PALEOMAGNETISM IN GREECE AND GEODYNAMIC IMPLICATIONS: A REVIEW OF DATA FROM PALEOZOIC, MESOZOIC AND CENOZOIC FORMATIONS

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A B S T R A C T

In the last decade or so an important number of paleomagnetic data have been obtained in Greece by different research teams. These data can be schematically divided in two groups according to their age. In the Paleozoic-Mesozoic which is more scarcely covered, information is mainly provided about latitudinal movements because of the extreme complexity of the geological history at that period. The Cenozoic, where plate movements are better constrained, provides a dense network of paleomagnetic directions. An emphasis is thus given to the evaluation of this set of data and their compilation with new concepts of the regional tectonics.

ΠΑΛΑΙΟΜΑΓΝΤΗΙΣΜΟΣ ΣΤΗΝ ΕΛΛΑΔΑ ΚΑΙ ΓΕΩΔΥΝΑΜΙΚΕΣ ΣΥΝΕΠΕΙΕΣ: ΜΙΑ ΑΝΑΣΚΟΠΗΣΗ ΔΕΔΟΜΕΝΩΝ ΑΠΟ ΜΕΣΟΖΩΙΚΟΥΣ ΚΑΙ ΚΑΙΝΟΖΩΙΚΟΥΣ ΣΧΗΜΑΤΙΣΜΟΥΣ

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Π Ε Ρ Ι Λ Η Ψ Η

Την τελευταία δεκαετία, σημαντικός αριθμός παλαιομαγνητικών δεδομένων δημοσιεύθηκαν για την Ελλάδα από διάφορους ερευνητές. Ανάλογα με την ηλικία μπορούμε σχηματικά να τα χωρίσουμε σε δύο ομάδες. Το Παλαιοζωικό-Μεσοζωικό, αραιότερα καλυμμένο, δίνει πληροφορίες κυρίως για κατά πλάτος μετακινήσεις λόγω της περίπλοκης γεωλογικής του ιστορίας. Το Καινοζωικό, όπου οι κινήσεις των πλακών είναι καλύτερα προσδιορισμένες, παρέχει ένα πυκνό δίκτυο παλαιομαγνητικών διευθύνσεων. Εμφαση δίνεται στην αξιολόγηση αυτών των δεδομένων και τον συνδυασμό τους με νέες αντιλήψεις για την τεκτονική της περιοχής.

INTRODUCTION

In a general way, the initiation of the paleomagnetic method has been derived by geomagnetic and rock magnetic studies before being applied to geological problems. In Greece, the evolution has been similar though the geological applications have rapidly become dominant.

The first magnetic studies on rocks have been published by Kiskyras (1938, 1942) and Stavrou (1957). The first paleomagnetic results appeared almost ten years later on Pliocene volcanics

(Bobier, 1968), followed by a study of some jurassic volcanics (Pucher et al., 1974).

A remarkable progress has started around 1980 with simultaneous efforts by different persons or teams in various research centers (Papamarinopoulos, 1978; Laj et al., 1982; Kondopoulou, 1982). In the following ten years an important set of data has been accumulated by different researchers on a broad band of subjects (magnetostratigraphy, archeomagnetism, magnetic mineralogy, paleomagnetism applied to geology).

The present synthesis will focus to the paleomagnetic data with geodynamic and structural implications.

Some detailed and well-documented data compilation and arising interpretations for the area (Greece, the Aegean and surroundings) have been included in recent reviews (Marton, 1993; Van der Voo, 1993). In the present work, nevertheless, additional data not available to these authors-published in local journals, recently published or submitted - will complete the above compilations and possibly highlight questions and controversies pointed out by the previous authors.

This work will be organised in two major parts. In the first one all available data for the Paleozoic and Mesozoic (quite scarce) will be grouped and discussed. In the second part, the Cenozoic, much more covered, will be examined together with a number of independent models proposed after seismological, structural, and geodetic studies.

As these data sets are the products of different persons or/and research centers, it is of great importance to determine their reliability. For this purpose the following approaches will be used:

1. Quality factors established by data banks (i.e. Strasbourg).
2. Quality factors or classifications used by other authors for the same data (Marton, 1993; Van der Voo, 1993).
3. Finally, for the cases of data non-qualified by independent authors an effort will be made to attribute to them a quality factor using standard, broadly accepted criteria (statistical parameters, age determination, stability tests etc).

PALEOZOIC AND MESOZOIC DATA

The present-day tectonic setting of the Eastern Mediterranean is the result of a long and complex history of lithospheric openings and closures since late Paleozoic times. Studies and geological synthesis have attempted to model the plate evolution in the area, showing a number of microplates drifting between Africa and Eurasia during the Mesozoic closure of the Tethys ocean (Biju - Duval et al., 1977; Smith and Woodcock, 1976b; Robertson and Dixon, 1984). The paleolocations of several microplates remain still uncertain and paleomagnetism can allow choices between different paleopositions proposed by the geological reconstructions.

In the Greek area plate convergence started in the Mid Jurassic, resulting in intra-oceanic subduction followed by ophiolites emplacement. These ophiolites occuring abundantly in the mobile zones of Yugoslavia, Greece, Cyprus and Turkey, could be the obducted remnants of the Paleo-Tethys which closed in

Post-Triassic times. There have been controversial theories about the origin of ophiolites in Greece and the rare paleomagnetic data available cannot support sufficient arguments on this (Ricou et al. 1984; Robertson and Dixon, 1984).

In a general way, we will see that much work remains to be done in the Greek Paleozoic-Mesozoic for the establishment of consistent paleomagnetic directions. A number of studies driven between 1980 and 1992 try to estimate:

a) The paleolatitudes.
b) The intrablock rotations.

Before proceeding to the detailed analysis of the Paleozoic and Mesozoic data presently available for Greece an important remark has to be made.

In old, tectonised units, unique magnetic components are rarely observed. The sometimes numerous secondary ones may obscure the interpretation but also provide information about the tectonic evolution and the timing of remagnetization.

In most of the following data overprints, partial or complete, are very frequent and only the establishment of well-documented series of them will enable us to unravel the succession of events affecting the different formations.

We will now proceed to the detailed examination of all available Paleozoic and Mesozoic data by chronological order, that is, from older to younger formations. The locations of the studied sites are given in figure 1.

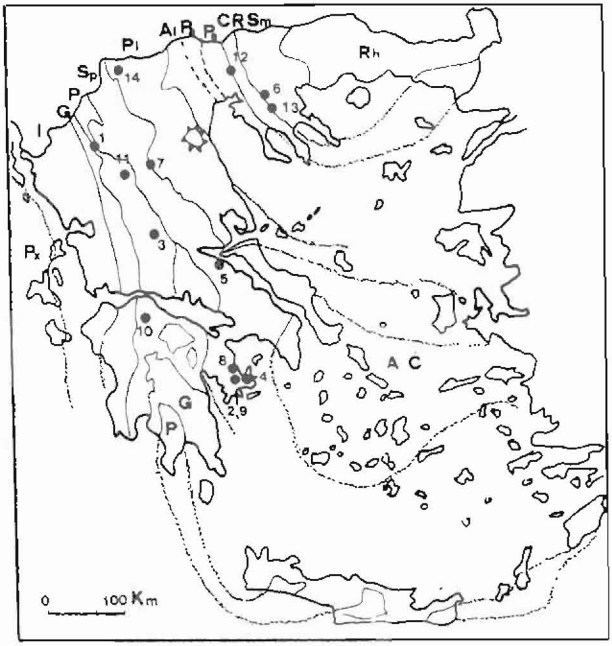


Fig.1. Simplified sketch map of Greece (after Moundrakis, 1985) with the localities sampled for the Paleozoic-Mesozoic.

