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THE PALEOGENE HISTORY OF THE PELAGONIAN ZONE S. L. (HELLENIDES, GREECE): HEAVY MINERAL STUDY FROM TERRIGENOUS FLYSCH SEDIMENTS

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Abstract: The terrigenous material of the flysch of the Pelagonian Zone s.l. of the Internal Hellenides in Pelion, Skopelos, Euboea, Othrys Mountain and Argolis have been characterized by their heavy mineral assemblages, based on 114 samples. The terrigenous input can be divided into a garnet-dominated association, restricted to flysch sediments of both western Othrys and Ligourion (Argolis), and assemblages with variable amounts of the stable ZTR group (zircon, tourmaline, rutile) and apatite, found at all the other localities. The garnet assemblage is assumed to have been derived from mica schist complexes existing at the western margin of the Pelagonian microcontinent, tectonically active due to the closure of the Pindos Ocean. The situation is similar to that already known from the Pindos and Parnassos-Ghiona zones. Blue amphiboles detected in western Othrys witness the existence of blueschist terrains. The ZTR-apatite group points to a different source province, not connected regionally with the former source. The activity of this source terrain can be related to the closure of a Neotethyan ocean in the Vardar Zone, along the eastern margin of the Pelagonian Unit, during the early Tertiary. The heavy mineral assemblages indicate that in this source area ophiolitic complexes are tectonically incorporated to a lesser extent. Blueschists seem to be absent, as no detrital blue amphibole was found.

Key words: Hellenides, Pelagonian Zone, Paleogene, terminal flysch, heavy minerals.

Introduction

The Pelagonian Zone belongs to the Internal Hellenides (Brunn 1956) and is tectonically situated between the External Hellenides (Paxos, Ionian, Gavrovo-Tripolitza, Pindos, Parnassos-Ghiona zones) and the Vardar-Axios Zone (Fig. 1). The Pelagonian zone s.l. is subdivded into an unmetamorphosed western and a metamorphosed eastern part. The unmetamorphosed part is called the Subpelagonian Zone (Aubouin 1959) and comprises Othrys Mountain and the Argolis peninsula, including the islands of Aegina, Poros and Hydra. According to the same author, the metamorphosed units are exposed in Thessaly, Pelion, in parts of Euboea, and on several islands, such as the Northern Sporades.

Paleogeographically, the Pelagonian Zone can be considered as a microcontinental fragment of the Cimmeria continent between two oceanic domains (Mountrakis 1985; Papanikolaou 1986): the Pindos Ocean towards the west (see also Robertson et al. 1991; Jones et al. 1992) and the Vardar Ocean in the east (see also Bernoulli & Laubscher 1972; Godfriaux & Ricou 1990). From Middle Jurassic times on, the closure of the oceanic domains started, with accompanying ophiolite obduction contributing to the development of the Pelagonian Zone (Godfriaux & Mercier 1965; Katsikatsos et al. 1982). The final closure of both the oceanic domains occurred in early Tertiary times (e.g. Robertson 1990; Jones & Robertson 1991) and was accompanied by flysch sedimentation. Ideas about the origin of certain ophiolites depends strongly on the favoured tectonic concept.

The Pelagonian Zone s.l. is characterized, in general, by a common development (e.g. Mountrakis 1985; Katsikatsos 1992). Above a Hercynian basement, Early Paleozoic sediments were deposited, followed by a volcano-sedimentary succession of Early Triassic age and a Middle Triassic to Liassic shallow-water limestone (Pantokrator Limestone; Renz 1955) as well as related intra-platform and marginal carbonate sequences. During the Jurassic, the basin deepened and radiolarite fomations appeared. In this period the obduction of ophiolite complexes occurred accompanied by deep-water clastic sedimentation. After a period of superficial exposure, this tectonically composite succession was transgressed by the sea from mid-Cretaceous times on (Cenomanian-Turonian transgression). A widespread Late Cretaceous rudist-bearing shallow-water limestone facies covered the whole Pelagonian realm. A marginal facies (Ermioni Limestone, Poros Formation) of the Late Cretaceous shallow-water platform has been reported from the eastern Argolis and Poros island (Clift & Robertson 1990). From the Maastrichtian on, the carbonate platform collapsed. On down-faulted regions, pelagic limestones were deposited, while uplifted parts suffered erosion and partial karstification. During the Paleocene and Eocene terrigenous deep-water sediments spread over the whole Pelagonian Unit. The sedimentary evolution of the Pelagonian Zone ceased with these flysch deposits, which are the response to the Paleogene compressional deformation in the Hellenides.

In the present paper, the authors contribute new data to the discussion about the paleogeographic position of the source terrains of the vast mass of terrigenous flysch sediment in the Pelagonian realm and also try to give some information

