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Paleomagnetism and the tectonic evolution of the Ionian zone, northwestern Greece

Lena Broadley*
Department of Earth Sciences, University College London, Gower Street,
London, England, WC1E 6BT, UK
E. Platzman
J. Platt
Department of Earth Sciences, University of Southern California,
Los Angeles, CA 90089-0740, USA
M. Papanikolaou
Department of Geography, University of Cambridge, Downing Place,
Cambridge, England, CB2 3EN, UK
S. Matthews
BP, Chertsey Road, Sunbury-on-Thames, Middlesex, England, TW16 7LN, UK

ABSTRACT

The Ionian zone is a classic thin-skinned linear fold and thrust belt forming a part of the external Hellenides, in westernmost Greece. The region has been a focus of intensive paleomagnetic investigation since the early 1980s, and it is now generally believed to have undergone a multiphase clockwise vertical-axis rotation of 40°–60° since the Miocene, although the timings are disputed, and spatial variations within this trend have been largely ignored thus far. We present data from thirty new paleomagnetic sites and a reappraisal of previous results from the Ionian zone in an attempt to construct a unified model for the tectonic evolution of the Ionian zone. We find that the clockwise rotations may be due, at least partially, to rotation during thrust sheet emplacement, with evidence of a forelandward decrease in rotation. However, superimposed on this pattern of thin-skinned rotations we observe post-Pliocene rotations that affect multiple thrust sheets in a consistent manner. These are interpreted to result from regional tectonics associated with, for example, the Kefallonia fault zone at the western termination of the Hellenic arc and from deformation in the transition zone between Anatolian westward extrusion and southern Aegean extension. Overall, the result is a pattern of thin-skinned, westward-decreasing clockwise rotations distorted by superimposed thick-skinned rotations resulting from the complex interplay of plate motions in the eastern Mediterranean.

Keywords: Ionian zone, paleomagnetism, vertical axis rotation, tectonics, Greece

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*E-mail: l.tailor@ucl.ac.uk.

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INTRODUCTION

The Ionian zone is a classic example of a thin-skinned linear fold and thrust belt forming a part of the external Hellenides, in westernmost Greece. Since the early 1980s, it has been the subject of several detailed paleomagnetic studies (e.g., Horner and Freeman, 1983; Kissel et al., 1985; Birch, 1994; Duermeijer et al., 1999; van Hinsbergen et al., 2005), all of which have concluded that it has undergone a net clockwise vertical-axis rotation of 40°–60° since the Miocene and that the rotation occurred in stages. However, the timings and rates of rotation are disputed, and the issue of regional variations in the magnitude of rotations has yet to be properly addressed. Until the late 1990s, the popular opinion was that the entire Ionian zone underwent two episodes of rotational deformation (Horner and Freeman, 1983; Kissel et al., 1985; Birch, 1994) coinciding with lower Miocene and Plio-Quaternary calc-alkaline volcanic activity in the Aegean Sea (Kissel et al., 1984). More recently, Duermeijer et al. (1999) presented compelling evidence that the second rotation phase may have occurred later and more rapidly, with at least Zakynthos and the western Peloponnesus rotating around 20° since 0.77 Ma. These variations are discussed in more detail later. However, it can be seen from these examples that some contention exists regarding the timings of vertical-axis rotations, and, as mentioned earlier, the spatial distribution of these rotations has not yet been addressed in a coherent manner.

In this article, we present new results from thirty sites along with a re-evaluation of existing results distributed across the Ionian zone in an attempt to present an integrated and coherent model describing the tectonic evolution of the region.

GEOLOGY

Regional Setting

The Hellenide orogenic belt dominates the structure of Greece and has long been recognized to comprise numerous distinct sedimentary facies belts. These linear belts were termed “isopic” zones by Aubouin (1959) on the basis of their distinct depositional and deformational histories (Fig. 1A).

Since the advent of plate tectonic theory, subsequent workers have modified Aubouin’s ideas. The Hellenides are now considered to represent the growth and the later shortening of the Apulian passive continental margin associated with the Middle Jurassic formation of strands of the Neo-Tethyan Ocean and their Cretaceous–Paleocene closure (Robertson and Dixon, 1984; Underhill, 1989). Several distinct thrust sheets developed as a result of oceanic closure, and these correspond roughly to Aubouin’s isopic zones, so that zonal boundaries are commonly demarcated by overthrusts. Thrusting commenced in the eastern Hellenides near the Maastrichtian, centered on Neo-Tethys, and progressively migrated westward, toward the foreland (Smith and Moores, 1974; Robertson and Dixon, 1984). The main phase of thrust sheet emplacement in the Ionian zone occurred during the Miocene.

