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GEOTECTONIC EVOLUTION OF THE AEGEAN

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Abstract

The Aegean area has been for long considered as an old area, stabilised before the alpine cycle with only minor block movements creating transgressions and regressions of the sea during Late Paleozoic-Mesozoic and with final characteristic event the Quaternary subsidence of major parts of the present day Aegean. These views were based on immobilistic concepts and on the assumption that the metamorphic rocks of the Aegean were of pre-Alpidic age.
The plate tectonics theory in the Aegean accepted that the Axios ocean separated Rhodope and adjacent areas to the North from "Pelagonian" and the External Hellenides to the South in the period Triassic-Early Cretaceous. Lateron, another ocean was considered, developed during Triassic-Late Cretaceous more to the South, running along the ophiolitic outcrops of Northern Pindos-Cyclades-Izmir.
The evolution of the Aegean area has been considered to be controled by the continuous growth of the active European margin through successive orogenic arcs migrating to the South. The Tertiary evolutionary stages can be restored especially on the grounds of the position of the palaeovolcanic arcs with distinct zones from the present day volcanics in the South to the early Tertiary volcanics in the North. The Late Jurassic-Early Cretaceous volcanic arc has been tectonically translated to a more external position, ovelaping the Miocene volcanic arc.
The new concept of tectonostratigraphic terranes introduced the existence of several large continental fragments within the Aegean area, which are of African origin and have been rifted and drifted northwards during Late Paleozoic-Triassic and have successively collided and accreted to the Southern European margin during Jurassic-Tertiary.
Thus, from the most internal Upper Rhodopean units in the North to the most external lower units of Crete in the South we can distinguish the large continental Pre-Alpine crustal fragments, separated by the oceanic material of the temporary basins of the Tethyan ocean, occurring in the form of ophiolite suture zones or ophiolite tectonic klippen. The genesis of the present day Aegean lithosphere is due to the combination of distinct micro collision events resulting from the accretion of the continental terranes and a rather continuous subduction process of southward derived oceanic lithosphere beneath the European margin in the North.

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1. Introduction-Evolution of geotectonic concepts in the Aegean.

The views on the evolution of the Aegean have been developed throughout this century starting from immobolistic and ending to extremely mobile concepts. In the old views, the Aegean area has been regarded as a stable area, which existed already in Palaeozoic times (Lepsius, 1893, Philippson, 1898, 1901, 1930; Renz, 1940, 1955, Brunn, 1956 and others) with rather simple palaeogeographic evolution throughout Mesozoic and Cenozoic, consisting of vertical block movements with temporary transgressions and regressions of the sea (e.g. in the Late Cretaceous, Trikkalinos, 1954). In this aspect, the Aegean lithosphere should have been created before the Alpine cycle and even before the birth of the Tethys Ocean, implying that the rocks cropping out in the Aegean islands should represent either pre-Alpine basement rocks, belonging to the Variscan or older orogenic cycles, or sediments covering the pre-Alpine basement rocks during the transgressive periods. Some diverging views have contested the above general assumptions (Negris, 1915, Kober, 1929, 1931, Marinos & Petrascheck, 1956) but were not convictive due to lack of data.

The more recent and actual views on the geotectonic structure and evolution of the Aegean are based on plate tectonics (McKenzie, 1970, 1972, 1978, Ninkovich & Hays, 1972, Dercourt, 1972; Dewey et al, 1973; Aubouin, 1977; Durr et al 1978; Jacobshagen et al, 1986) and consider that its lithosphere is still in the process of stabilization. Its southern part below the present-day Cretan Basin lies within the active Hellenic Arc (Fig. 1) and its northern part from the Cyclades islands up to the Rhodopean coastal area has been gradually transformed in a rather stabilized status in the back-arc area within Cenozoic times (Early Tertiary-Late Miocene). These new ideas have been based on the documentation of the Alpine character of the Cycladic blueschists both from new stratigraphic evidence and radiochronologic data (Durr et al, 1978, Papanikolaou, 1978, 1979, 1980, Andriessen et al, 1979, Blake et al, 1981, Altherr et al, 1982) resulting in the notion of the Metamorphic Hellenides (Papanikolaou, 1980).

The overall structure of the Aegean is the result of a continuous process of tectonic activity within the evolving orogenic arc of the Hellenides which started since Late Jurasic-Early Cretaceous but has been documented throughout Cenozoic with geodynamic phenomena occurring both at its deep and shallow tectonic levels (Papanikolaou, 1984).