PALEOZOIC DATA

1. **LATE CARBONIFEROUS** (approximately 300 Ma). The granites of the N. Pelagonian (Edel et al., 1992) display three groups of directions. The oldest one, interpreted as an overprint acquired in Late Jurassic - Cretaceous, is labelled M (D=320° I=26°). The younger C_2 is a Tertiary overprint with a very low inclination (D=64° I=3°) whereas prior to this a direction C′ (D=39°, I=-9°) is interpreted as due to the backthrusting of the N.Pelagonian during the Early - Middle Tertiary convergence phase. The succession of directions suggests a Late Cretaceous counterclockwise rotation, followed by a Tertiary clockwise one.

2. **UPPER CARBONIFEROUS TO LOWER TRIASSIC.** Rhyolites in the SM massif studied by Lauer and Kondopoulou (1991) yield a primary direction with D=339° I=8; which is almost antiparallel to the one obtained by Turnell (1988) in Triassic lavas more to the South (D=170° I=-8°). Consequently the authors suggest that the latitudinal distance between the SM and Pelagonian zones did not change much in later times. At the same time the presence of NE secondary components favours a model of older CCW and younger clockwise rotations as stated also in 1.

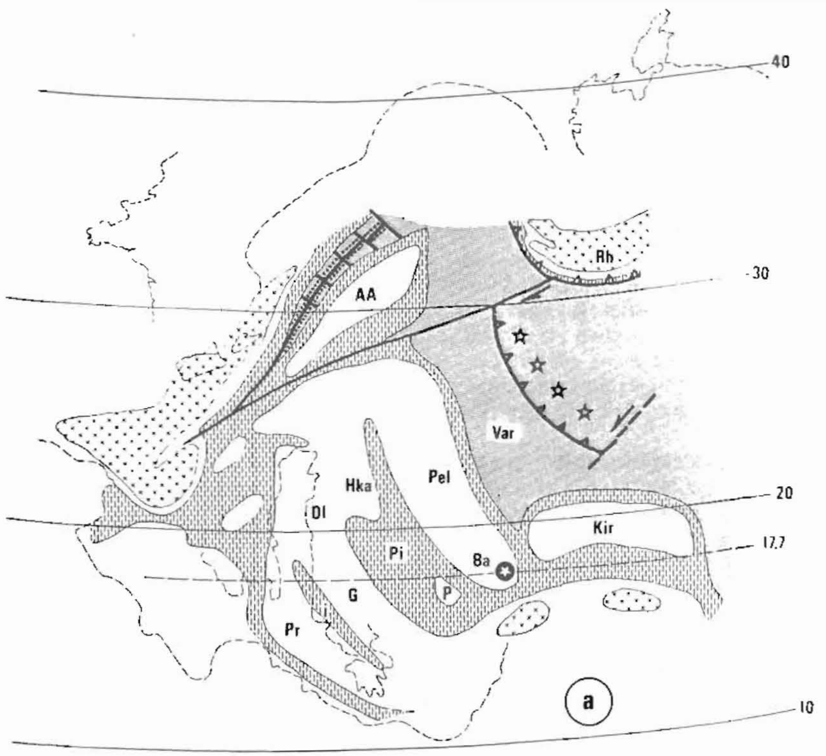
MESOZOIC DATA

1. **PERMOTRIASSIC.** Volcanics in the S.Pelagonian (Lauer and Kondopoulou, 1987) yield a direction D=352° I=-7° very similar to the ones obtained later in other areas (see 1,2). This direction is also similar to those found within the triassic units of W. Antalya. Attention is drawn to the very low paleolatitudes and a model with considerable CCW and CW rotations for the Pelagonian is proposed for the first time.

2. **TRIASSIC.** In sub-Pelagonian lavas, Turnell (1988) has obtained a mean direction D=170° I=-8° discussed already in 2. The author claims that the absence of rotations is not real, as we know that in neighbouring areas about 40° of CW rotation occurred in Tertiary and CCW ones before. Thus, the net rotation displayed here is the sum of these two opposite ones.

3. **EARLY TO MIDDLE JURASSIC.** Sedimentary rocks of about 170 Ma have been sampled and carefully studied in Argolis peninsula (Bafi) by Surmont (1989). The author claims that because of the strong tectonic disruption the calculated declinations are only of local interest. On the contrary inclinations remain significant giving a paleolatitude of 15.3°N.
A paleogeographic reconstruction is also proposed (fig.2.).

4. **JURASSIC.** Carbonates in Argolis have been studied by Turnell (1988) and by Morris (1990). The first author calculates from I values a paleolatitude of about 20°N which is in satisfactory agreement with the one obtained in the same region by Surmont. Both Turnell and Morris calculate an about 70° CW rotation since Jurassic and claim that part of this rotation was pre-Middle Miocene, whereas another part (≈25°) is recent.



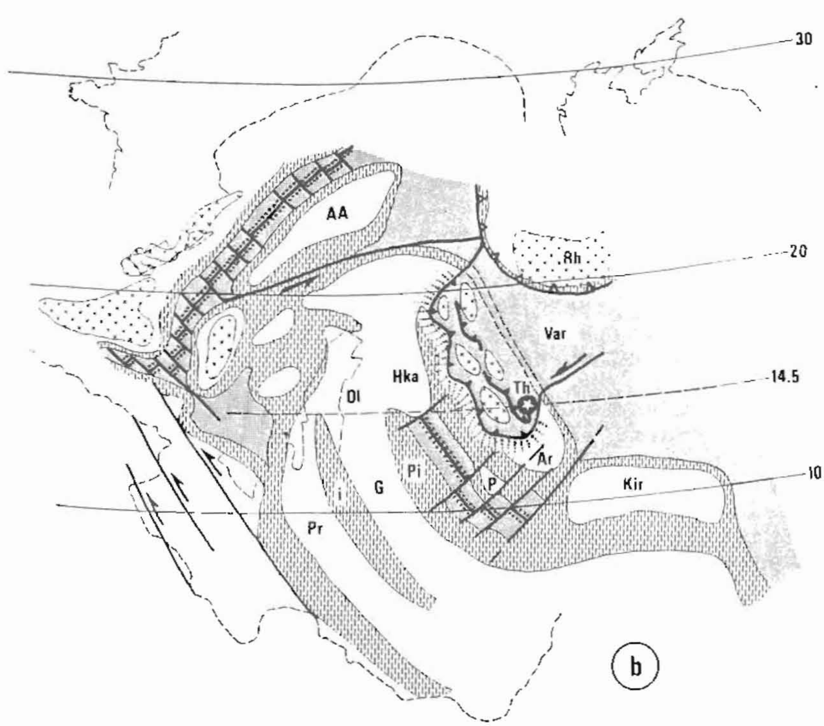


Fig.2. Paleogeographic reconstructions a) for 177 Ma b) for 130 Ma. stars:studied sites. From Surmont (1989).

5. **JURASSIC-CRETACEOUS.** The Chalkidiki ophiolitic sequence has been studied briefly by Filippopoulos (1988) and extensively by Edel et al. (1991). The first author calculates a mean direction D=75° I=47°. In the second study three groups of directions have been isolated a) D=62° I=27.5° interpreted as a Tertiary overprint b) D=242° I=30° possibly due to tilting in Late Cretaceous and c) D=314° I=34°, labelled as the oldest one of Jurassic, Early Cretaceous age. It is thus evident that Filippopoulos mean direction is simply the Tertiary overprint and no other component could be detected, probably because of insufficient cleaning. The oldest component found by Edel et al. (1991), falls into a group obtained in other areas mentionned above (see 1,2,4) and is probably syntectonic with the emplacement of the ophiolites. Additionally the authors suggest that as a consequence to this grouping relative motions between the different sites in different zones should have been negligible. A possible reconstruction is proposed by Edel et al. (1992) in Figure 3.

