks; emplacement of the Sithonia granodiorite; acid volcanism in the Kilkis area (Upper Jurassic - Tertiary).

Fig. 3. Schematic evolution of the "Sithonia-Doirani" subduction zone through time.

Σχ. 3. Σχηματική γεωχρονολογική εξέλιξη της ζώνης βύθισης "Σιθωνίας-Δοϊράνης".

of two oceanic areas of unequal width (the Axios zone narrower than the Sub-Pelagonian zone) with subparallel Benioff planes both dipping north-northeast. Their interpretation is in partial agreement with the present study as regards chronological evolution of events but is completely different in terms of direction of movement and subduction of the oceanic plates. In any case, all geological data discussed earlier, in conjunction with the westward displacement of gneissic nappes favour the suggestion for motion (and subduction) of an oceanic plate towards the southwest.

Finally, we must indicate that in the supposed oceanic ridge of Kerdyllia, ideal conditions of movement and destruction of lithospheric plates were not achieved, as it happens with the Pacific and Atlandic oceans. Actually, there was a source of basalt origin, but the acid continental margins (Serbo-Macedonian massif) were either in short distance from the genesis center of the lithospheres or inserted in their moving direction (Fig. 3a). As a result of this peculiarity was the very low speed of the lithosphere's movement and destruction. This fact explains also the long time evolution from the mature subduction stage (Middle Jurassic) up to the stage of rhyodacitic volcanic activity of the Kilkis zone (Tertiary) Basides, we have clear indications that there was a destruction of a mixed composition lithosphere (acid + basic material), while the sediments of the autochtonous Svoula series may have been parths deposited on the Serbo-Macedonian basement.

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