The palaeogeographic organisation of the Hellenides according to the plate-tectonics theory has started with the assumption of the existence of one major ophiolite suture zone in the Vardar/Axios zone, separating Rhodope s.l. from the Pelagonian block and the external Hellenides to the South (Smith, 1971, Dewey et al, 1973). Lateron, after controversing views (Robertson & Dixon, 1984) the existence of the Pindos-Cyclades ophiolite suture zone was documented, including the outcrops of the Northern Pindos ophiolite and several outcrops spread all over the Cycladic blueschists, characterised by the Eocene tectonic emplacement in contrast to the Pre-Cenomanian tectonic emplacement of the Axios ophiolite. This Pindos-Cyclades ocean separated two large continental fragments within the Aegean lithosphere along the medial tectonometamorphise belt of the Hellenides, the Ios-Menderes continental

crustal block at the base and the Pelagonian crystalline basement nappe on top (Papanikolaou 1986, Fig. 2 & 4).

The above crustal continental fragments have been interpreted as tectonostratigraphic terranes of Gondwanian origin, which during Late Palaeozoic-Triassic have been rifted and drifted from Northern Africa and subsequently have been accreted to the European margin in Jurassic-Tertiary (Papanikolaou , 1989, 1990).

The geotectonic evolution of the Aegean will be described in the following, first focusing on the physicogeographic character of the Aegean Sea and its palaeogeographic representations and second on the evolution of its lithosphere.

2. The paleogeographic Evolution of the Aegean

2.1 The Tertiary Evolution

The present-day physicogeographic character of the Aegean is the result of its geotectonic position and of its geotectonic history. The geotectonic position of the Aegean includes the back-arc basin, the volcanic arc and the back-arc area of the present-day Hellenic Orogenic Arc (Fig. 1). The island arc, represented by Peloponnese, Crete and the Dodekanese Islands and the Hellenic Trench south of Crete are the outer parts of the Hellenic Orogenic Arc, which are not included in the Aegean Sea. Thus, the southern Aegean Sea, including mainly the Cretan Basin, is part of the active arc whereas from the Cyclades Islands to the Rhodope area the Central and Northern Aegean Sea lies outside the present active arc. The boundary between this active arc area and the inactive area of the Aegean lies along the present volcanic arc in the southern margin of the Cycladic platform.

If one takes into consideration the geotectonic history of the Aegean and the tertiary evolution of the Hellenic Arc (Papanikolaou, 1984, 1986), then it is obvious that the presently inactive parts of the Aegean have been active parts in the previous geological periods, constituting the former back-arc basins and volcanic arcs. This palinspastic restoration of the former arcs in the Aegean area has been elaborated for the Late Miocene- Pliocene period (Fig. 2), the Oligocene-Early Miocene period (Fig. 3) and the Eocene period (Fig. 4).

The extension of the paleo-back-arc basins has been determined mainly on the basis of the outcrops of molassic sediments occurring in the Aegean area, either on land along the Aegean coastlines or the Aegean islands or offshore at the sea-bottom below the Aegean Sea. These outcrops of molassic sediments can be grouped in former molassic basins which occurred in the Aegean area, like the Upper Miocene-Quaternaty sediments of the Cretan Basin (Jongsma et al, 1977), the Lower Miocene molasse of the Cyclades islands, which is the SEward prolongation of the Messohellenic Molassic basin (Dermitzakis & Papanikolaou, 1980) and the early Tertiary molassic sediments of the Northern Aegean (Kopp, 1966; Papanikolaou & Dermitzakis, 1981).

The extension of the paleo-volcanic arcs is based on the outcrops of tertiary volcanic rocks (Bellon et al, 1979, Fytikas et al, 1984) or of their corresponding plutonites (Altherr et al, 1982, Schliested et al, 1987, Schuiling et al, 1987). In several