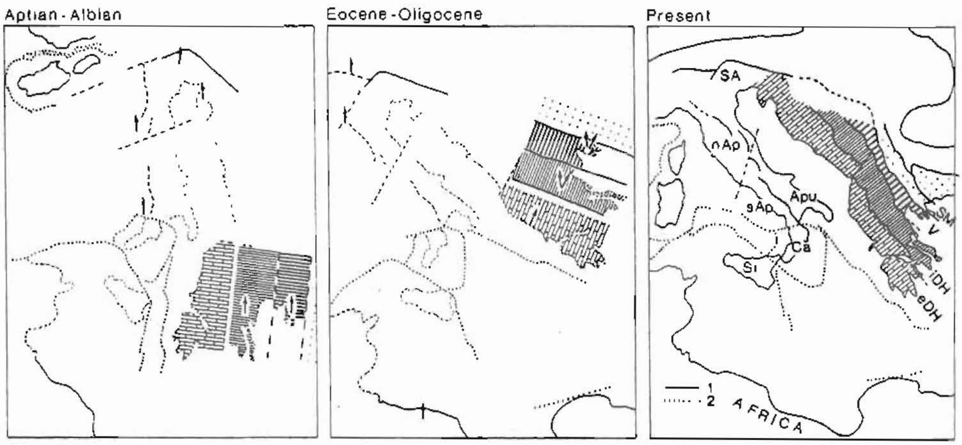


Fig.3. Possible reconstruction of Central Mediterranean drawn from paleomagnetic directions (after Edel, 1980), and the directions listed in Westphal et al. (1986) and the relative positions of Africa and Europe (Olibet, 1978). The lateral extension of the external (eDH), internal (iDH) Dinarides-Hellenides, the Vardar (V) and Serbo-Macedonian (SM) zones (after Sandulescu, 1984) is arbitrary. The reconstruction for the Eocene-Oligocene is based on the C1 directions; at time of emplacement of the C2 magnetizations (probably Oligocene), the Hellenides were striking E-W.
1: faults and thrusts; 2: present block boundary; SA: southern Alps; nAp:northern Apennine; sAp: southern Apennine; Apu: Apulia; Ca: Calabria; Si: Sicily. All references in Edel et al. (1992).

6. **JURASSIC - EARLY CRETACEOUS.** A post-ophiolithic sedimentary sequence of about 130 Ma has been also studied by Surmont (1989) in the S.Pelagonian. Though the author concentrates again only in paleolatitudes (=15°N) and arizing paleogeographic reconstructions, the mean direction obtained in this study (D=321° I=27°) is very coherent with the pattern proposed by the other authors in almost all studies mentioned above.

7. **JURASSIC - CRETACEOUS TO CRETACEOUS.** The Mesozoic clockwise rotation mentioned for Argolis (see 4) is not unique in the area. A number of independent studies in the Pindos, Paxos and Ionian Zones (Horner, 1983; Marton et al., 1990; Morris, 1990) report declinations deviated to the East with variable angles (from 10° to almost 90°).

Clockwise rotated Mesozoic formations have also been found in the Ionian zone of Albania (Mauritsch et al., 1993). With the present state of knowledge we can conclude that a differentiation exists between internal and external parts of the Hellenides as far as the rotational behaviour is concerned. (Fig.4.)

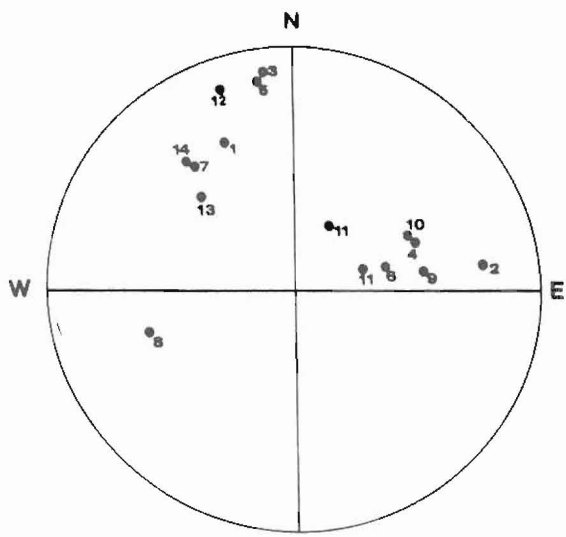


Fig.4. Stereographic projection of mean directions for the Mesozoic. Numbers correspond to Table 1.

To our knowledge no other data set is available for the Paleozoic-Mesozoic in Greece. A synopsis of all the above data would lead to the following conclusions:

1. The oldest magnetizations detected are of Triassic age. Though carboniferous formations have also been studied, their initial primary component has been lost because of total remagnetization.

2. From Triassic to Jurassic - Early Cretaceous a satisfactory group of directions is displayed around D=330° I=20° which is considered as the primary component for Pelagonian, sub-Pelagonian and Vardar zones.

3. For the same sites an eastward component with D=70° I=25° is also isolated. This component is, at least partially, a Tertiary overprint. Consequently, a pattern of old counterclockwise and recent clockwise rotations is proposed for these zones by independent studies.

4. A different pattern seems to arise for the Argolis peninsula and the Pindos, Paxos and Ionian zones as the characteristic component suggests a clockwise rotation since Jurassic, reaching values up to 90°.

5. Finally, emphasis is given to the inclination values which converge towards a paleolatitude of 15°N to 20°N for all the studied zones. Consequently, some paleogeographic reconstructions have been proposed (Fig.2.).

Very recently, a number of paleomagnetic data from upper Triassic to Maastrichtian have been obtained in the outer and inner Albanides (Mauritsch et al., 1993). All these data show evidence of CW rotations with varying magnitudes. The problem which arizes is to locate the boundary between CW and CCW rotated parts for this time span.

Before proceeding to the Cenozoic data set, two issues should be addressed:

1. There is clearly much more work to be done on Mesozoic and especially on Cretaceous rocks in Greece. The Cretaceous being the "bridge" between the Mesozoic and the Cenozoic, it is of capital importance to be considered as the "next step" in the paleomagneticians priorities for this area.

2. Another unsolved question is the ophiolite formation. There should be more paleomagnetic contributions to the problem of whether the ophiolites represent their spreading basin or whether they were transported over large distances (Ricou et al., 1984; Robertson and Dixon, 1984). Albanian results prove the latter case since bottom and overburden of the ophiolites show the same magnetic pattern (Mauritsch et al., 1993).

All the available mean directions for the Paleozoic and Mesozoic are plotted in Figure 4.

CENOZOIC DATA

The dominant feature of the broader Aegean area is the convergence between Africa and Eurasia manifested by subduction under the Hellenic arc. The strong curvature of this arc, together with the extensive geological and geophysical studies driven on it, have attracted in the early eighties the paleomagneticians attention as this curvature could originate from opposite rotations of the lateral arc-flanks. It is well known that paleomagnetic data are a useful tool in determining both the magnitude and sense of such rotations.

In an extensive research program of the paleomagnetic team at Gif-sur-Yvette (France) a wide amount of data has been obtained on Cenozoic formations in Western Greece, Southern, Eastern and Central Aegean, starting with the sedimentary arc (Valente et al., 1982; Laj et al., 1982). In their latest compilation, Kissel and Laj (1988) summarize all the obtained results along the Hellenic arc in the following way. The arc has acquired its curvature during two dinstinct phases: between 16-

12.5 Ma deformation was continuous along the arc, constrained by a CW rotation in the West, CCW rotation in the east and no rotation in the south. Between 6-0 Ma a CW rotation is restricted to the western segment, whereas no rotation at all is referred for the time period between 12 and 6 Ma. The above configuration seems to be coherent at least partly, with results obtained in Western Greece and Eastern Aegean by independent studies (Horner, 1983; Horner and Freeman, 1983; Marton et al., 1990; Lovlie et al., 1990). Additionally, new paleomagnetic results from southern Albania confirm that the 45° rotation of the Ionian zone is uniform in post-oligocene times between S.Albania and the Gulf of Corinth (Speranza et al., 1992).