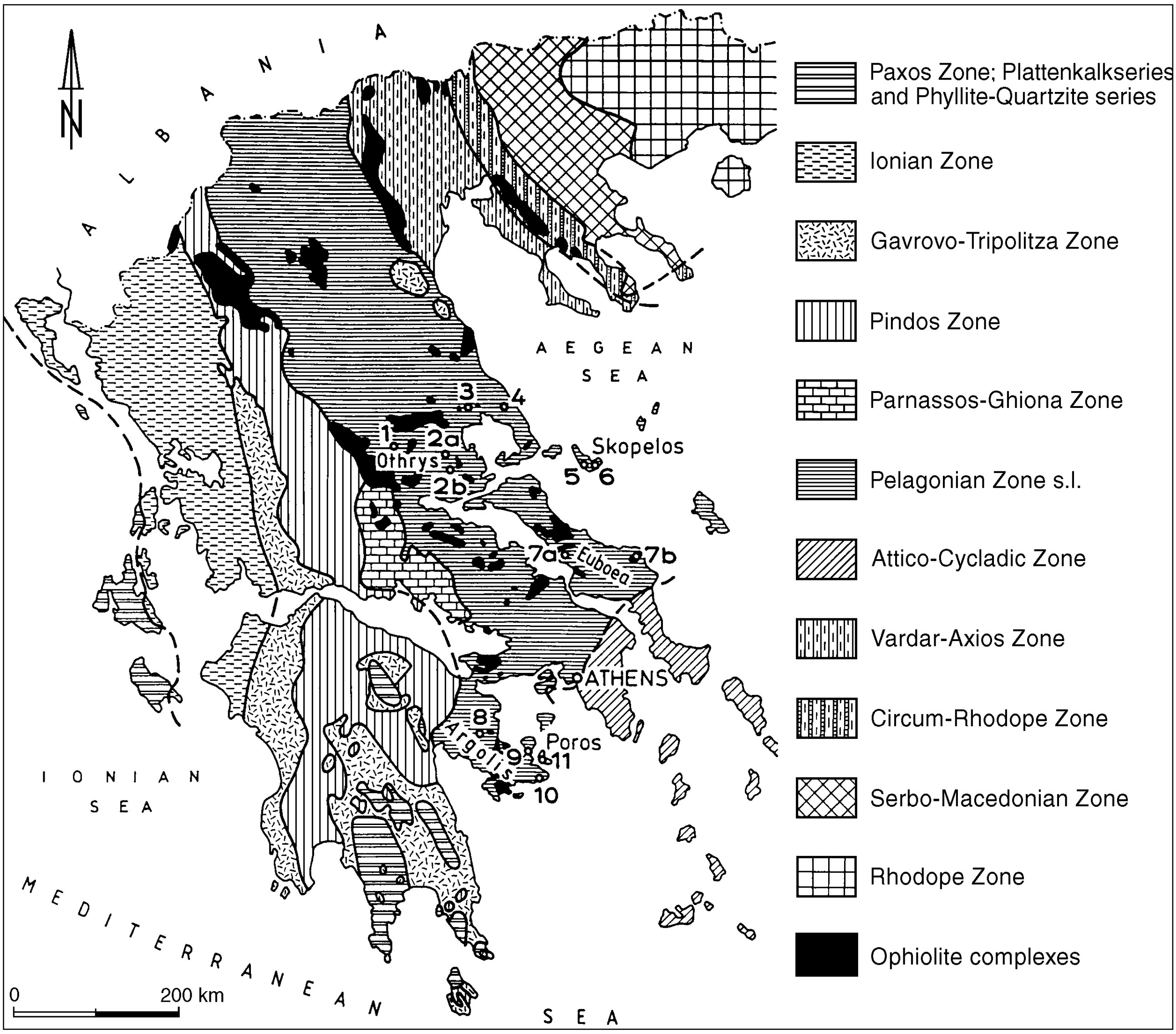

Fig. 1. Geological sketch map of the Hellenides showing the position of the flysch sample groups. 1 — western Othrys Mountain, two sections to the north of Domokos; 2a — northeastern sector of the Othrys Mountain, region of Neraida-Anavra; 2b — eastern sector of the Othrys Mountain, regions of Vrinena-Ag. Joannis and Kofi-Kokkoti; 3 — exposure at the national road near Ag. Georgios, in the Volos region; 4 — Pelion, “Flysch of Plesidi”; 5 — Skopelos island, lower tectonic Pelagonian Unit in the central part of the island; 6 — Skopelos island, upper tectonic Palouki Unit in the eastern part of the island; 7a — Euboea, roadcut at the national road between Psachna and Aghios Pass; 7b — Euboea, region of Kimi; 8 — Argolis, NE Ligourion; 9 — Argolis, southern part of Methana peninsula; 10 — Argolis, Adheres peninsula; 11 — Poros island.

about the composition of these source areas. Although heavy mineral studies are an appropriate tool for such investigations; the method has not been systematically utilized until now in this internal part of the Hellenides. These investigations, based on microscopical examinations, give a first insight into the heavy mineral distributions, but the authors are aware that further detailed mineralogical and chemical studies on several of the minerals would markedly increase the information about the source terrains.

Geological setting and sample locations

The heavy mineral composition of the Paleogene terrigenous flysch deposits of the Pelagonian Zone s.l. have been investigated in 11 regions, shown in Fig. 1. The stratigraphic charts of Fig. 2 exhibit the Cretaceous to Paleogene geological evolution. Detailed biostratigraphic information about the flysch sediments is relatively sparse in some regions, especially about the range of the flysch successions. Only their stratigraphic onset has been relatively well documented (e.g. Richter et al. 1996).

In Othrys Mountain, a western, northeastern and eastern sample group were investigated. In the western region, towards the north of Domokos (Fig. 1-1), the Paleocene to Eocene Dhirvi Formation (Smith et al. 1975) started with a stratigraphic gap in the Early Paleocene (Richter et al. 1996) above the karstified relief of the Upper Cretaceous carbonate platform (Goura Formation, Smith et al. 1975). In eastern Othrys Mountain, in the sectors of Neraida Anavra (Fig. 1-2a),