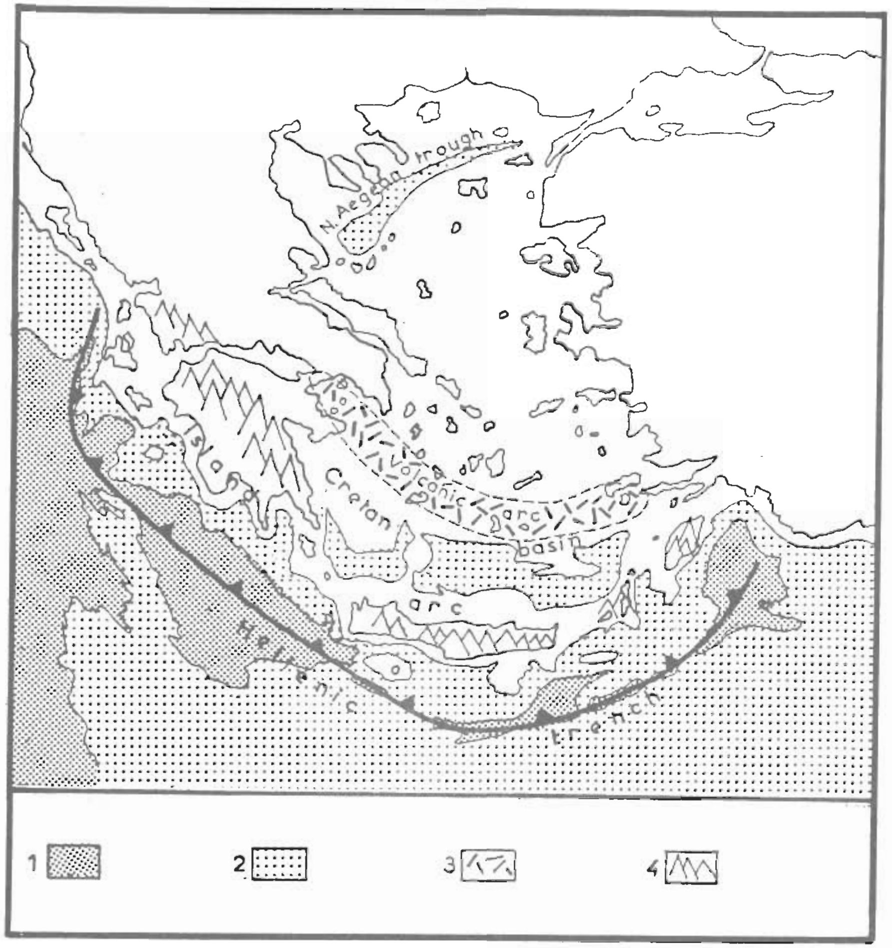

Fig. 1: Present day geotectonic situation of the Aegean indicating the actualistic configuration of the Hellenic Orogenic Arc with the succession of a) the *fore-arc* basin along the Hellenic Trench, b) the island arc along Peloponnese, Crete and Dodekanese, c) the back-arc basin along the Cretan Basin and d) the volcanic arc along the Southern border of the Cyclades.

1: Depths more than 3.000 m.
2: Depths between 1000-3000 m. (white areas offshore represent depths between 0-1000 m).
3: Active volcanic arc.
4: Mountainous area of the island arc.

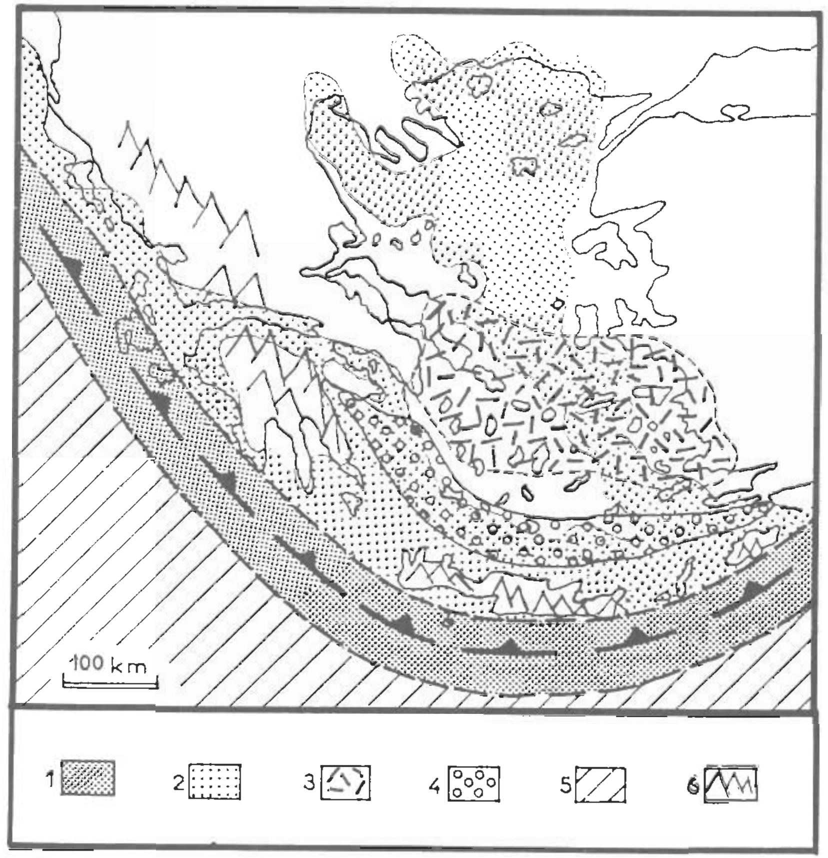

Fig. 2: Palaeogeographic representation of the Aegean at Late Miocene-Pliocene times.
1: Fore-arc basin along the palaeo-trench.
2: Marine environment (in white the emerged land).
3: Volcanic arc.
4: Mollasic sedimentation of the back-arc basin
5: Pre-Orogenic area to the South of the Pliocene orogenic arc
6: Island arc

cases, like in Lemnos and Lesvos islands, the volcanic rocks are preserved in extended outcrops. However, in other cases the volcanic rocks have been eroded in the meantime, mainly due to important tectonic uplift of the area, as in the case of the Cyclades Islands, where the Miocene volcanic arc is represented by numerous granodiorite plutons and dykes (Serifos, Tinos, Naxos, Ikaria, Andros) without outcrops of volcanic rocks. This uplift has been followed by epidermic deformation of gravitational character with low angle normal faults and extension of the rocks (Dermitzakis & Papanikolaou, 1979, Papanikolaou, 1980, Lister et al, 1984, Avigad & Garfunkel, 1989, Gautier et al, 1990, Lee & Lister, 1992).