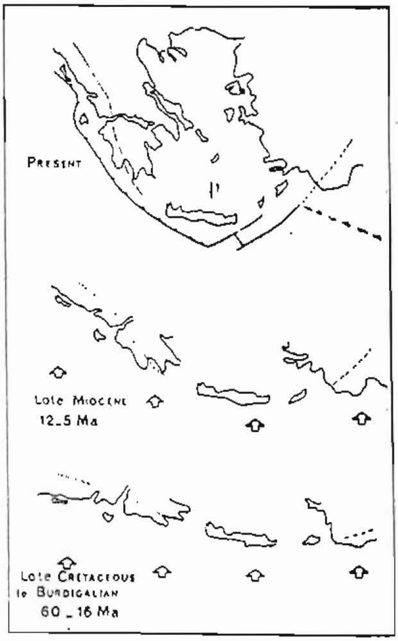


Fig.5. Possible evolution of the curvature of the Aegean arc during the Cenozoic. After Kissel and Laj (1988).

Nevertheless this attractive model has been strongly criticised by Marton (1993) who qualifies it as "oversimplified" on the basis of unpublished -but of high quality -data by Horner (1983) and using as well data published some years after the above studies (Marton et al., 1990). The main objections of the author refer to a) The continuous deformation along the sedimentary arc which is poorly constrained for the older phase. b) The rotation angle which does not always change in space or in time as predicted by Kissel and Laj's model, even for the younger phase. The above objections are documented by examples from Corfu, Paxos and Lefcas, where an about 90° CW rotation was measured. Finally, Marton suggests that differences, if any, exist rather between the different zones of the Hellenids. The case of Lefkas should be particularly discussed as the measured angle of rotation on Eocene and Cretaceous rocks seems unrealistic. According to Marton (1993), nevertheless, this rotation could be plausible for two reasons: it was found by independent studies (Horner, 1983; Marton E. et al., 1990a) and it is not unique in the area, but present also in Mesozoic units of Central and Eastern Greece.

Morris (1993) has interpreted them as related to a shear zone connecting the North Anatolian Transform fault to the Hellenic Trough. It seems reasonable to regard the direction obtained in Lefkas island as the missing link as suggested by Marton (1993).

Before closing the sedimentary arc configuration we draw the attention to an additional point. The rotational behaviour of Peloponnesus appears very poorly constrained and this observation has been neglected by almost all authors using the relevant paleomagnetic data for various interpretations (Lyberis, et al., 1982 ; Morris, 1993). In the southern part the rotation angle is only 13° since Pliocene whereas in Argolis peninsula an about 70° R is interpreted as partly due to this very recent one. To complicate the situation further, preliminary results on Pliocene volcanics in Egina (Kondopoulou and Pavlides, 1990) do not indicate any significant rotation. It is obvious that much more data are needed in this area if it has to be included in various reconstructions.

On the contrary of the sedimentary arc, the volcanic arc has not been extensively studied. The best documented formations are the recent (2,5-1 Ma) volcanics of Milos island where declinations are slightly northwestern but significantly deviated from the ones obtained in neighbouring areas for the same period (Kondopoulou and Pavlides, 1990). At the same time declinations are N-S for the very recent (<1Ma) volcanics of Santorini (Downey and Tarling, 1984) and also N-S for the Plioquaternary volcanics of Egina (preliminary results) as stated above. Pavlides (1988) and Kondopoulou and Pavlides (1990) based on seismological and structural data which support evidence for a block separation in the strait of Kythera, use these paleomagnetic data to reinforce the existence of a "Cretan block" comprising areas where paleomagnetic declinations deviate from the ones obtained in the Ionian zone and Peloponnesus. Since the rotation of Peloponnesus is so poorly constrained, the need of additional - Cenozoic - data there arises once more.

In Central and Eastern Aegean - Western Anatolia the interior of the arc does display rotations but not to a systematic extent and the overall picture is rather mosaic like, probably due to the tectonic extensional regime. On the Western side of the Aegean Sea, (Fig.6) adjacent regions such as Volos, Evia (N and S) and Skyros display declination values either N-S or NE with various angles for the same period reaching a factor of 2 (Kissel and Laj, 1988 and references therein). The authors interpret these observations in terms of rotations of fault-bounded blocks in a shear zone connecting the North Aegean Trough to the Hellenic Trench, using the model of McKenzie and Jackson (1983, 1986). In the same review as above, Marton (1993) points out a number of objections on these results among which "non-averaged out secular variation, high-percentage of data rejected and treatment of non-conform sites in a deliberate way". This last remark concerns results from the Eastern Aegean-western Anatolia (Fig.7.) where adjacent blocks display rotations varying

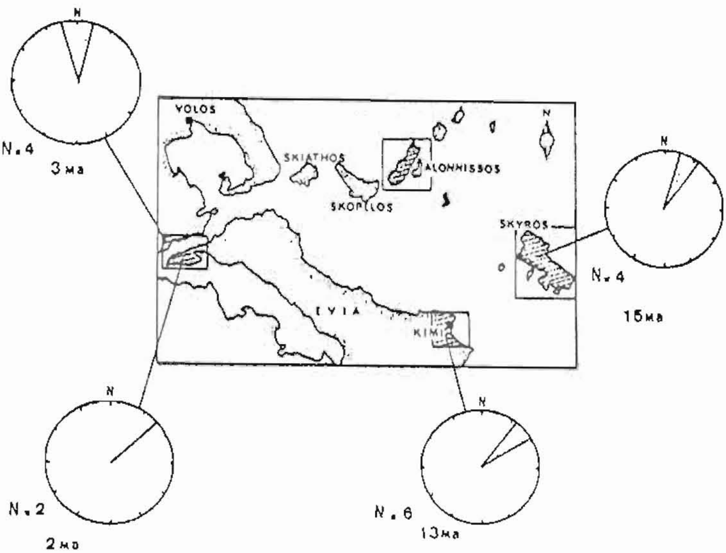


Fig.6. Location of sites and obtained rotations by Kissel and Laj (1988) on the Western coast of the Aegean Sea. The authors interpret these results by a model of McKenzie and Jackson (1983) in which this region is considered as a shear zone formed by fault limited rotating blocks.

in magnitude and sense (zero for Lesbos and Canakkale, strong clockwise for Karaburun, strong anticlockwise for Izmir). This complicated pattern is attributed by Kissel and Laj (1988) to the neotectonic regime prevailing since the beginning of Tortonian. Nevertheless, Marton's objection about this last case seems justified by the quality - low - of part of these data which are in the origin of the CW rotation postulated there (statistical parameters show a considerable dispersion). In addition to this, data recently obtained in the island of Chios both on sediments and lavas indicate a strong counter-clockwise rotation since Middle-Miocene (Kondopoulou et al., 1993a,b). We will further discuss this in the last paragraph of this study.

Finally we draw the attention to the unjustified statistical treatment of Volos-Evia areas (Fig.6). A mean direction has been calculated between sites of different age (2 Ma and 13 Ma) situated approximately 80Km apart whereas other sites of 3 Ma have been treated separately. Though a shear zone is supposed to separate Evia from Thessaly we think this site grouping is arbitrary especially as far as the mean direction for Evia is concerned.

Before we examine the rotational pattern in Northern Greece we complete the directions obtained along the North Aegean Trough (Kissel et al., 1986c) with data from Lemnos island displaying an about 25° CW rotation, since 17 Ma, in agreement with the general tendency along the N.A.T. (Westphal and Kondopoulou 1989).