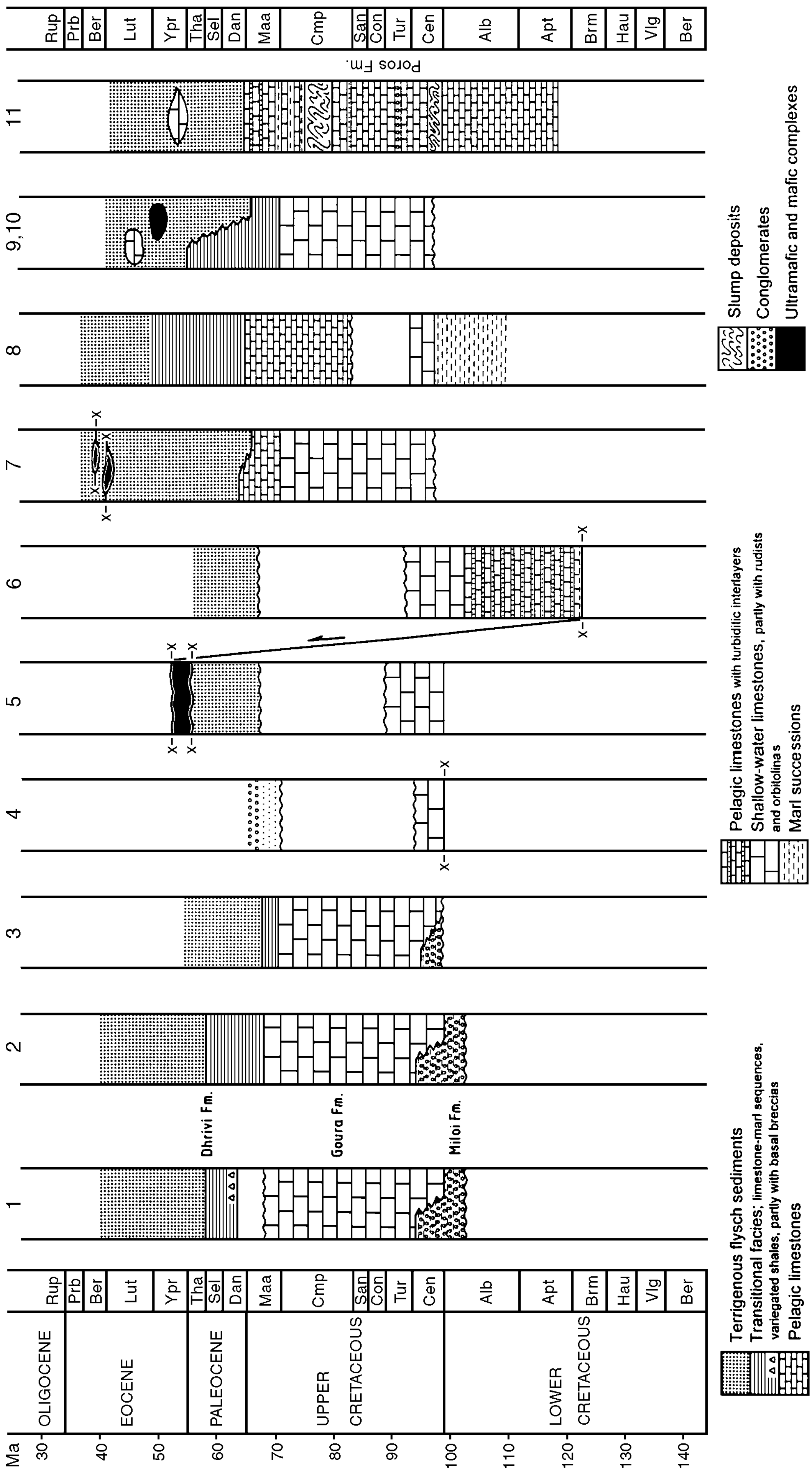

Fig. 2. Stratigraphic columns schematically showing the Cretaceous and Paleogene geological evolution in the sampling regions.

Vrinena-Ag. Joannis and Kofi-Kokkoti (Fig. 1-2b), a transitional contact between the limestones of the Goura and the Dhirvi Formation exists (Migiros & Pavlopoulos 1993). The true terrigenous flysch sediments lying upon the transitional facies, commenced in the Late Paleocene and passed up into the Eocene (Richter et al. 1996).

Along the national road near Aghios Georgios (Fig. 1-3), west of Volos, a low-grade metamorphic flysch succession has been examined in roadcuts. The Upper Cretaceous Pelagonian limestone passes with transitional beds of red pelites into the flysch sediments. The flysch succession of Maastrichtian to Paleocene age (Ferriére 1982; Katsikatsos et al. 1986) is mainly composed of pelites and sandstones but also contains intercalations of clastic limestones.

On the Pelion peninsula, the so-called "Flysch of Plesidi" (Fig. 1-4) was sampled. This siliciclastic sequence of Maastrichtian age is composed of sandy-pelitic beds which also contains red conglomerates and overlies the Cenomanian limestones. The conglomerates contain limestone pebbles and rarely sandstone elements. The succesion is part of the Plesidi-Lechonia-Veneto klippe (Ferriére 1982; Katsikatsos et al. 1986).

On the island of Skopelos, three tectonic units occur: Palouki, Glossa and Pelagonian (upper, intermediate, lower respectively; Matarangas & Jacobshagen 1988). The Pelagonian and Palouki units are crowned by an Upper Cretaceous sequence of transgressive rudist limestones covered by Maastrichtian to Paleocene flysch. Between the flysch successions and the underlying Upper Cretaceous limestones, a stratigraphic gap exists (Matarangas 1992). A volcano-sedimentary formation (= Glossa Unit), including ultramafic bodies, is intercalated between the lower (Pelagonian) and upper (Palouki) tectonic unit. The rocks of the Pelagonian Unit seem to be somewhat higher metamorphosed than those of the Palouki one. In the Palouki Unit, the Albian-Cenomanian carbonate platform is underlain by thin-bedded deep-water carbonates of mainly Aptian–Albian age, which are interbedded with thin siliciclastic turbidites. The flysch deposits of the Pelagonian Unit (Fig. 1-5) were investigated in the central part of the island (to the south and east of Skopelos town), whereas the Palouki Unit was studied in the eastern part of the island, near the Evangelismos Monastery (Fig. 1-6).

The terminal flysch sediments of Euboea developed gradationally from Maastrichtian deep-water limestones, which are underlain by Upper Cretaceous platform carbonates (Katsikatsos 1977; Robertson 1990, 1991). The samples were collected from two locations: along the Psachna-Mantoudi road (Fig. 1-7a) to the north of Psachna, where the pelagic limestone reaches up to the Early Paleocene, and in the region of Kimi (Fig. 1-7b), where the flysch deposition had already commenced in the uppermost Maastrichtian (Richter et al. 1996). In the Kimi region, the upper part of the flysch sequence is interleaved with thrust sheets of ultramafic and mafic rocks as well as Maastrichtian pelagic limestones (Robertson 1990). Robertson (l.c.) interpreted this as a development of a subduction-accretion complex which originated during the closure of the Neotethyan ocean.