The Ionian zone is one of the most external of the isopic zones, spanning Epiros and Akarnania in northwestern Greece and the northern Ionian islands (Fig. 1). To the west, it is thrust over the Paxos zone, the foremost zone before the Apulian foreland, and to the east it is flanked by the Gavrovo zone. Both the Ionian and the Gavrovo zones are overthrust to the east by the Pindos zone (Fig. 1). The western boundary of the Ionian zone was once considered to mark the western limit of thrusting, but evidence from the southern Ionian islands of Zakynthos and Kefallonia now suggests that thrusting continued to migrate westward into the Paxos zone from the late Miocene into the Quaternary (Underhill, 1989).

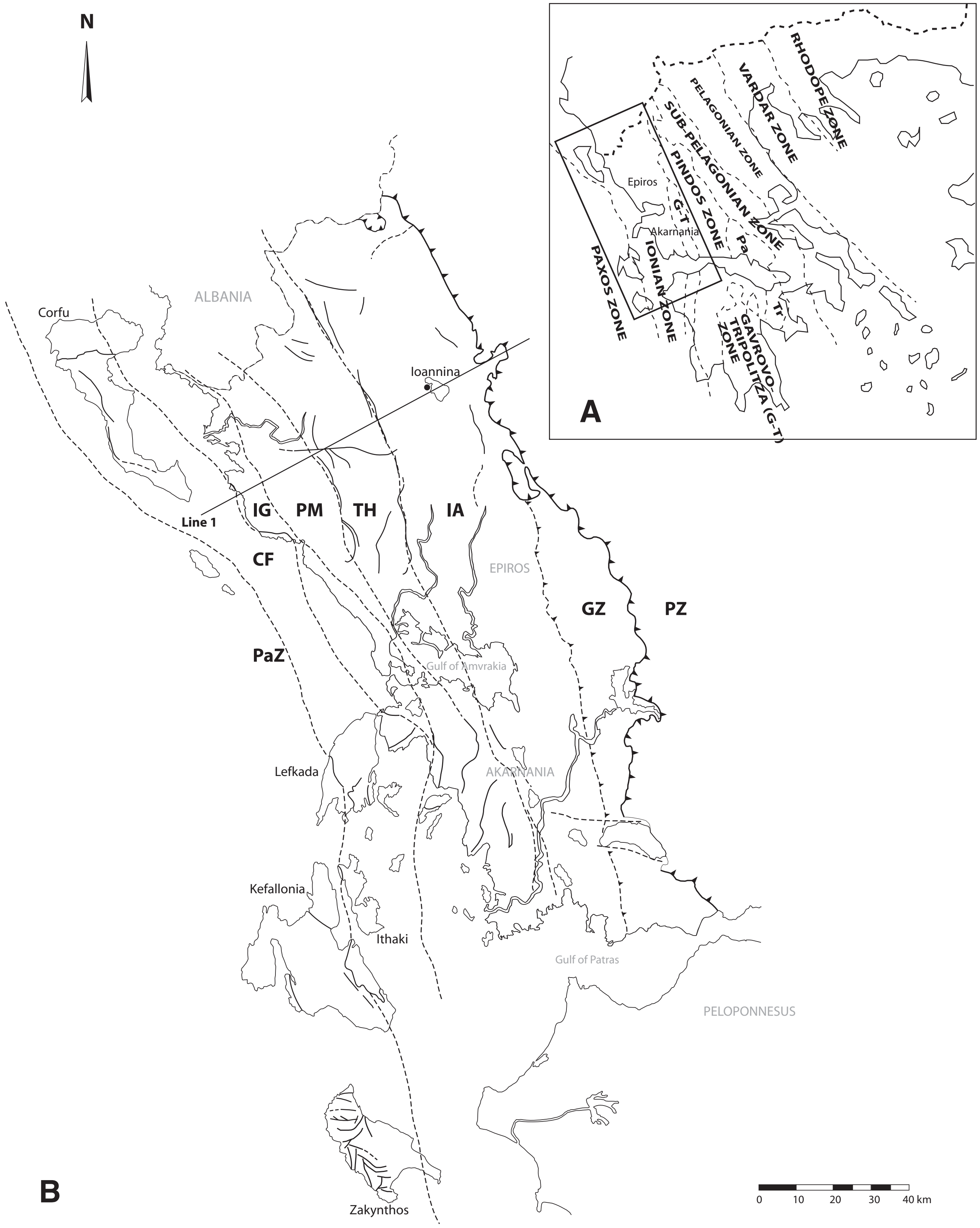
Stratigraphy and Lithologies Investigated

The stratigraphic column exposed in the Ionian zone consists of Permo-Triassic to Holocene sedimentary rocks. There are no basement exposures in the entire zone, nor have any boreholes reached the basement, but it is thought that a Hercynian basement of uncertain trend and nature underlies the Ionian zone and much of the External Hellenides (Smith and Moores, 1974).