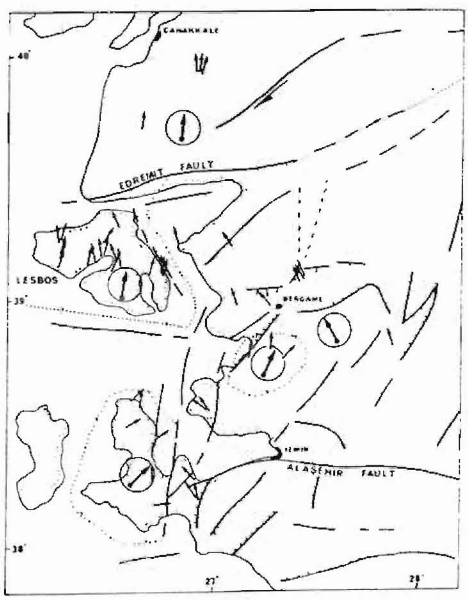


Fig.7. A complex pattern of rotations for the Eastern coast of the Aegean. From Kissel et al., 1986.

Further to the North, the rotations documented along an E-W transverse from the Mesohellenic Trough to the Greek Rhodope show a rather systematic pattern with CW rotations obtained in Eocene, Oligocene, Miocene and Pliocene formations both sedimentary and igneous (Kondopoulou and Westphal, 1986; Kissel and Laj, 1988; Westphal et al., 1991).

The amplitude of the rotation is, nevertheless, varying reaching 30° for Eo-Oligocene rocks but not exceeding 20° for younger ones. In some cases, the angle is almost null for recent sediments (Ptolemais region) but this could be attributed to a remagnetization because of sulfides formation (Kondopoulou, 1993). One case which also needs special attention is the CCW rotation documented in the N.Serbomacedonian massif whereas the S.part displays a clockwise one. This pattern is supported by equivalent rotation of the stress field (Pavlides et al., 1988). Opposite rotations in an extensional area are also documented in Israel, California, etc (Ron et al., 1984; Hornafius, 1985; Luyendyk et al., 1985).

In previous studies it has been formulated that the progressive decrease of the rotation angle reaches zero in Thrace (Greek Rhodope), (Kissel et al., 1986b). Some results had reported NE declinations in the same area (Spais, 1987) whereas preliminary results from the Kavala-Xanthi granites suggested also possible clockwise rotations (Kondopoulou and Atzemoglou, 1989). More recently, Atzemoglou et al., (1992) have reported detailed data from an area extending between the Strymon valley in the West to Xanthi in the East and from Kavala to the Greek-Bulgarian borders. These data obtained in Oligo-miocene plutonics but also in some volcanics, show the same tendency and magnitude

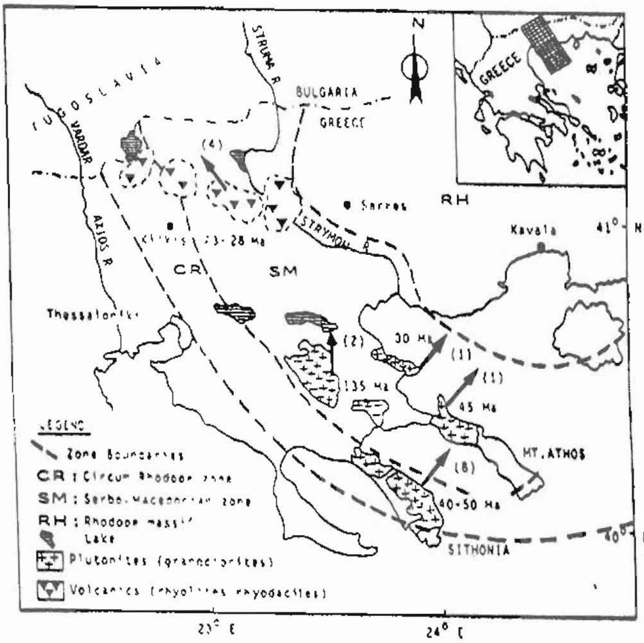


Fig.8. Paleomagnetic declinations in opposite senses for the same geotectonic unit. From Pavlides et al. (1988).

as previously mentioned for the area (≈20° CW). It seems, thus, plausible that these data support a large-scale movement of the internal and external Hellenides as suggested by Westphal et al., (1991). Nevertheless, a problem arises also here with the discrepancy between these results and the ones obtained in the Bulgarian Rhodope where no rotations have been detected for the same time span (Nozharov et al., 1990 and references therein).

Discussing the possible reasons for such a discrepancy, Atzemoglou et al., (1992) favour rather possible divergencies in the methods used by the Bulgarian researchers and call for additionnal detailed data in the Bulgarian Rhodope. In addition, Mauritsch (1993, personal communication) after checking the original data in Sofia, states that only present day field is seen because of insufficient cleaning.

Before closing the paragraph on Cenozoic data a short discussion is necessary on the inclination values obtained all over the broader Aegean area which are systematically lower (of about 10°) than the expected ones on the basis of a geocentered dipole field. This observation has been discussed by various authors (Kissel and Laj, 1988; Surmont, 1989; Van der Voo, 1993) either as due to a large northward drift of the Aegean during Tertiary or as due to unrecognised tilts and sediments compaction. Nevertheless, systematic deviations of paleolatitudes have been observed in many Tethyan blocks (Westphal et al., 1986) and a tilt-compaction effect is not applicable to the plutonic and volcanic formations. Besides, though a slightly more southerly paleolocation is possible, 10° are unrealistic. In a recent paper, Westphal (1993) claims that the low paleolatitudes in Eocene to Oligocene formations from the Tethyan belts do not correspond to errors or large tectonic movements and suggests an alternate pole position for Eurasia by 69°N and 215°E. All the available mean directions for the cenozoic are compiled in the Stereographic projection of Figure 9.

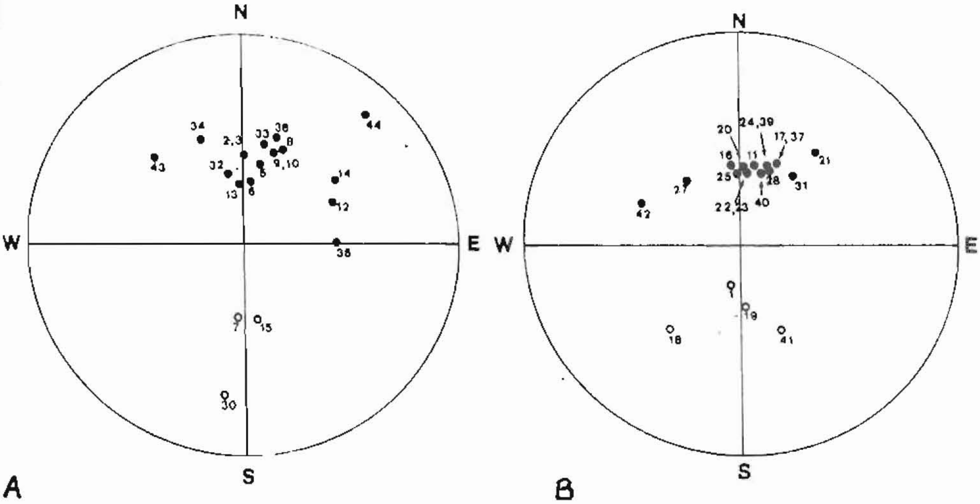


Fig.9. Stereographic projection of mean directions obtained in Greece for the Cenozoic. Numbers correspond to Table II. A: Sedimentary arc, South Aegean. B: Central Aegean and Northern Greece.

GEODYNAMIC IMPLICATIONS FOR THE CENOZOIC DATA

The rotations measured in different units in the investigated area display often important magnitudes and are quite recent (Fig.10.). It is, thus, reasonable to check, at least tentatively whether or not and to what extent the implied deformations fit independent models proposed for the area.