On the Argolis peninsula of the Peloponnese, the terminal flysch sequences were investigated at three locations: (1) the flysch succession NE of Ligourion, (2) the flysch exposed in the roadcuts in the southern part of the Methana peninsula and (3) flysch outcrops along the coast of the Adheres peninsula (Fig. 1-8, -9, -10 respectively). The onset of the terrigenous flysch deposition youngs from east towards the west. The Ligourion flysch commenced in the Middle Eocene and is underlain by transitional beds of Paleocene to Early Eocene age and Campanian to Upper Maastrichtian pelagic limestones. The latter rest upon Cenomanian shallow-water carbonates bearing rudists and orbitolines (Photiades & Skourtsis-Coroneou 1994; Richter et al. 1996). The flysch sedimentation on the Methana peninsula and on Adheres seems to have already started in the Maastrichtian (Bachmann & Risch 1979). The youngest ages observed in flysch sediments are of the Middle Eocene (Richter et al. 1996).

On Poros island (Fig. 1-11), a late Cretaceous (Aptian–Maastrichtian) deep-water slope succession (Bachmann & Risch 1979; Poros Formation, Clift & Robertson 1990), composed of pelagic carbonates, carbonate-rich turbidites, limestone conglomerates and slump deposits, is overlain by a terrigenous flysch succession, named the Ermioni Complex (Robertson et al. 1987). The Poros Formation is considered to be a lateral equivalent to the Upper Cretaceous carbonate platform (Akros Limestone). In the terrigenous flysch succession of the Ermioni Complex, huge neritic limestone olistolites occur. Illite crystallinity data indicate a very low-grade metamorphism, up to a high diagenetic grade, whereas on the adjacent mainland somewhat higher metamorphic overprinting is reported (Clift & Robertson 1990). The heavy mineral samples were gathered at the western part of the island (see geological map of Strauss 1979 in Jacobshagen 1986).

Heavy mineral assemblages

Methods

The heavy minerals were separated from crushed and sieved sandstone samples (fraction 0.4–0.063 mm) (for details see Faupl et al. 1998). The carbonate minerals were dissolved in acetic acid. Tetrabromoethane (ρ = 2.96 g.cm^{-3}) was used for the gravitational separation procedure. After mounting the heavy minerals in Canada Balsam, the translucent minerals were examined under the petrographic microscope. Using the ribbon counting method, more than 200 heavy minerals were counted from each sample. In many cases the heavy minerals examined only microscopically represent mineral groups, such as the tourmaline group, garnet group, chrome spinel group etc. In cases of large sample numbers, a cluster analysis was used to differentiate heavy mineral assemblages in an objective manner. For the statistical procedure, the software package WinSTAT®, ver. 3.0 (Kalmia Com. Inc., Cambridge MA, 1994) was used. The stepwise formation of the clusters was done by the incremental sums of square (Ward's method).

The data regarding heavy mineral composition in grain-% and the coordinates of sample locations are available in the Editorial Office or from the authors.

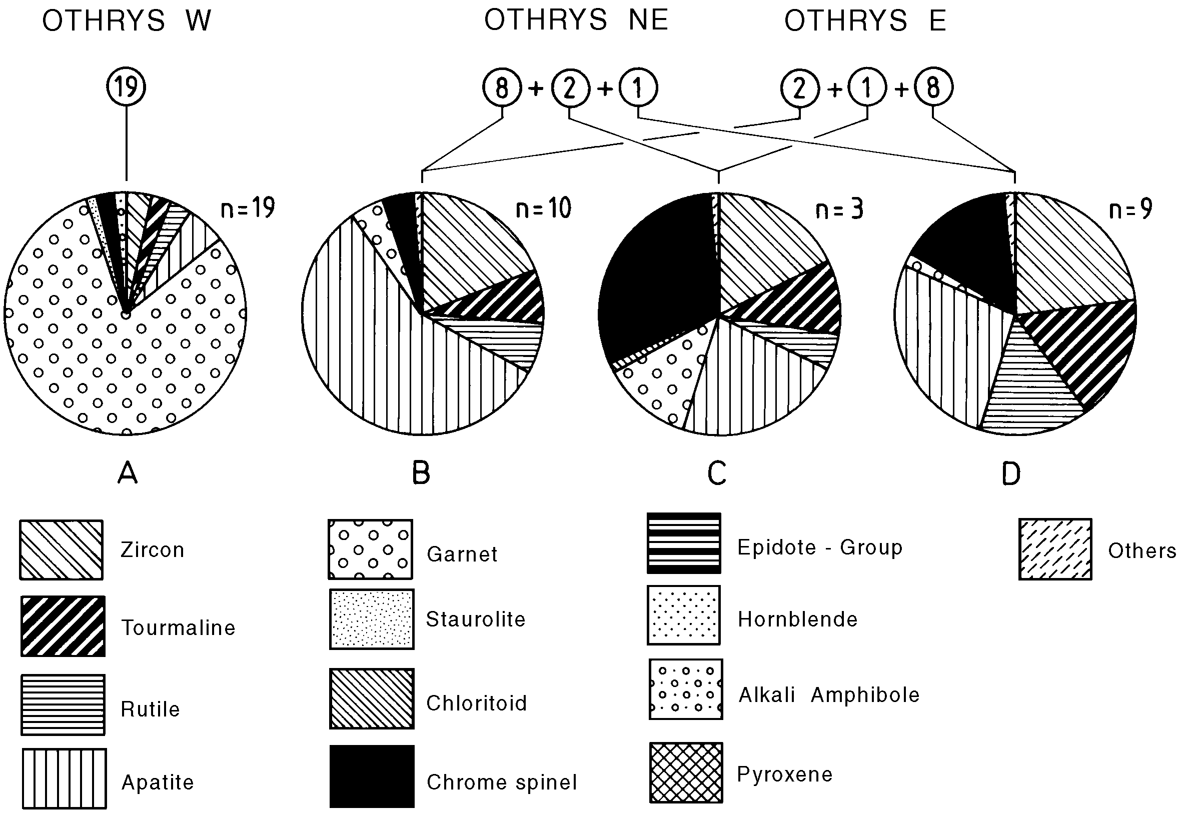

Fig. 3. Average heavy mineral composition of 4 major clusters (A, B, C, D) of the flysch sediments on the Othrys Mountain, separated by a cluster analysis (WinSTAT®, ver. 3.0). The contribution of the individual clusters to the sample locations is shown.