In the Late Miocene-Pliocene and the Oligocene-Early Miocene paleogeographic representations, (Fig. 2 and Fig. 3) the volcanic arc is occurring parallel to and behind the molassic back-arc basins, as this is the case also in the actual tectonic setting (Fig. 1). On the contrary, at the early Tertiary paleogeographic representation (Fig. 4) the extension of the paleo-volcanic arc largely overlaps with the extension of the paleo-back-arc basin. This coincidence indicates that either the subduction was effected with higher angle or the subduction rate was lower and thus the melting of the subducted rocks occurred closer to the back-arc basin.

The first conclusion is that the Aegean area has existed since early Tertiary, when the molassic back-arc basin of the Rhodope and Northern Aegean was formed and then successively it was grown up to its present extension by a southward migration of the arc, which resulted in the present-day back-arc basin in the Cretan Sea and the back-arc area covering the Central and Northern Aegean Sea. In other words, the Northern Aegean area has been, in fact, a permanent marine environment throughout Cenozoic with dominance of deep sedimentation first of molassic type, during Eocene-Oligocene times and second of post-orogenic sedimentation within the Saros Neotectonic Graben since Miocene times.

During this Cenozoic evolution of the Aegean there have been periods when the Aegean was dominated by a unique marine environment and periods when the Aegean was divided in a Northern Aegean basin and a Southern Aegean Basin, separated by an intermediate land area, known as "Aegaeis" (Philippson, 1898, 1930, Trikkalinos, 1954). This basic change of the Aegean geography has occurred in Early Miocene times, when the Cycladic molassic back-arc basin was formed approximately at the area of the Southern Cyclades, separated by the Northern Aegean Basin in the North (Fig. 3). At this period the areas of continental Greece were linked to Minor Asia through Attica, Southern Evia, Northern Cyclades, Ikaria and Samos. This Aegaeis land area separating the Northern Aegean from the molassic basin in the South was maintained also in Late Miocene times (Fig. 2), when intensive volcanic activity dominated. Well known Miocene mammal fossils indicate the existence of the bridge between the two Aegean coasts.

In the meantime, the new molassic basin was formed in the Cretan Basin between Aegaeis and Crete, representing the island arc, whereas the previous molassic basin of the Cyclades has been uplifted and slightly displaced in parautochthonous position by gravidational movements (Dermitzakis & Papanikolaou, 1979). The reorganization of the arc is related to the lateral escape of Anatolia (Papanikolaou & Dermitzakis, 1981) under the new tectonic regime established after the collision of