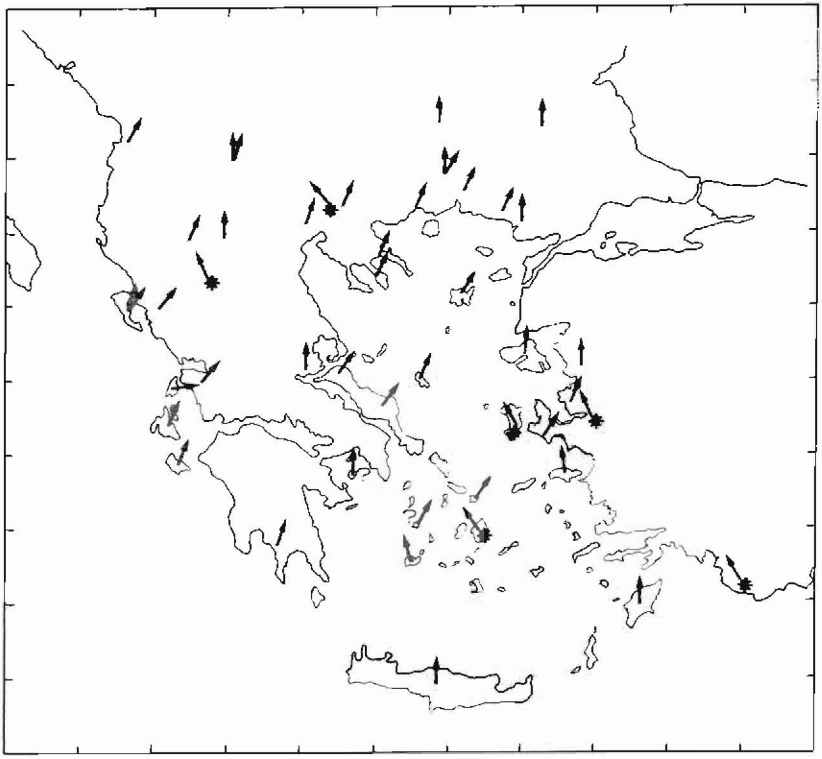


Fig.10. Schematic configuration of mean declinations in the Broader area for the Cenozoic. Starred arrows: Counterclockwise rotations.

For instance Le Pichon and Angelier (1979, 1981) have considered an over the last 13.5 Ma clockwise rotation of the Aegean around a pole situated in the southern Adriatic Sea. This pattern is quite consistent with the paleomagnetic data with two exceptions:

First, the time span of the rotation is much shorter as deduced from paleomagnetic data (5 Ma), consequently the movement should be multiplied by a factor of two. Second, the rotation extends much further to the North than predicted by the above model.

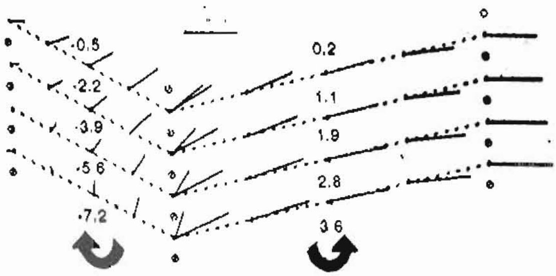


Fig.11. The slat model of Taymaz et al. (1991) illustrating the kinematics of fault motion in the Central and Northern Aegean Sea. Rotation rates relative to the northern boundary (in degrees per million years), clockwise on the western slats, counterclockwise on the right.

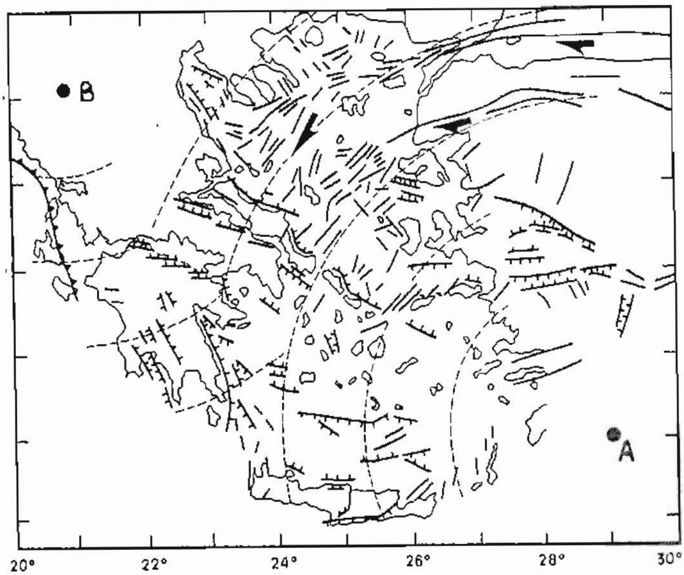


Fig.12a. Active and fossil faults in the Aegean and small circles about A: proposed rotation pole for the eastern part from tectonic, morphological and bathymetric observations. B: rotation pole after Le Pichon and Angelier (1981). (Jolivet, 1993).

As far as the opposite (eastern) side of the Aegean is concerned, Sonder and England (1989) and Taymaz et al. (1991) propose CCW rotations while Westaway (1990 a,b) suggests that most of the domains in W.Turkey rotate counterclockwise. Jolivet (1993) defines a rotation pole in the eastern part of the Aegean and claims that extension in this area proceeds through CCW rotations about this pole. More recently, Le Pichon et al. (1993) using available measurements of Spatial Geodesy in Greece and

Turkey predict also a westward rotation of about -2°/ma which is in excellent agreement with the paleomagnetic results obtained in Chios (≈25°-30° CCW rotation for the last 15 Ma). It seems that such a movement for this area is now welcome by most of the researchers and thus the existence of clockwise rotating blocks in W.Anatolia is once more called into question.

Further to the North the eastward declinations obtained in the Greek Rhodope are reinforced by the model of Taymaz et al., (1991). According to this, the similarity of the stress field between Thrace (Greek Rhodope) and the North Aegean islands would lead to the conclusion that both areas are part of the same rotational (or non-rotational) domain. As clockwise rotations prevail in these islands (Lemnos, Skyros), the ones obtained in Thrace, also clockwise, seem to be well-established.

Finally, paleomagnetic and structural data in this area (N.Greece and along the North Aegean Trough) are mutually supported both in the sense and magnitude of the movements (Pavlides et al., 1988; Westphal and Kondopoulou, 1989 and Symeakis et al., 1989). Such a combination is extremely useful and has been applied with success in other extensional areas (Ron et al., 1993).

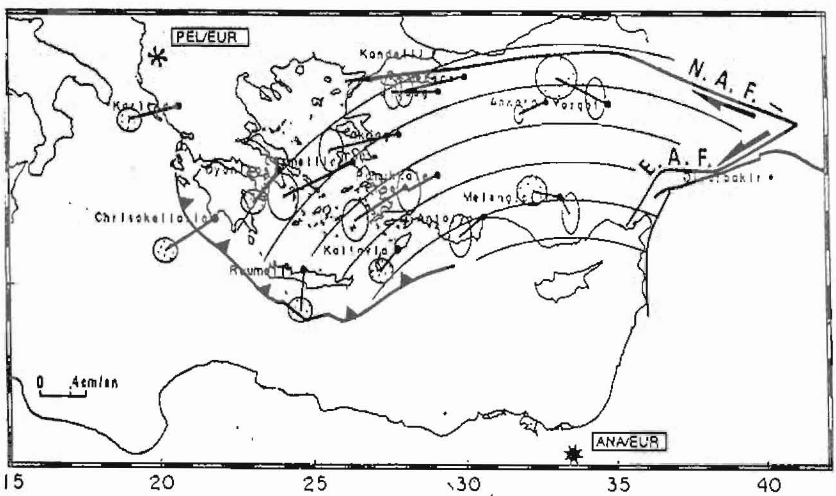


Fig.12b. SLR - dotted ovals - and GPS - open ovals -in Anatolia and Aegea from Noomen et al. (1993) and Oral et al. (1993). Small circles about the ANA - EUR pole fitted to the geodetic data. The PEL-EUR pole is obtained from paleomagnetic considerations. Redrawn from Le Pichon et al., 1993.