Othrys Mountain

In Othrys Mountain, the western sampling groups, to the north of Domokos, are clearly distinguished from the north-eastern and eastern locations (Fig. 3). These western assemblages are strongly garnet-dominated (av. > 80 %) and contain about 10 % of the stable group (zircon-tourmaline-rutile). Apatite, with few exceptions, is below 10 %. Garnet is frequently accompanied by minor amounts of staurolite and traces of chloritoid. The abundance of blue amphiboles as an indicator mineral for blueschist rocks in the source terrain is of specific interest. Normally, these conspicuous minerals occur only in traces; but in one sample, their content rises up to 10 %. Western Othrys was the only part within the Pelagonian realm investigated where these detrital blue amphiboles were frequently observed. Detrital chrome spinel has been detected only in very minor percentages within the western sector.

Towards the east, the garnet content diminishes dramatically to below an average of 2 % (Fig. 3). The northeastern sampling sites, with an average of about 8 %, follows the same trend. Only a few samples from these eastern sites show a still relatively high garnet content (cluster C in Fig. 3). The sandstones from the easternmost region of the Othrys Mountain are mainly characterized by the predominance of the stable ZTR group (cluster D, Fig. 3) or apatite (cluster B, Fig. 3). Detrital chrome spinel increases towards the east reaching average values of 31 % in cluster C and 15 % in D (Fig. 3).

Aghios Georgios (Volos region)

From these flysch meta-sediments only two samples (Fig. 4) were gathered in order to see some changes due to metamorphism within the assemblages. The sandstones are characterized by the ZTR group and apatite. All the other heavy minerals, such as garnet and chrome spinel, occur in traces.

Pelion peninsula— "Flysch of Plesidi"

The heavy mineral composition of the samples from outcrop pe-132 (Fig. 4) is very similar to that of the eastern Othrys, with a clear predominance of the ZTR group and apatite and minor percentages of garnet. Detrital chrome spinel rises up to nearly 20 %. The red conglomerates, which obviously do not belong to a deep-water succession, are strongly apatite-dominated (av. 74 %) with a garnet content of max. 3 %.

Skopelos island

The terminal flysch deposits of both the upper (Palouki) and lower (Pelagonian) tectonic units (Fig. 5) are dominated by the stable ZTR group and are practically free of garnet (av. < 1 %). Chrome spinel occurs only with a host of av. < 1 % in the Pelagonian Unit, whereas, in the Palouki Unit, the average is somewhat higher (2.6 %, max. 7 %). Apatite is observed, in most cases, as a major constituent.

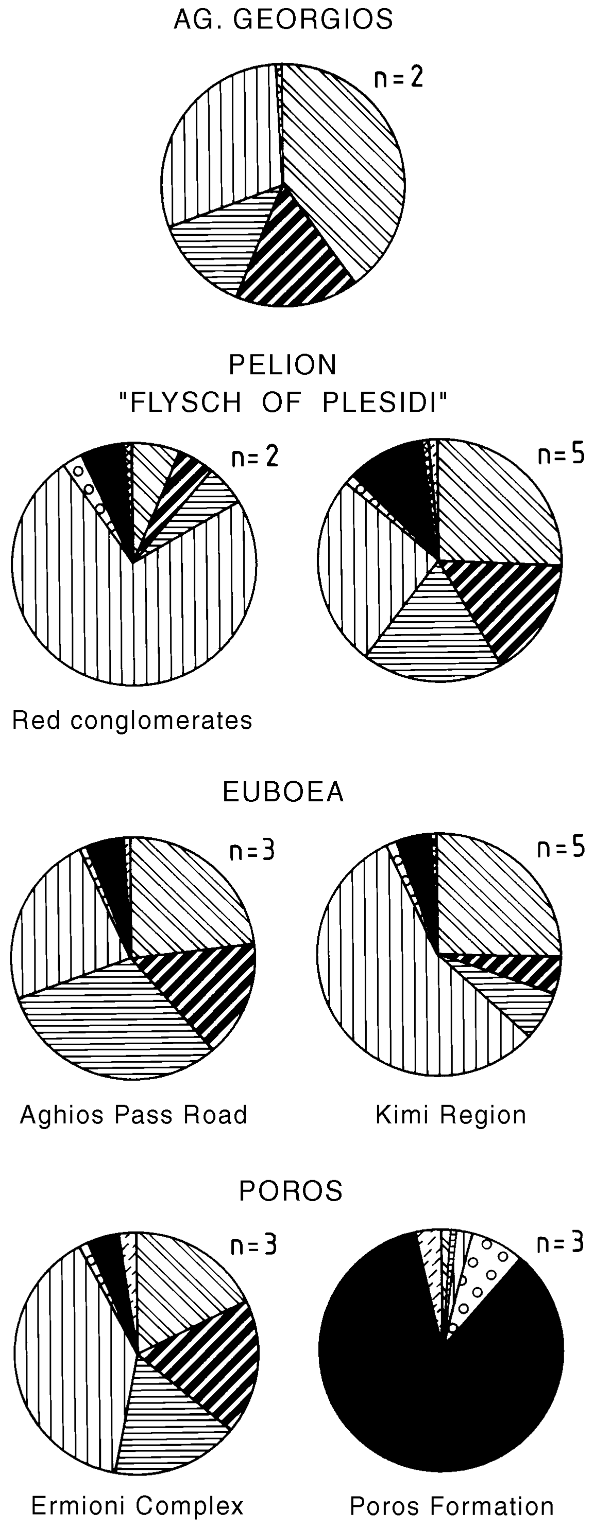

Fig. 4. Average heavy mineral composition of the terminal flysch sediments of Aghios Georgios (Volos region) (3), Pelion peninsula —"Flysch of Plesidi" (4), Euboea (7) and Poros island (11). For explanation of ornament see Fig. 3.