Thick Permo-Triassic evaporites lie at the base of the known Ionian zone section. They are the oldest lithology encountered in wells, and while not accurately dated, are known to be of Pre-Carnian age (Smith and Moores, 1974). In wells, they consist of anhydrite, halite, and potassium salts, often interbedded with dolomites (Jenkins, 1972), and they are estimated to be over 1600 m thick in places. It is likely that the evaporites played a central role in the initial stages of thrusting by providing a weak and mobile layer along which décollement could occur. Additionally, the presence of evaporites may have facilitated thrusting by increasing the hydrostatic pressure if water released from the dehydration of gypsum to anhydrite was held in the overlying carbonates (Jenkins, 1972).

Overlying the evaporites is a thick Carnian to Eocene carbonate sequence. The lowest unit in this succession is the massive platform facies of the Carnian–Pliensbachian Pantokrator limestone, predominantly a massive white algal limestone, locally dolomitized and up to 1980 m thick. The upper members of the Pantokrator formation are locally replaced by the Siniais limestones, a bedded white limestone deposit with bands and lenses of black chert (Bernoulli and Renz, 1970; Smith and Moores, 1974).

Figure 1. (A) Map of Greece showing the main isopic zones (modified from Jenkins, 1972). The box shows the area of interest in this study. (B) Detailed map of the Ionian zone (box in panel A) showing faults and the approximate extent of major thrust sheets. PaZ—Paxos zone; GZ—Gavrovo zone; PZ—Pindos zone; CF—Corfu thrust sheet; IG—Igoumenitsa thrust sheet; PM—Paramythia thrust sheet; TH—Thesprotika thrust sheet; IA—Ioannina thrust sheet. Line 1—location of data used in Figure 8.


N
A
Epiros
Akarnania
RHODOPE ZONE
VARDAR ZONE
PELAGONIAN ZONE
SUB-PELAGONIAN ZONE
PINDOS ZONE
G-T
Pa
IONIAN ZONE
PAXOS ZONE
Tr
GAVROVO-TRIPOLITZA (G-T)
TRIPOLITZA ZONE
B
ALBANIA
Corfu
Ioannina
Line 1
IG
PM
TH
IA
CF
EPIROS
GZ
PZ
PaZ
Gulf of Amvrakia
Lefkada
AKARNANIA
Kefallonia
Ithaki
Gulf of Patras
PELOPONNESUS
Zakynthos
0
10
20
30
40 km

In the Middle Jurassic, the Ionian zone was characterized by rapid lateral facies and thickness changes. These may have been a result of deposition in irregularities in the seafloor, combined with subsidence and downwarping as the Ionian basin began to form, and of low depositional rates (Jenkins, 1972). Locally, in the Ionian zone evidence of the Middle Jurassic can be absent or can be represented by the red nodular marly limestones of the Toarcian–Aalenian Ammonitico Rosso or by the shales and bedded cherts of the Toarcian–Oxfordian Posidonia beds.

The Middle Jurassic phase of rapid environmental change abruptly came to an end in the Uppermost Jurassic with the deposition of a thick sequence of predominantly pelagic limestones across the entire Ionian zone. These limestones range in age from Tithonian to upper Eocene and in thickness from ~450 to 1800 m. The sequence generally consists of well-bedded white radiolarian and foraminiferal micrites. However, contained within the series are two distinctive bands of pink micrites, both of which have been used to obtain paleomagnetic data for this study. The first is a thick band of dark pink, well-bedded micrites of upper Santonian age, generally lacking cherts, but containing occasional brown chert nodules or intercalations. They are a part of the Vigla formation, which otherwise typically consists of white micrites. They do not occur everywhere within the Ionian zone, but are very well developed in northwestern parts of Epiros and, to a lesser extent, in Akarnania. The second series of pink micrites is of post–middle Eocene age and occurs as intercalations of pink limestones within upper Eocene white limestones. These are usually much harder than the pink micrites in the Vigla formation and have a far more variable color, ranging from pale to dark pink. They can also have a bluish-gray color either in patches or entirely, where the ferric iron phase has been reduced.