A last point should be emphasized. In a previous study, Marton (1987) has stated that the paleomagnetic units of the central Mediterranean do not always coincide with geological units, and that important tectonic features are crossed without any significant change in the paleodeclinations.

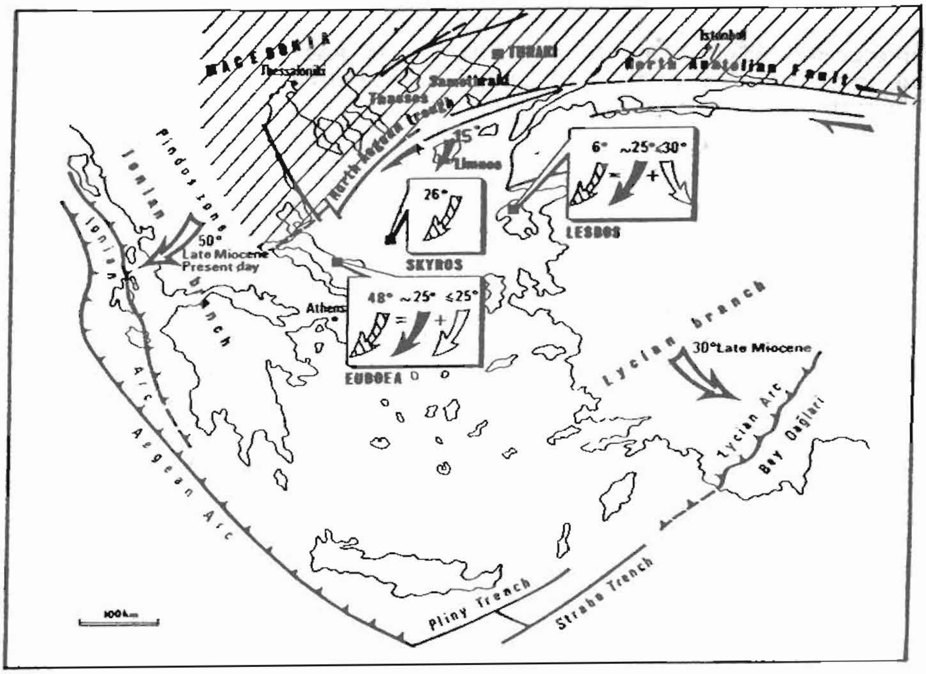


Fig.13. Combined paleomagnetic and structural data for central and Northern Aegea. From Symeakis et al., 1989.

This remark is, at a great extent valuable also for this area of Eastern Mediterranean as changes may occur within one geological unit (e.g. Serbomacedonian massif) whereas a passage from a tectonic unit to another (Ionian to Pelagonian, Serbomacedonian to Rhodope), is not followed by divergent declinations.

PERSPECTIVES AND CONCLUSIONS

1. The evolution of the sedimentary arc should be further scrutinized by better constraining the older rotational phase.
2. Additional data are needed in the Eastern part of Aegean and/or Western Anatolia in order to define the dominant sense of rotation.
3. The back arc area is lacking sufficient paleomagnetic data for the establishement of a continuous deformation.
4. Additional accurate results should be obtained from the Bulgarian Rhodope.

Compiling the available palaeomagnetic results for Greece and independent models recently proposed for the area, we could assess a possible generalized model as proposed by Westphal et al. (1991).

The whole movement in the broader area (Greece, Aegea and surroundings) is a large scale one, with a continuous expansion and deformation of Aegean and brittle deformation with small-scale rotations. Nevertheless this reconstruction has to be questioned since the Scutari-Pec line has not proved yet to be the critical line for CW and CCW rotations (Speranza et al., 1992; Mauritsch et al., 1993).

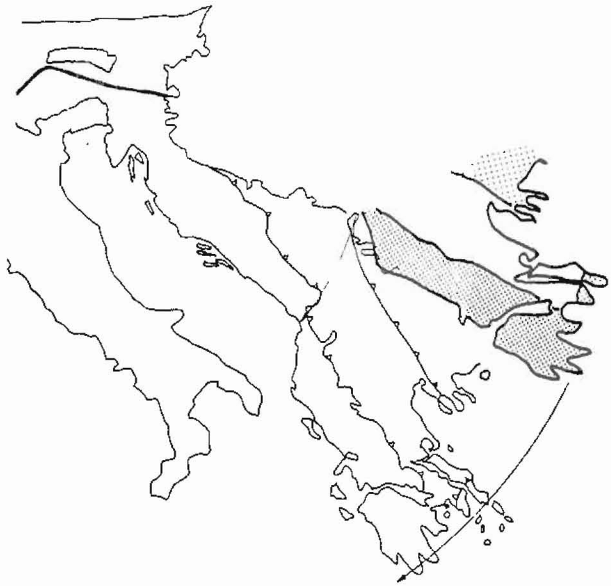


Fig.14. Map of Apulia and the Dinaric - Hellenic chain and inferred clockwise rotation of continental Greece. From Westphal et al., (1991).

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This work has been achieved "honoris causa" for the almost fifteen years of paleomagnetic research in Greece. The author takes this opportunity to thank all the persons and organizations who have helped with financial and moral support: Prof.A.Roche, Prof.B.C.Papazachos, Dr.M.Westphal, the Geological Department of the University of Thessaloniki, the French CNRS, the Greek E.I.E. and two EEC programs have decisively assisted different stages for the development of paleomagnetism in Greece. Fruitful discussions with A.Atzemoglou, S.Dimitriadis, M.Jelenska, M.Hofmokl, C.Kissel, C.Laj, E.Marton, J.L.Mercier, A.Morris, D.Moundrakis, S.Papamarinopoulos, S.Pavlides, S.Sen and C.Symeakis are mentioned with pleasure.

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This work is dedicated to Dr.M.Westphal who initiated the author to the mysteries and fascination of paleomagnetism.

Table 1. Mesozoic data in Greece.

LOCALITY	Geographic Coordinates (°N) (°E)	Rock type	Age(Ma)	D	I	Q_1	Q_2	Paleopole Lat	Paleopole Long	References
1. Pindos	40.0-21.4	Gabbros	144-208	334	22	2*		53	248	Pusher et al. (1974)
2. Argolis	37.5-23.2	Diabase	144-208	82	19	2*		-12	70	Pusher et al. (1974)
3. Pelagonian and Sub-Pelagonian	39.0-22.0	volcanics	Permo-triassic	352	-7	3		-	-	Lauer and Kondopoulou (1987)
4. Argolis	37 5-23.3	Limestones	150-178	70	36	3*	C	27	107	Turnell (1988)
5. Atalandi	38.7-23.0	volcanics	215-245	350	8	3*	C	54	221	Turnell (1988)
6. Chalkidiki	40.4-23.2	ophiolites	Jur-Cretaceous	78	53	2	C	30	86.5	Filippopoulos (1988)
7. Theopetra	39.7-21.7	sediments	126-135	320	27	5*	C	47	267	Surmont (1989)
8. Bafi (Argolis)	37.6-23.2	Amm. Rosso	135-164	253	29	5*	C	-4	316	Surmont (1989)
9. Pindos	39.5-21.6	Limestones	65-85	42	51	-	C	-	-	Marton et al. (1990)
10. Argolis (Askl.)	37.5-23.2	Carbonates	Triassic	82	35	6	-	-	-	Morris (1990)
11. NW Peloponnesos	38.0-22.0	Carbonates	up. Cret	67	39	5	-	-	-	Morris (1990)
12. N.Sanda	41.0-23.8	volcanics	up. Carb-Lower Triassic	339	8	4	C	49	236	Lauer and Kondopoulou (1991)
13. Chalkidiki	40.4-23.2	ophiolites	Jur.-Cret	314	34	5	C	37	273	Edel et al. (1991)
14. Florina	40.7-21 0	granites	L.Carboniferous	321	26	5	-	46	265	Edel et al. (1992)

Q_1 = Quality factor ranging from 1 (min) to 7 (max) (Van der Voo, 1990) starred Q_1 = given by Van der Voo (1993). The remaining Q factors have been given by the authors following to V. der Voo's criteria.