On the basis of a cluster analysis, it is demonstrated that four types of heavy mineral assemblages contribute to the terrigenous material of the flysch sandstones exposed in the Skopelos island (Fig. 5). The Pelagonian Unit consists of > 60 % of samples with heavy mineral associations rich in zircon and very small percentages of apatite (cluster A, Fig. 5). These zircon-rich associations are charcteristic for the Pelagonian Unit only, whereas assemblages with nearly equal amounts of zircon and apatite (cluster B, Fig. 5) and apatite-rich assemblages (cluster C, Fig. 5) are of much lower frequency. The terminal flysch of the Palouki Unit is composed of heavy mineral assemblages type B, C and D (Fig. 5). The D-type heavy mineral association, rich in rutile, has not been observed in the Pelagonian Unit.

In the turbiditic sandstone intercalations of Early Cretaceous age from the Palouki Unit, only rutile-rich (cluster D, Fig. 5) and apatite-dominated heavy mineral assemblages (cluster C, Fig. 5) have been observed.

Euboea

The heavy mineral composition is dominated by the ZTR group and apatite (Fig. 4). The content of chrome spinel is below 10 %. Other components, such as garnet, play only a subordinate role. Differences between the two sampling locations are visible in the amount of rutile and tourmaline, which are more abundant in the Psachna–Aghios Pass Road, whereas apatite is more frequent in the Kimi region. Zircon is nearly equal distributed in both locations.

Argolis peninsula

The terminal flysch sediments of Ligourion are clearly distinguished from the other Argolis locations by their high percentages of garnet (av. 63 %) accompanied by apatite and a low content of the ZTR group (Fig. 6). Chrome spinel is only detected in traces. These heavy mineral assemblages are comparable with those of the western Othrys, only with the exception that blue amphiboles were not found in the Ligourion flysch. In the Adheres sample group, only a few samples with such an elevated amount of garnet were observed. The Ligourion samples belong completely to cluster A (Fig. 6).

The Methana sample group comprises mainly heavy mineral associations of cluster B (nearly equal percentages of the ZTR group and of apatite, Fig. 6) and only a few of cluster C (predominance of apatite with relatively high tourmaline). The samples from the Adheres peninsula belong predominantly to the apatite-rich type of cluster C (Fig. 6), whereas a few samples correspond to clusters A and B. Detrital influence of chrome spinel is in both the Methana and Adheres locations higher than in the Ligourion flysch. The highest chrome spinel values are observed in cluster B-type associations (av. 5 %, max. 9).

Poros island

The three samples from the terminal flysch, characterized by high percentages of the ZTR group and apatite (Fig. 4), are in good correspondence with the samples collected in the southern part of the Methana peninsula (Fig. 6, cluster B). In contrast, the turbiditic interlayers within the Poros Formation contain very high values of chrome spinel (av. 85 %) accompanied by only a few percentages of garnet and apatite (Fig. 4).

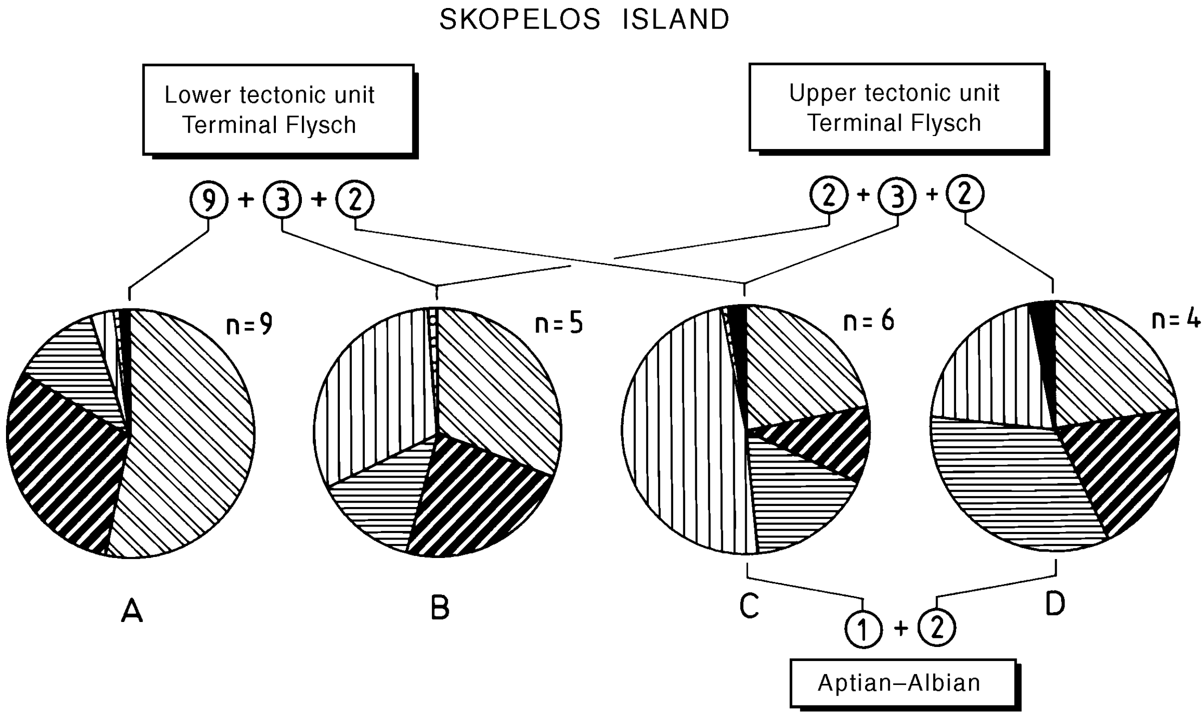

Fig. 5. Average heavy mineral composition of 4 major clusters (A, B, C, D) of the flysch sediments on Skopelos island, separated by a cluster analysis (WinSTAT®, ver. 3.0). The contribution of the individual clusters to the lower (Pelagonian) and upper tectonic (Palouki) unit is shown. For explanation of ornament see Fig. 3.