With the onset of contractional deformation in the external Hellenides, there was a rapid transformation from carbonate to terrigenous clastic sedimentation. The Oligo-Miocene sediments of the Ionian zone are collectively referred to as flysch. They are essentially of turbiditic origin and consist of interbedded blue-gray sandstones and marls containing material derived from the uplift and erosion of the Pindos zone. It is believed that the flysch sedimentation occurred in a trough that migrated westward ahead of the advancing thrust front, and that shortly after deposition it was overridden by thrusts. The formation is most developed in more internal parts of the Ionian zone, reaching thicknesses close to 6000 m in the east and up to 2200 m in the west. The Ionian zone flysch ranges in age from Oligocene–Aquitanian in the most internal parts of the zone (Smith and Moores, 1974). However, in the most external parts of the zone, clastic sediments of Pliocene age can be seen to be involved in thrusting along coastal sections and could, in a sense, be classified as flysch. They consist of coarse conglomerates and blue-gray marls that in surface outcrop are usually oxidized to a yellow-brown color. Samples for paleomagnetic analysis taken from Oligo-Miocene blue-gray marls of the Ionian flysch and from Pliocene "flyschlike" blue-gray marls were used in this study.

The Ionian zone molasse overlies and is differentiated from the flysch in that it locally postdates and has been undisturbed by tectonic movement. Otherwise, it is lithologically similar to the flysch but of Burdigalian age. Blue-gray marls from this formation were also sampled as part of this investigation.

In the Ionian zone, the Pliocene to Holocene are represented by lacustrine and marine marls, coarse-grained conglomerates and breccias, poorly consolidated sands, and unconsolidated alluvium.

Regional Tectonics

The eastern Mediterranean is one of the most rapidly deforming regions in the world. Essentially, its deformation is related to the convergence of Africa-Arabia and Eurasia, but due to the complex interplay of microplates and the variable nature of crustal response in the region, the resulting deformation is highly complex. From the east, the Anatolia plate is being extruded westward between the dextral North Anatolian fault and the sinistral East Anatolian fault. The northern Aegean and central Greece are subject to north-south extension and crustal thinning, while the southern Aegean translates southwestward toward the Africa plate (Jackson, 1994; Walcott and White, 1998; Cocard et al., 1999). Oceanic lithosphere of the Africa plate is subducted beneath the Aegean at the Hellenic arc, with ENE-WSW extension above the subducting plate in the southern Peloponnesus (Jackson, 1994). This arcuate subduction zone meets the dextral Kefallonia fault (Fig. 2) at its northwestern termination, and north of the transform fault the nature of convergence alters from oceanic subduction to continental collision between the Aegea and the Apulia plates. Vertical-axis rotations play an important part in this pattern of deformation. The observed rotations are discussed in more detail later in this article, but to summarize, large rotations are widely documented to have occurred and to persist, clockwise in northern and western Greece (e.g., Horner and Freeman, 1983; Kissel et al., 1984; Atzemoglou et al., 1994; Le Pichon et al., 1995; Dimitriadis et al., 1998) and counterclockwise in Anatolia and the southern Aegean (Le Pichon et al., 1995; Duermeijer et al., 2000). Until recently, Crete was considered to fall on an axis between the two senses of rotation, showing no significant rotation (e.g., Laj et al., 1982), but recent work has unveiled a complex pattern of post-Messinian counterclockwise rotations (Duermeijer et al., 1998). For an extensive review of rotations implied by paleomagnetic data in the Aegean region, the reader is referred to Kondopoulou (2000).

Figure 2. Simplified geological map of the Ionian zone showing site locations from this study and their rotations relative to geographic North. (i) Igoumenitsa region, (ii) Saloniki region, and (iii) Lefkada-Vonitsa region. See text for a description of these regions. AR—Arilla Beach.