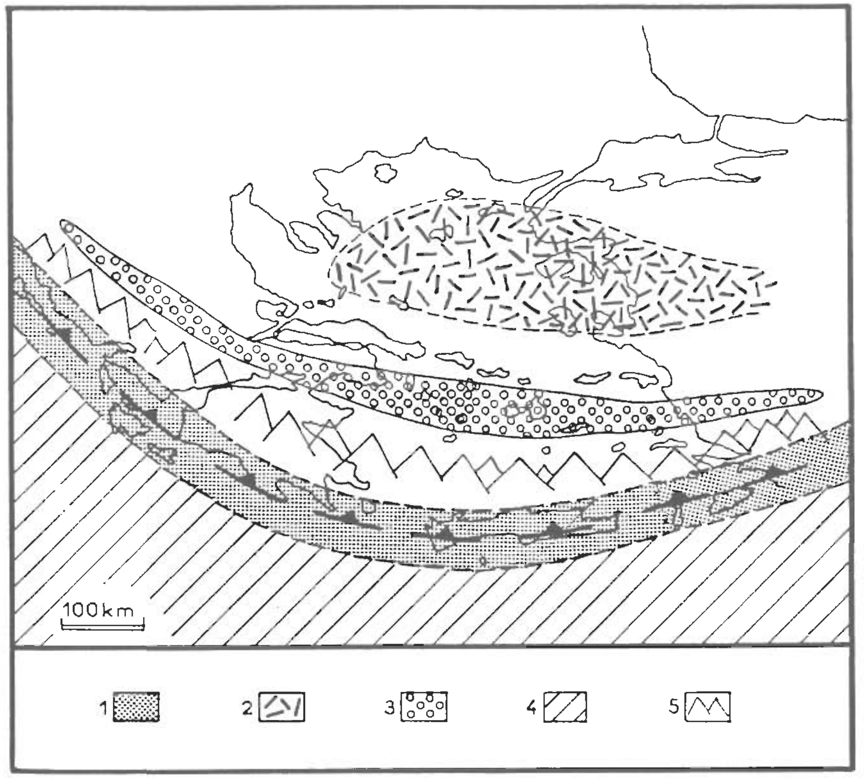

Fig. 3: Palaeogeographic representation of the Aegean at Early Miocene times
1: Fore-arc basin along the palaeotrench
2: Volcanic arc
3: molassic sedimentation along the back-arc basin
4: pre-orogenic areas
5: island arc

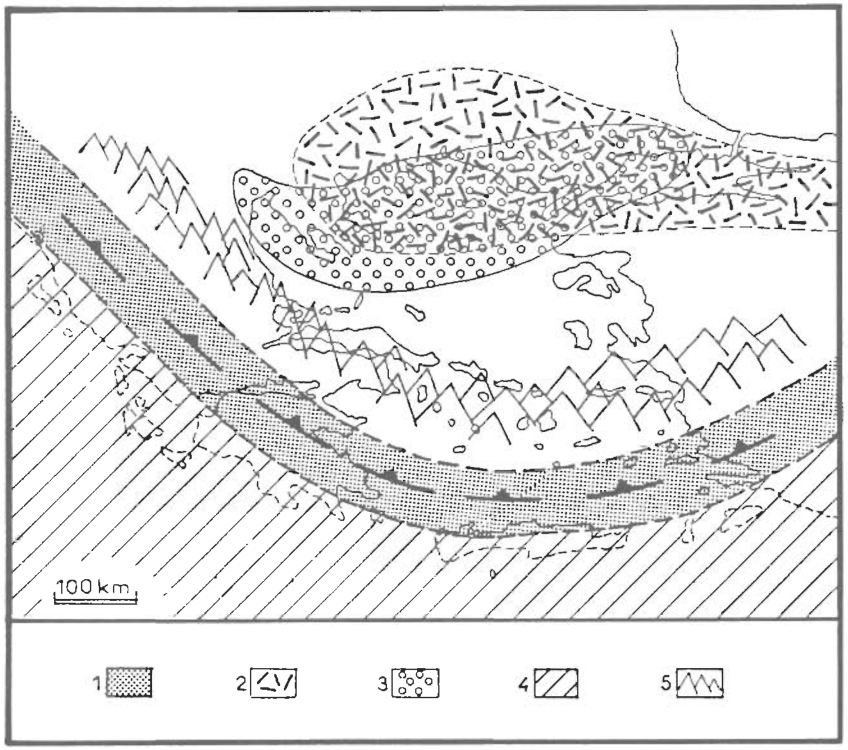

Fig. 4: Palaeogeographic representation of the Aegean at Late Eocene-Oligocene times.
1: fore-arc basin along the palaeo-trench (flysch sedimentation)
2: volcanic arc
3: back-arc basin (molassic sedimentation)
4: pre-orogenic areas
5: island arc

Arabia with Eurasia in Late Middle Miocene times (McKennzie, 1970, 1972, 1978, Mercier, 1979). This lateral escape resulted in the beginning of the bending of the Hellenic Arc, which step by step obtained its high curvature of more than 90^0, as this has been calculated by Le Pichon & Angelier (1981) and has been verified recently by geodetic measurements (Biliris et al, 1991).

Since Late Miocene times the Aegean area has been modified in two parts: (i) the opening of the Cretan Basin and the resulting southward migration of Crete from the Cyclades area and (ii) the subsidence of the Aegaeis intermediate land, which resulted in the creation of the Cyclades Islands, representing the summits of the former land area. The first linkage of the Northern Aegean basin with the Cretan basin has occurred in latemost Miocene-Pliocene, as the very few outcrops of marine sediments on the islands of Skyros, Ikaria and Milos permit to suggest. In any case, the generalized subsidence of the Cyclades area has occurred quite recently in Quaternary and this is also reflected in the submarine cycladic platform unifying all the islands at a depth of 100-140 m. The edge of this platform delineates the submerged paleocoast of the recent glacial period, which subsided due to vertical eustatic movements, following the climatic flunctuations of Quaternary.

2.2 The pre-Tertiary situation.

The evolution of the Aegean area from Present to early Tertiary has been previously described and illustrated in Figs 1-4. The earliest paleogeographic representation, representing the Eocene period, includes the northern parts of the Aegean which were configurated at first. These areas can not be accepted as parts of the Aegean in prior times because the arc should occupy other areas more to the North within Rhodope, outside the Aegean coastal areas.