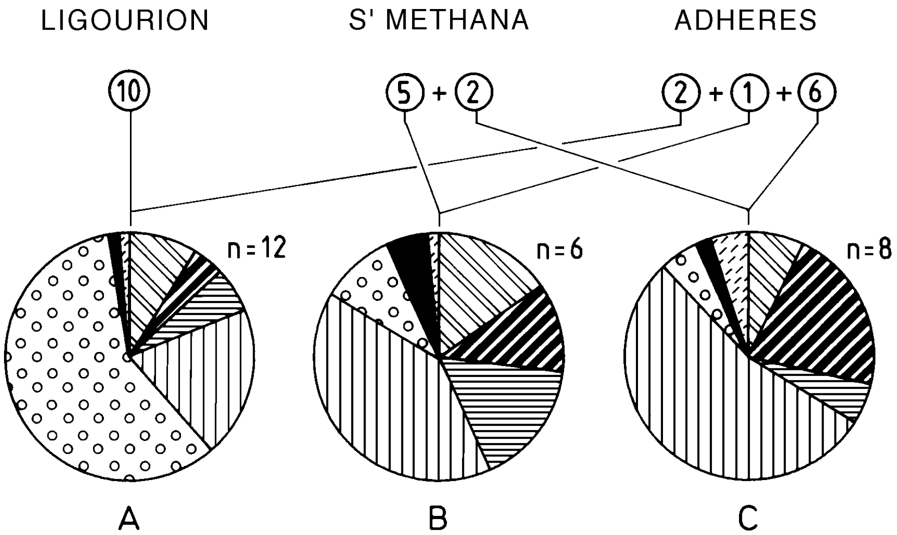

Fig. 6. Average heavy mineral composition of 3 major clusters (A, B, C) of the flysch sediments on Argolis peninsula, separated by a cluster analysis (WinSTAT®, ver. 3.0). The contribution of the individual clusters to the sample locations is shown. For explanation of ornament see Fig. 3.

On the source terrains of the Pelagonian flysch sandstones

On the basis of heavy mineral studies, two major source provinces have been distinguished. The garnet-dominated flysch deposits of western Othrys and Ligourion were supplied from a crystalline basement complex predominantly of medium to high metamorphic grade, indicated by garnet and staurolite. Mica schist complexes seem to play an important role. The abundance of blue amphiboles in the western Othrys gives evidence of the existence of blueschists as part of this metamorphic terrain which had already been exposed during the Paleocene (Faupl et al. 1996). The traces of detrital chloritoid could derived from these high-pressure rock complexes. Otherwise, ophiolitic complexes were only of minor importance in the composition of this source terrain, as indicated by the low percentages of detrital chrome spinel.

All the other sample locations of the Pelagonian Zone s.l. are characterized by the predominance of stable heavy minerals of the ZTR group and of apatite. For these assemblages, principally two explanations are possible: (1) The stable heavy mineral associations are the products of post-sedimentary processes of passive enrichment, such as the dissolution of unstable minerals during burial diagenesis or metamorphism (for stability sequence during burial see Mange & Maurer 1991). (2) These heavy mineral associations mirror, to a broad extent, the petrological composition of a hinterland mainly composed of granitoid rock complexes.

The feldspar-rich composition of the sandstones seems to be a clear indication for the occurrence of feldspar-bearing rocks as major constituents of the source area. Therefore, it can be assumed that the stable heavy mineral associations of the Pelagonian flysch sandstones actually reflect a granitoid hinterland and that post-sedimentary alterations are only of a minor degree. Garnet-bearing rocks, such as mica schist complexes, accordingly, were not of great significance in this source terrain. Only a few exceptions have been observed in the eastern parts of the Othrys and in the Argolis. Ophiolitic rocks, especially ultramafic series, indicated by detrital chrome spinel, appear to have been somewhat more represented in the source of the stable assemblages than within the garnet-dominated one (western Othrys, Ligourion). A large part of the ophiolites obducted during the Late Jurassic and Early Cretaceous were covered during Paleogene, as can be documented on Poros island, where Cretaceous formations bear high amounts of chrome spinel while the Paleocene flysch resting above has only very small amounts.

The heavy mineral stability during progressive metamorphism, especially of detrital chrome spinel or garnet, is hard to estimate, but is of great importance for the interpretation of the heavy mineral assemblages in several regions. In other words, is the stable composition of the heavy minerals, widely distributed in the Pelagonian Zone s.l., the product of metamorphic alterations? An estimation appears to be possible on Skopelos island, where two tectonic units, both with similar heavy mineral associations, occur and where the lower tectonic unit had obviously experienced a somewhat higher metamorphism (Matarangas 1992), clearly seen in the field. Looking at the distribution of detrital chrome spinel, the upper tectonic unit contains somewhat more percentages than the lower tectonic unit, so that a decrease of chrome spinel with progressive metamorphism could be supposed. Otherwise, such a trend is not visible for detrital garnet. Investigations on the stability of accessory chrome spinels within serpentinites in the Alps during progressive metamorphism by Burkhard (1993) demonstrate that the degree of alteration depends highly on spinel chemistry. Fe-rich Cr-spinels are subject to alteration, whereas Fe-poor Cr-spinels are more resistant. The presence of CO_2 is also an important factor. Therefore, we can conclude that a loss of detrital chrome spinel during metamorphism, to a minor extent, has to be expected, but a total elimination of these detrital mineral grains is rather unlikely. There is a good reason to assume that the stable heavy mineral assemblages reflect largely the primarily composition of the hinterland and that post-depositional dissolutions altered the composition of the terrigenous material to only a minor extent.

Summarizing, two major source provinces for the terrigenous material of the Pelagonian flysch sediments can be distinguished: (1) western flysch succession, such as western Othrys and the flysch of Ligourion/Argolis were supplied from a mainly metamorphic source terrain, rich in mica schist complexes, whereas (2) all the other locations derived their material predominantly from a granitoid source.