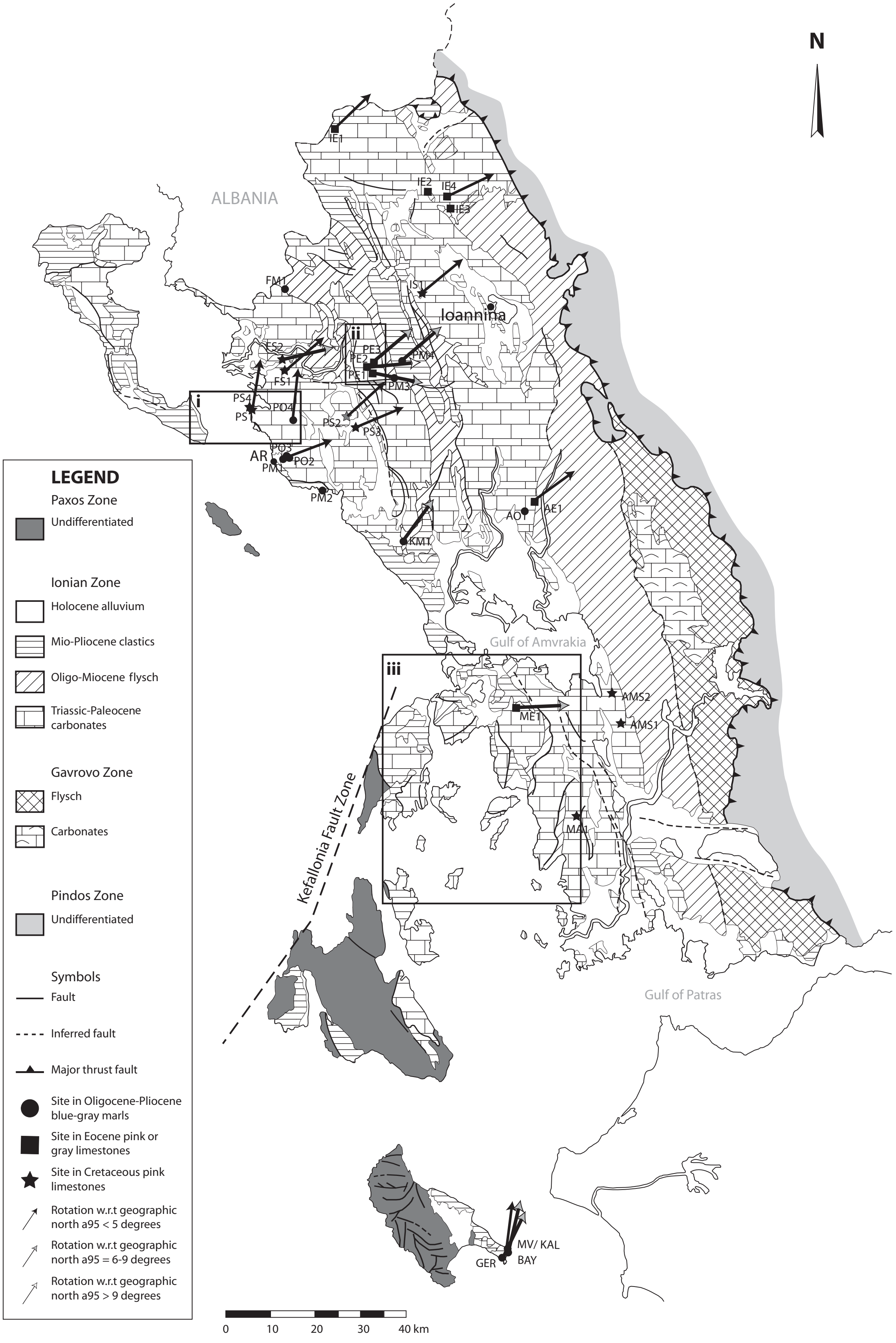

N
ALBANIA
IE1
IE2
IE4
IE3
FM1
IS1
Ioannina
ii
PE3
PE2
PE1
PM4
PM3
FS2
FS1
i
PS4
PS1
PO4
PS2
PS3
PO3
AR
PO2
PM1
PM2
AO1
AE1
KM1
Gulf of Amvrakia
iii
AMS2
ME1
AMS1
MA1
Kefallonia Fault Zone
Gulf of Patras
MV/ KAL
BAY
GER
LEGEND
Paxos Zone
Undifferentiated
Ionian Zone
Holocene alluvium
Mio-Pliocene clastics
Oligo-Miocene flysch
Triassic-Paleocene carbonates
Gavrovo Zone
Flysch
Carbonates
Pindos Zone
Undifferentiated
Symbols
Fault
Inferred fault
Major thrust fault
Site in Oligocene-Pliocene blue-gray marls
Site in Eocene pink or gray limestones
Site in Cretaceous pink limestones
Rotation w.r.t geographic north a95 < 5 degrees
Rotation w.r.t geographic north a95 = 6-9 degrees
Rotation w.r.t geographic north a95 > 9 degrees
0
10
20
30
40 km