Q_2 = Quality factor ranging from D (min) to A (max) (M.Westphal, Strasbourg paleomagnetic database).

Table 2. Cenozoic data in Greece.

Locality	Coordinates N^o E^o	Age (Ma)	Rock-type	D^o	I^o	K	a_{95}	Paleopole	Q_1	Q_2	Q_3	References
1. Almopias	41.1-21.8	2-4	volcanics	195	-66.5	40	10	77 / 77	2*			Bobier (1968)
2. Rhodos	36.1-28.0	2-6	sediments	0.8	47.0	86	8	82 / 202	5*	A		Laj et al. (1982)
3. Crete	35.0-25.0	2-6	sediments	0.1	46.0	62	7	82 / 204	5*	A		Laj et al. (1982)
4. Crete	35.0-25.0	7-13	sediments	356.5	45	53	5	81 / 221	5*	B		Laj et al. (1982)
5. Peloponnesos	36.8-22.6	1-4	sediments	12.6	47	75	9	76.5 / 147.2	5*	B	II	Laj et al. (1982)
6. Kefallinia	38.3-20.5	1-4	sediments	8.7	53	316	5	81 5 / 141.0	5*	B		Laj et al. (1982)
7. Zakinthos	37.8-20.7	1-2	sediments	184.0	-57	85	5	87 / 113	4*	C		Laj et al. (1982)
8. Zakinthos	37.8-20.7	7-13	sediments	26	42	455	12	64 / 134	4*	C		Laj et al. (1982)
9. Corfou	39.6-19.8	2-5	sediments	17.5	44	27	13	69.4 / 147.4	5*	B		Laj et al. (1982)
10. Corfou	39.6-19.8	10-15	sediments	27	46	611	10	64.2 / 130.3	5*	B		Laj et al. (1982)
11 Lesbos	39.3-26.4	15-18	volcanics	12	49	11	15	78.6 / 146	4*	B		Kondopoulou (1982)
12. Epirus	39.5-20.0	40-60	volcanics	65	43	51	3	48 / 116	6*	A		Horner & Freeman (1983)
13. Crete - Santorini	35.5-25.5	0.2	Arch-material	357	58 5	584	2	86 / 356		A		Downey & Tarling (1984)
14. Epirus	39.5-20.6	21-27	sediments	58	39	30	5	38 / 112	6*	A		Kissel et al. (1985)
15. Crete (Kastellios)	35.3-24.5	10-11	sediments	172	-52	19	4	82.7 / 273.8		B		Sen et al. (1986)
16. Samos	37.8-26 8	6	sediments	354	51	18	4	82.3 / 248		C		Sen & Valet (1986)
17. Skyros	38.8-24.6	14-16	volcanics	26	46	82	8	65 / 135	4*	C	II	Kissel et al. (1986a)
18. Evia	38.7-24.0	2-14	volc+sed	224	-35	31	9	48 / 115	4*	B	II	Kissel et al. (1986a)
19. Volos	39.0-23.0	3	volcanics	178	-59	85	8	88 / 321	4*	C		Kissel et al. (1986a)
20. Lesbos	39.2-26.3	15-18	volcanics	6	49	25	7	79.5 / 177	5*	B		Kissel et al. (1986c)
21. Chalkidiki	40.2-23 8	30-50	batholith	37	31	28	9	50 / 139	5*		III	Kondopoulou & Westphal (1986)
22. Thrace	40.9-26.0	25-35	volc+plut	7	47	23	8	76 / 180	5*	A	II	Kissel et al. (1986b)
23. Thrace (Essimi)	41.1-25.9	25-35	volc+plut	2	52	-	6	81 / 192			III	Spais (1987)

24. Thrace (Lept)	41.1-25.9	25-35	putonics	23	46	-	5	67 / 324			III	Spais (1987)
25. Almopias	41.1-21.8	2-4	volcanics	356	56	36	14	75 / 132	3*		II	Kondopoulou & Lauer (1984)
26. Serres	41.2-23.8	30	putonics	8	50	26	19	- -			II	Kondopoulou (1986)
27. Gr. Serbomac.	41.1-23.1	23-28	volcanics	326	48	46	18	60 / 280	3*	C	III	Pavlides et al. (1988)
28. Mesoh. Trough	40.0-1.5	24-36	sediments	27	47	16	10	65 / 131	5*			Kissel & Laj (1988)
29. Rhodes	36.1-28.0	0.5-3.5	sediments	348	50	36	9	79 / 274		B		Lovlie et al. (1989)
30. Rhodes	36.1-28.0	0.5-3.5	sediments	189	-20	25	11	72 / 180		B		Lovlie et al. (1989)
31. Lemnos	39.8-25.2	17-21	volcanics	34	48	18	15	- -	3		II	Westphal & Kondopoulou (1989)
32. Melos	36.1-24.4	1-3	volcanics	349	50	46	9	79 / 267	5		III	Kondopoulou & Pavlides (1990)
33. Mesohellenic Tr.	39.4-21.8	5-25	sediments	15	37	23	26	80 / 175		B	II	Marton et al. (1990)
34. Pindos	39.3-21.8	35-65	flysch	335	34	8	-	60 / 255		C		Marton et al. (1990)
35. Lefkas (Ion)	38.6-21.7	28-52	sediments	90	43	17	13	15 / 92		D		Marton et al. (1990)
36. Lefkas (Pax)	38.6-21.7	25-45	sediments	23	32	16	16	81 / 168		D		Marton et al. (1990)
37. Strymonikos	41.1-23.0	20-30	lavas	26	47	-	-	65 / 136		C		Westphal et al. (1991)
38. Ptolemais	40.5-22.0	1-5	sediments	4	50	21	15	84 / 194		B		Westphal et al. (1991)
39. Gr.Rhodope	41.2-24.0	18-35	plut-volc.	22	48	56	9	68.6 / 140.5	4		III	Atzemoglou et al. (1992)
40. Axios Z.	40.7-22.8	4-11	sediments	18	47	31	16		5			Kondopoulou (1993)
41. Chios Isl.	38.3-26.1	15-17	sediments	155	-45	18	12		3		III	Kondopoulou et al. (1993a)
42. Chios Isl.	38.2-26.1	14-15	lavas	295	37	16	16		3		II	Kondopoulou et al. (1993b)
43. Naxos Isl.	37.1-25.5	11	granod.	315	30	81	9	- -	4			Morris (1993)
44. Mykonos Isl.	37.5-25.3	11	granod.	44,5	11	275	5	- -	4			Morris (1993)

Q_1 = Quality factor ranging from 1 (min) to 7 (max) (Van der Voo, 1990) starred Q_1 = given by V. der Voo (1993). The remaining Q factors have been given by the authors following to V. der Voo's criteria.

Q_2 = Quality factor ranging from D (min) to A (max) (M.Westphal, Strasbourg paleomagnetic database).

Q_3 : additional quality factor attributed by the present author in cases where either a direct control, independent criticism on the data or other information make it possible

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