The Early Tertiary paleogeographic evolution of the Pelagonian realm

According to the Paleocene and Eocene deformational processes within the internal Hellenides, the sedimentary evolution of the Pelagonian domain s.l. is characterized by a remarkable change from a pelagic limestone facies into a terrigenous flysch. The two major heavy mineral assemblages discovered in the flysch sediments of the Pelagonian domain may indicate that two regional different source terrains supplied these flysch sediments. The flysch deposits of the western Othrys Mountains and of Ligourion are clearly distinguished from the other sample locations by their garnet-dominated assemblages. Although no paleocurrent information are available, a source area at the western active margin of the Pelagonian microcontinent can be assumed (Fig. 7). The convergent tectonic activities at this western margin, in accordance with the final closure of the Pindos Ocean (e.g. Robertson et al. 1991), situated paleogeographically to the west of the Pelagonian Unit, caused the uplift of basement rocks which acted as the western source terrain of the Pelagonian Zone. From the same source province, huge masses of flysch sediments of the Pindos and Parnassos-Ghiona zones were derived, also characterized to a large extent by garnet-rich heavy mineral assemblages (Faupl et al. 1994, 1998). The closure of the Pindos Ocean was also accompanied by the obduction of ophiolitic complexes, such as the Pindos Ophiolites (Kemp & McCaig 1984; Jones & Robertson 1991), now resting upon Tertiary flysch sediments. In the terminal Pindos flysch, a massive influx of ophiolitic detritus occurred approximately from Middle Eocene time on, whereas the older sediments are mostly garnet-dominated. The heavy mineral composition of the flysch sediments of the western Othrys and of Ligourion are largely in good accordance with the lower part of the Pindos flysch sediments. In

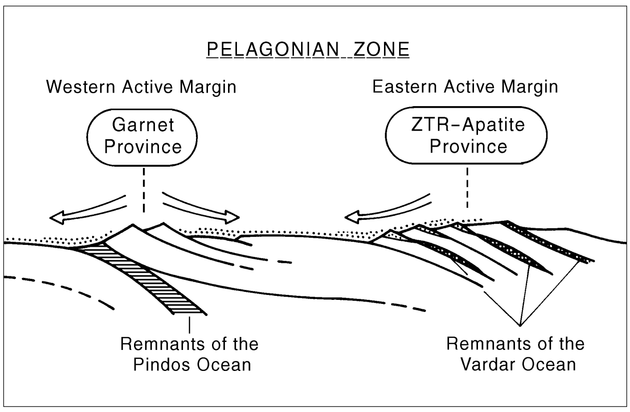

Fig. 7. Sketch depicting the paleotectonic position of the two major source terrains of the terminal flysch sediments of the Pelagonian Zone s.l. during the Paleocene–Eocene (not to scale).

the Pindos flysch successions, especially in the central and southern Pindos Zone, detrital blue alkali amphiboles have been observed, which are also quite frequent in the western Othrys Mountain (Faupl et al. 1996).

The major part of the Pelagonian flysch sediments, characterized predominantly by different mixtures of the ZTR group and apatite, points to a further source province, not regionally connected with the former source. The activity of this source terrain can be interpreted with the closure of a Neotethyan Ocean in the Vardar Zone along the eastern margin of the Pelagonian Unit during the Early Tertiary (Fig. 7), as has been described in models by Clift & Robertson (1989) for the flysch of the Ermioni Complex on the Argolis peninsula and Poros island, as well as for the flysch sediments at Euboea island (Robertson 1990). In this model, an accretionary prism of flysch sediments was emplaced along the collapsed eastern margin of the Pelagonian Zone and shifted further to the west with increasing compressional deformation. Ophiolitic complexes are tectonically incorporated to a lesser extent, and had have only a minor and local influence on the composition of the Tertiary heavy mineral assemblages, as can be especially documented on Euboea, Poros and Adheres. On Poros island, in contrast, the turbiditic detritus of the Cretaceous Poros Formation was dominantly supplied from ophiolitic sequences.

In the detritus derived from the proposed eastern source province, an indication for blueschist rocks has not been detected until now, although the formation of Eo-Alpine blueschists have been reported from the innermost part of the Hellenides, such as the Peri-Rhodopian Zone (Michard et al. 1994a,b). For this reason, we are not longer convinced, as Faupl et al. (1996) supposed, that these very internal zones were the source for the detrital blue amphiboles in the western Othrys. We rather believe that the source of the terrigenous material of the western Othrys, including the blueschist detritus, was situated somewhere at the western margin of the Pelagonian Zone and that the blue amphibole detritus of the Pindos Zone had practically the same source.

In the model shown in Fig. 7, the regional differences in heavy mineral composition were explained by the existence of two active continental margins of the Pelagonian microcontinent which operated as source terrains at approximately the same time. However, these two source areas do not necessarily imply that two clearly separated, parallel flysch basins existed in the Pelagonian Zone.

Conclusions

During Paleocene and Eocene times, terrigenous flysch sedimentation was distributed in the whole Pelagonian Zone s.l., in accordance with the Mesohellenic compressional tectonics. The terrigenous input can be divided into a garnet-dominated heavy mineral assemblage, restricted to flysch sediments of western Othrys and the flysch of Ligourion, and associations with variable amounts of the stable ZTR group and apatite, from all the other locations investigated.

The garnet assemblage, only observed in western locations, is assumed to has been derived from a source at the western margin of the Pelagonian microcontinent, tectonically active due to the closure of the Pindos Ocean. Comparable heavy mineral associations, rich in garnet, are already known from the paleogeographically adjoining Pindos and Parnassos-Ghiona zones.

The stable heavy mineral assemblages seem to principally reflect the primary composition of a predominantly granitoid source situated at the eastern margin of the Pelagonian realm, where flysch sedimentation occurred within an accretionary belt interrelated with the closure of the Neotethyan Ocean (Clift & Robertson 1989; Robertson 1990).

Ophiolite complexes as a source for the Pelagonian flysch sediments generally played a subordinate role. An alteration and reduction of the indicator mineral chrome spinel by low-grade progressive metamorphism in several regions of the Pelagonian Zone has to be expected, but probably only to a minor extent. Blueschist complexes were only exposed in the western source province, which also supplied the Pindos Zone with this typical high-pressure detritus.

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