Aubouin (1977) demonstrated the existence of an orogenic arc in the Internal Hellenides during Late Jurassic-Early Cretaceous, which resulted in the so-called paleo-alpine (or eo-alpine) orogeny. This paleo-geodynamic reconstruction includes the subduction of the Vardar-Axios Ocean below the Serbo-Macedonian Massif with a back-arc basin in the Peonia Unit and a volcanic arc in the Paikon Unit and the Serbo-Macedonian Massif. The Granodiorite of Fanos and the Rhyolites of Paikon of Upper Jurassic age (Mercier, 1968) are characteristic indicators of this early paleo-volcanic arc of the Hellenides.

Nevertheless, the position of these paleo-volcanic outcrops within the tectonic structure of the Hellenides is not where it would be expected, following the overall evolution of the orogenic arcs. Thus, the Upper Jurassic-Lower Cretaceous volcanic arc is occurring approximately at the area on the Miocene volcanic arc. Instead, the "normally" expected position should be in more internal position than the Eocene volcanics of Rhodope shown on Fig. 4. It is remarkable that the volcanic arc of Late Cretaceous occurs in the area of the Sredno-Gorie zone in the Southern Balkanides as at is expected (Fig. 5). The "anomalous" position of the Late Jurassic-Early Cretaceous volcanic arc is attributed to the very important tectonic reworking of the European margin during the Late Cretaceous-Early Tertiary period, when the nappe structure of the internal tectonometamorphic belt was formed (Papanikolaou, 1984, 1985).

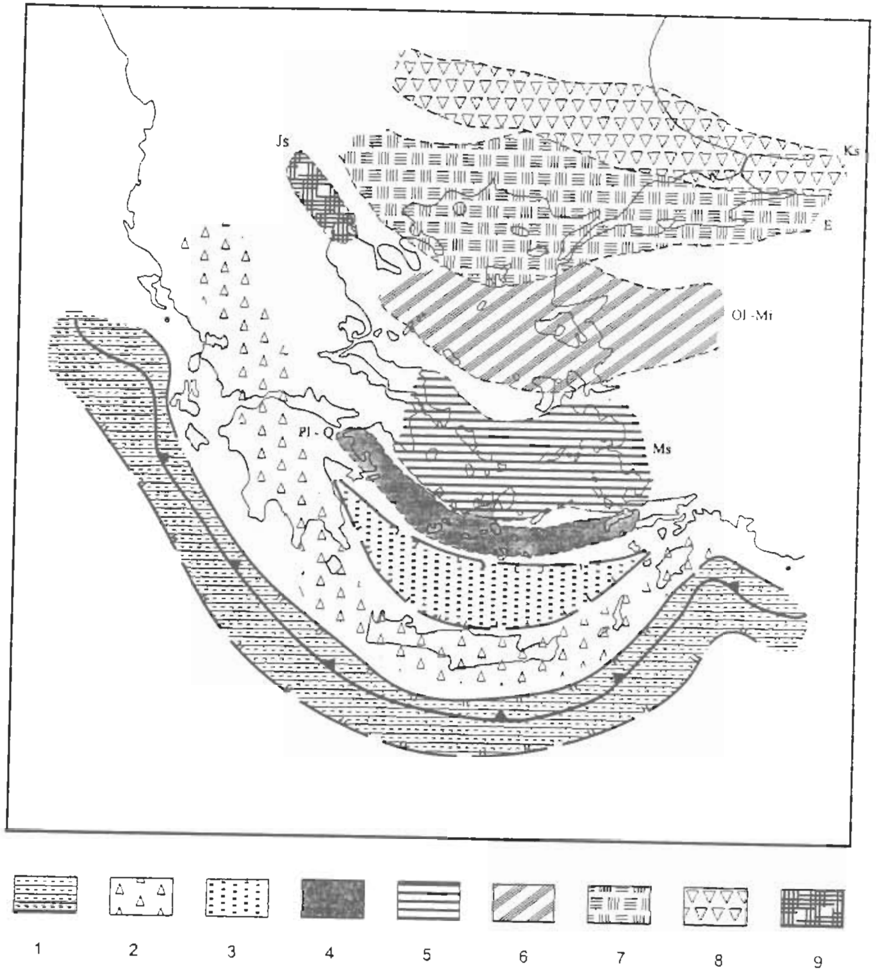

Fig. 5: Schematic representation of the actual Hellenic Orogenic Arc and of the previous positions of the volcanic arcs. The general outcome is that the previous positions of the volcanic arcs can be traced back to the North, step by step, as early as Late Cretaceous times (Ks), whereas the paleo-volcanic arc of Late Jurassic-Early Cretaceous is lying within the zone of early Tertiary orogenic volcanic arcs. This "anomalous" position implies a great scale allochthony of lithosphaeric fragments in early Tertiary.
1: Actual Hellenic Trench –fore-arc basin
2: Actual Hellenic Island Arc
3: Actual Hellenic back-arc basin
4: Actual Hellenic volcanic arc (Pl-Q)
5: Volcanic arc during Late Miocene (Ms)
6: Volcanic arc during Oligocene-Early Miocene (Ol-Mi)
7: Volcanic arc during Eocene (E)
8: Volcanic arc during Late Cretaceous (Ks)
9: Volcanic arc during Late Jurassic (Js)