TABLE 1. SUMMARY OF PALAEOMAGNETIC RESULTS FROM THE IONIAN ZONE AND PARTS OF THE EXTERNAL HELLENIDES

Study	Areas studied	*N*	Age and lithology sampled	Conclusions
1. Pucher et al. (1974)	Grevena, N. Pindos zone S. Argolis Peninsula, Peloponnesus	7	Jurassic gabbros and diabases	There was a relative rotation of around 110° between the studied regions, implying that the ~120° change in strike between the northern Hellenides and Argolis results from block rotations.
2. Laj et al. (1982)	Corfu, Zakynthos, and Kefallonia Crete and Rhodes	16 26	Lower Miocene to Pleistocene blue-gray marls	There was no rotation of the Ionian islands from ca. 11.5 to 5 Ma, then clockwise rotation at ~5°/ m.y. since 5 Ma. No significant rotation of Crete and Rhodes.
3. Horner and Freeman (1983)	Epiros, Corfu, and Paxos	51	Upper Cretaceous–upper Eocene pink limestones	There has been 38° clockwise rotation of the Ionian zone since the early Tertiary.
4. Kissel et al. (1985)	Epiros and Akarnania	29*	Lower–upper Oligocene blue-gray marls	There has been 45° total clockwise rotation of the Ionian zone, occurring in two phases of similar magnitude, one in the middle Miocene, followed by ~7 m.y. of no rotation and a second Pliocene–Quaternary rotation.
5. Marton et al. (1990)	External Hellenides: Pindos, Ionian, and Paxos zones	16	Maastrichtian–Miocene limestones and marls	No results from Paxos zone sites. There were net clockwise rotations of the Ionian and Pindos zones during the Mesozoic, followed by relative counterclockwise rotation of Pindos zone relative to the Ionian zone.
6. Birch (1994)	External Hellenides: Ionian, Pindos, Parnassus, and Sub-Pelagonian zones	32†	Toarcian–upper Eocene carbonates and Miocene–Pliocene marls	There was 28° counterclockwise rotation of western Greece sometime between the Toarcian and the late Mesozoic, followed by 60° clockwise rotation of the entire region in two stages as in study 4. There was a further 90° clockwise rotation of Lefkada and northern Akarnania during the Pliocene.
7. Morris (1995)	External Hellenides: Pindos and Pelagonian zones	37	Anisian–Palaeocene carbonates, Miocene marls and andesites	There was 94° total clockwise rotation of the southern Pelagonian zone in 2 phases, ~50° post–Late Cretaceous and ~45° post–middle Miocene. There was variable Eocene clockwise rotation of the Pindos thrust sheet.
8. Duermeijer et al. (1998)	Crete	12	Messinian marls and clays	There were Variable counterclockwise rotations of Crete of ~10°–20° in the east and the west, but up to 40° in central Crete.
9. Duermeijer et al. (1999)	Zakynthos	18	Eocene limestones and lower Miocene to Pleistocene marls	There was no rotation between 8.11 and 0.77 Ma, followed by a rapid clockwise rotation of ~22° between 0.77 Ma and the present.
10. van Hinsbergen et al. (2005)	Northern and western Greece, Peloponnesus, Ionian islands, and Aegina	34§	Tertiary terrestrial and marine sediments	There was 40° clockwise rotation of the western Aegean domain between ca. 15–13 and 8 Ma, followed by a further 10° post-Zanclean clockwise rotation.
11. This study	Ionian zone	30	Plio-Pleistocene–Santonian marls and limestones	There was an overall clockwise rotation of 49° of the Ionian zone, with significant local variations.

Notes: N—no. of sites.

* Includes data from sixteen sites in the same region from a previous study by Kissel et al. (1984).

† Sites in the Ionian zone only; additional sites were drilled in the other external zones.

§ Refers to the number of localities, defined by the authors as a coherent geological area containing one to thirteen individual sites or sections.

Paleomagnetism and the Ionian Zone

Until the early 1980s, Greece was largely unexplored in terms of paleomagnetism. An early paleomagnetic study of western Greece (Pucher et al., 1974) contrasted the structural trends of the Pindos zone (Fig. 1) and the eastern Peloponnesus with Jurassic magnetic remanence vectors from the two regions. The results implied a relative rotation of around 110°. However, this was a small study, with few sites, and it was not until the early 1980s that any detailed paleomagnetic investigation of western Greece was carried out.

Table 1 summarizes key results of previous paleomagnetic work that has been carried out in the Ionian zone and other parts of the External Hellenides. While most studies agree that there has been a net clockwise rotation of the Ionian zone since the Miocene and that the rotation occurred in stages, the timings and rates are disputed, and the significance of local variations in the magnitude of rotations has not been adequately addressed.