In conclusion, the history of the Aegean can not be traced back beyond Cenozoic, even if the concept of the Aegean is understood as the back-arc basin of each orogenic arc of the Hellenides.

3. The geotectonic structure and evolution of the Aegean Lithosphere.

The Aegean Lithosphere is consolidated only in the northern part, belonging to the Eurasian Plate, whereas the southern part is in the process of consolidation and/or deformation, belonging to the active European margin. If one accepts as basic criterion for the consolidation process the effect of the volcanic arc activity on the rocks, through the granite intrusions and the infiltration of magmatic fluids, creating HT/LP greenschist and amphibolite metamorphic assemblages and contact metamorphic aureoles around the intruding plutons, then the stabilised lithosphere of the Aegean extends to the North of the Southern Cyclades Islands, where the actual volcanic arc occurs (Fig. 6). Instead, the lithosphere in the Cretan Basin is subjected to stretching and internal deformation, related to the overall activity of the orogenic arc.

The previous description of the tertiary paleogeographic evolution of the Aegean, shown on Figs. 1-4, indicates also the gradual growth of the consolidated Eurasian lithosphere, which followed the southward migration of the volcanic arc. Thus, during early Tertiary the newly consolidated parts of the Eurasian Plate were extending until the Rhodope area, whereas in Miocene times they reached successively the Limnos, Lesvos, Chios and Samos islands until the present position in the Southern Cyclades Islands.

The structure of the Aegean Lithosphere comprises several tectonostratigraphic terranes, representing either pre-alpine continental crustal fragments together with their alpine sedimentary cover, which is usually shallow-water carbonate platforms or oceanic lithosphere and associated abyssal-pelagic sediments of the Tethyan basins (Papanikolaou, 1989). The N-S profile of the Aegean area showes the terrane structure (Fig. 6) which is characterized by the extended masses of the continental crustal rocks External Hellenides Platform-H_1, Internal Hellenides Platform-H_3 and Rhodope Massif-H_7, separated by the two main oceanic terranes forming the ophiolite suture zones of the Vardar-Axios-H_4 and the Pindos-Cyclades-H_2. Between the Axios ophiolites-H_4 and the Rhodope Massif, represented mainly by the Pangeon Unit-H_7 there are several terranes of small dimensions both of continental character, like Paikon Block-H_5 and Serbo-Macedonian-East Rhodope Massif-H_9 and of oceanic character, like the Circum Rhodope-H_6 and the Volvi-East Rhodope ophiolites-H_8.

The three major continental terranes H_1, H_3 and H_7 are composed of pre-alpine metamorphic rocks and of Mesozoic carbonate cover as follows: (i) Ios-Menderes basement rocks/ External carbonate platform, including the units of Olympus, Amorgos, Tripolis, Mani e.t.c. (ii) Pelagonian basement rocks including the Flambouron and Kastoria Units/ Internal carbonate platform including the Sub-Pelagonian, and Almopia Units, (iii) Rhodope Massif, including the basement rocks of Pangeon Unit and possibly also of Sidironero and Kerdylia Units/ Metamorphosed carbonate cover of Pangeon Unit. The above terranes constitute huge tectonic windows below the allochthonous rocks of the oceanic terranes. Especially at the Olympus Mt

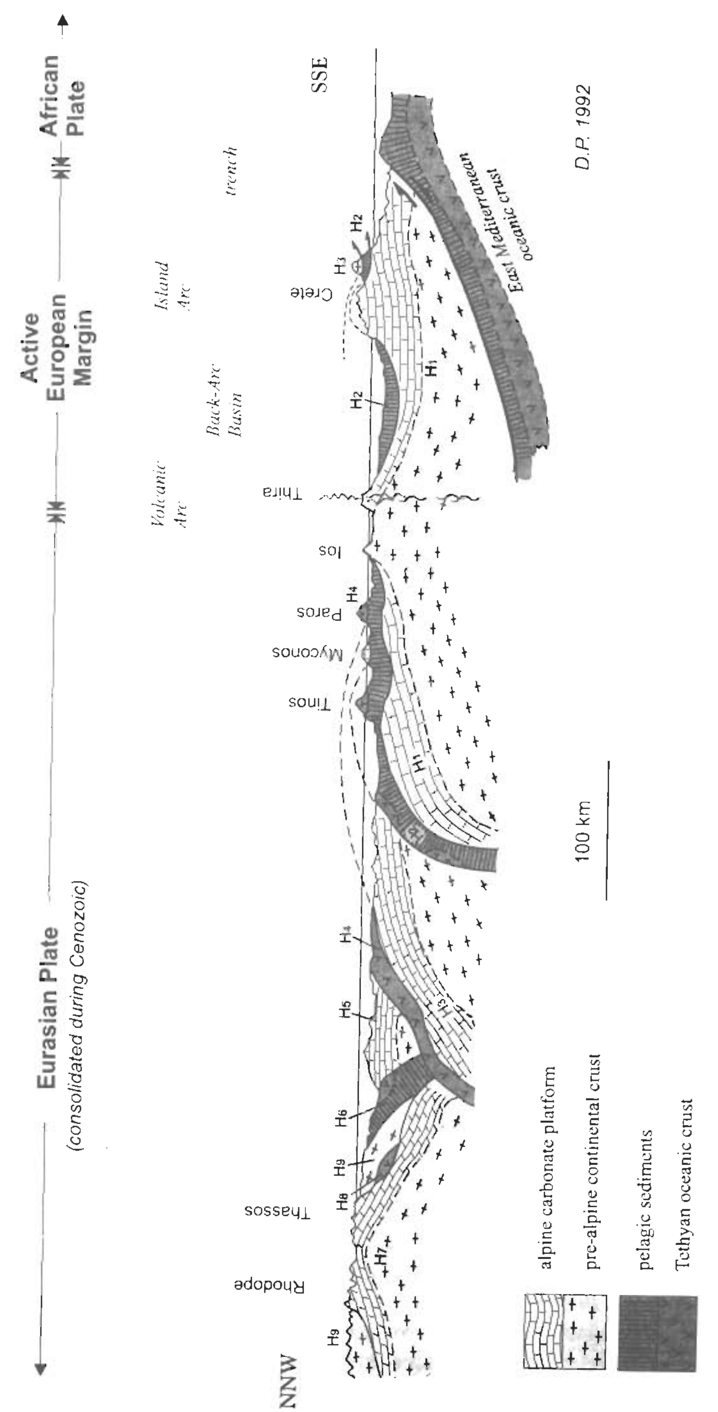

Fig. 6: The terrane structure of the Aegean Region along the tectonic profile Rhodope-Crete.

one can observe the tectonic superposition of the Vardar-Axios Oceanic terrane H_4 over the Internal Hellenides Platform of the continental terrane H_3, which in turn is overlying the blueschists and ophiolites of the oceanic terrane of the Pindos-Cyclades H_2, which in turn is tectonically overlying the External Hellenides Platform of the Olympus Unit H_1. This structure started with the Late Jurassic-Early Cretaceous emplacement of H_4 over H_3, as the Cenomanian transgression indicates (Brunn, 1956, Mercier, 1968) and ended with the late Eocene-Oligocene emplacement of terranes H_4, H_3 and H_2 over the relative autochthonous Olympus Unit H_1, as the Eocene flysch of Olympus Unit indicates (Godfriaux, 1968).

It is remarkable that the more internal terranes are observed in the form of tectonic klippen over more external terranes in various Aegean islands, demonstrating the southward tectonic transport. Thus, the oceanic terrane H_4 of Vardar Axios is observed on the island of Paros, where Barremian limestones are covering the ophiolites of the higher nappe of the island (Papanikolaou, 1980). The Internal Hellenides Platform-H_3 is observed in several outcrops, as in the case of Mykonos, where Triassic non-metamorphic carbonates tectonically overlie the crystalline basement (Papanikolaou, 1980). On Tinos Island there are important ophiolite outcrops over the blueschists of the Pindos-Cyclades terrane (Avigad & Garfunkel, 1989, 1991). On Ios Island the pre-alpine metamorphic basement of H_1 crops out below the Southern Cyclades blueschists of H_2 (Van der Maar & Jansen, 1983). Finally, in Crete the metamorphic rocks of the Asteroussia tectonic klippen (Bonneau, 1972, 1984) may be attributed to the basement of H_3 which is tectonically imbricated with the ophiolites and related sediments of the Pindos oceanic terrane H_2 which in turn is tectonically emplaced during Oligocene-Early Miocene times over the External Hellenides Platform H_1.

In conclusion, the geotectonic structure and evolution of the Aegean is the result of a continuous convergence between the European and the African Plate. This convergence includes subduction of oceanic basins of the Tethys Ocean and micro-collision events corresponding to the accretion of continental terranes of Gondwanian origin to the European margin.

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