The prevailing opinion throughout the 1980s and the early 1990s was that the two episodes of rotational deformation coincided with lower Miocene and Plio-Quaternary phases of calc-alkaline volcanic activity in the Aegean Sea (Kissel et al., 1985) and may have been associated with the resulting compressional deformation (Birch, 1994). However, Duermeijer et al. (1999) present compelling evidence, from Zakynthos, of a more rapid second rotation phase commencing later in the Quaternary. They propose that at least Zakynthos and the western Peloponnesus began to rotate clockwise rapidly during the mid-Pleistocene, and they ascribe this rapid rotation to Pleistocene uplift associated with detachment of the African slab underneath the Ionian zone.

From the results of Duermeijer et al. (1999), the question arises as to whether the rapid rotation phase extended to other parts of the Ionian zone. Local variations in the magnitude of rotations pose further questions regarding the mechanisms behind the rotations. The most striking variations are the large clockwise rotations of over 100° documented in Lefkada and in western Akarnania by Birch (1994). Birch attributes these anomalous rotations to the proximity of the two areas to the dextral Kefallonia fault zone and to the presence of thick underlying evaporites (Jenkins, 1972), which act as a décollement horizon. This is an attractive hypothesis, but requires further testing because many of the magnetic vectors defining the anomalous rotations are poorly defined, with uncertainties of $\alpha_{95} > 10°$. In addition, individual site rotations from previous studies are all given relative to present-day geographic North and are not corrected for polar wander. In this study, we find that this correction can make a significant difference to the inferred rotation—up to a further 29° of clockwise rotation for sites of Lower Cretaceous age—which, in addition to an uncertainty of $\alpha_{95} > 10°$, could lead to a considerable underestimation of the amount of rotation at a site. However, these examples illustrate that local variations in the magnitude and timing of rotations can yield important information for interpretation of the tectonic evolution of the Ionian zone and that in-depth study of these variations is necessary.

NEW PALEOMAGNETIC RESULTS FROM THE IONIAN ZONE

Sampling and Selection of Sites

As part of this study, over five hundred cores were drilled at thirty sites in the Ionian zone (Fig. 2). The sites were chosen on the basis of a suitable lithology, fresh outcrop, structural simplicity, accessibility, and location within the existing framework of paleomagnetic data from the Ionian zone. The samples from the four sites on Zakynthos (Fig. 2) were selected from a large number of samples drilled in four continuous sections for magnetostratigraphic work.

Based on the extensive body of existing paleomagnetic data from the Ionian zone, we chose, where possible, to sample only pink micritic limestones and blue-gray marls, for these lithologies have previously been proven to produce reliable paleomagnetic results (e.g., Horner and Freeman, 1983; Kissel et al., 1984).

Because weathering can produce a strong secondary magnetic overprint by means of mineral alteration or authigenic mineral growth, it is very important to avoid weathered outcrops when selecting paleomagnetic sites. In general, weathering was not a problem when sampling carbonate lithologies, but was an important issue when selecting blue-gray marls, which are easily weathered and can have strong secondary overprints. When no fresh outcrops were available, it was occasionally possible to expose fresh marl outcrops by digging the surface layers away from stream and cliff exposures.

When sampling folded sediments, we took particular care to sample only from folds with a horizontal or subhorizontal (<20°) fold axis to avoid the ambiguities introduced when correcting paleomagnetic results for both folding and tilting of beds.

Samples were drilled and oriented using routine paleomagnetic techniques, with at least twelve cores drilled from each site, covering enough stratigraphic section to average out variations due to geomagnetic secular variation.

Laboratory Techniques and Treatment of Data

Successful isolation of a characteristic remanent magnetization (ChRM) was achieved for twenty-one of the sampled sites, encompassing five different lithologies (Fig. 2, Table 2) and using a combination of stepwise alternating field (AF) and thermal demagnetization techniques.

For thermal treatment, specimens were heated in an ASC TD-48 furnace at intervals of 50 to 100 °C between 0 and 300°, and thereafter at intervals of 20 to 50° up to a maximum temperature of 675 °C. A Molspin shielded AF demagnetizer was used for AF demagnetization at intervals of 2.5–5 mT between 0 and

TABLE 2. MAIN FEATURES OF LITHOLOGIES USED TO IDENTIFY A CHARACTERISTIC REMANENT MAGNETIZATION IN THIS STUDY

Age	Formation and description	Age abbreviation	T_{min}–T_{max} (°C)	F_{min}–F_{max} (mT)
Plio-Pleistocene	Blue-gray marls	Pl	100–450	0–99.9
Oligo- Miocene	Blue-gray marls	M	T_{min} = 80–120 T_{max} = 250–675	10–99.9
Palaeocene–Eocene	Porcelainous pink pelagic micrites	Ep	T_{min} = 80–200 T_{max} = 450–600	F_{min} = 20 F_{max} = 70–99.9
	Porcelainous pale gray to blue-gray pelagic micrites	Eg	200–450	20–50
Upper Cretaceous	Pink pelagic micrites	K	300–625	10–99.9

Notes: T_{min} and T_{max} represent approximately the minimum and maximum temperatures between which the characteristic remanent magnetization (ChRM) was identified in a particular lithology during thermal demagnetization; F_{min} and F_{max} represent minimum and maximum fields between which the ChRM was identified by alternating field demagnetization.

40 mT, then at 10–20 mT up to a maximum field of 99.9 mT. The mode of demagnetization of specimens from a site (if only one was used), the exact progressions used in both thermal and AF demagnetization, and the maximum temperature or field applied were all dependent on lithology and were determined by carrying out detailed thermal and AF pilot studies on at least two samples per site. Magnetization was measured at the outset of the experiment and between thermal and AF steps using an Agico JR-5a spinner magnetometer. In addition to the magnetization, susceptibility was measured at the start of the experiment and monitored between thermal demagnetization steps using an Agico KLY-2 susceptibility bridge.

ChRM vectors were chosen for individual specimens by manually fitting a straight line to points on a Zijderveld plot (Fig. 3). Where appropriate, a single tectonic correction was made to the magnetization vector to compensate for the mean bedding tilt at a site. For sites drilled in folded sediments, individual bedding corrections were made for each sample. An additional correction was made to the declinations to yield the estimated rotation at a site relative to the expected declination at the time of acquisition of magnetization. For computation of the expected directions, we used the African poles given by Besse and Courtillot (2002) for the Pleistocene through to the Lower Jurassic. Although the Ionian zone is considered a part of Adria, we felt that use of African reference poles was justified because Adria is considered to have moved closely with Africa since at least the Permian (Muttoni et al., 2001), and evidence from dinosaur footprints is interpreted as showing that Adria behaved as an African promontory from Late Jurassic to Early Cretaceous times (Bosellini, 2002). Moreover, the present-day GPS velocity of southeastern Adria, which includes the Ionian zone of northwest Greece, is shown to be related to the motion of Africa by Oldow et al. (2002). We observed that this correction made a significant difference to the rotation inferred from the paleomagnetic vector (cf. Fig. 4A with Fig. 4B). In previous paleomagnetic studies, this type of correction had been applied to regional average results rather than to results from specific sites, so we felt that a direct comparison of results was inappropriate. Therefore, later we present a reappraisal of the existing paleomagnetic results from the Ionian zone, giving the inferred rotations relative to the African poles (Besse and Courtillot, 2002) previously discussed.

New Data

The results of this investigation are summarized in Table 3, and representative results from four different sites in the Ionian zone are shown in Figure 3 to illustrate typical demagnetization behavior from sites in pink Eocene and Upper Cretaceous limestones and from blue-gray marls of Oligo-Miocene and Plio-Pleistocene age.

In addition to a small present-day overprint, some of the sites exhibit two components of remanent magnetization—a dominant and stable high-temperature (at least 200 °C up to a maximum of 675 °C), medium-coercivity component (generally at least 20–99.9 mT) carried mainly by single-domain or pseudo–single domain magnetite grains (Fig. 3) and a low-temperature component (<200 °C). The low-temperature component generally appears to exhibit a rotation of the same sense, but of lower magnitude than the high-temperature component. However, this secondary magnetization is very poorly defined and of uncertain age, so it is not discussed further in this article.

The susceptibility of samples generally remained constant throughout thermal treatment, confirming that in most cases no secondary magnetic mineral growth or alteration occurred during treatment.

Figure 2 illustrates the vertical-axis rotations, relative to present-day geographic North, inferred from the primary magnetization vectors determined during this study. Overall, the results are in good agreement with previous paleomagnetic work from the Ionian zone, implying a net clockwise rotation of the Ionian zone since the Oligo-Miocene, with a mean declination (D) = 42.3°, an inclination (I) = 42.7°, and a 95% cone of confidence (α_{95}) = 9.4°.

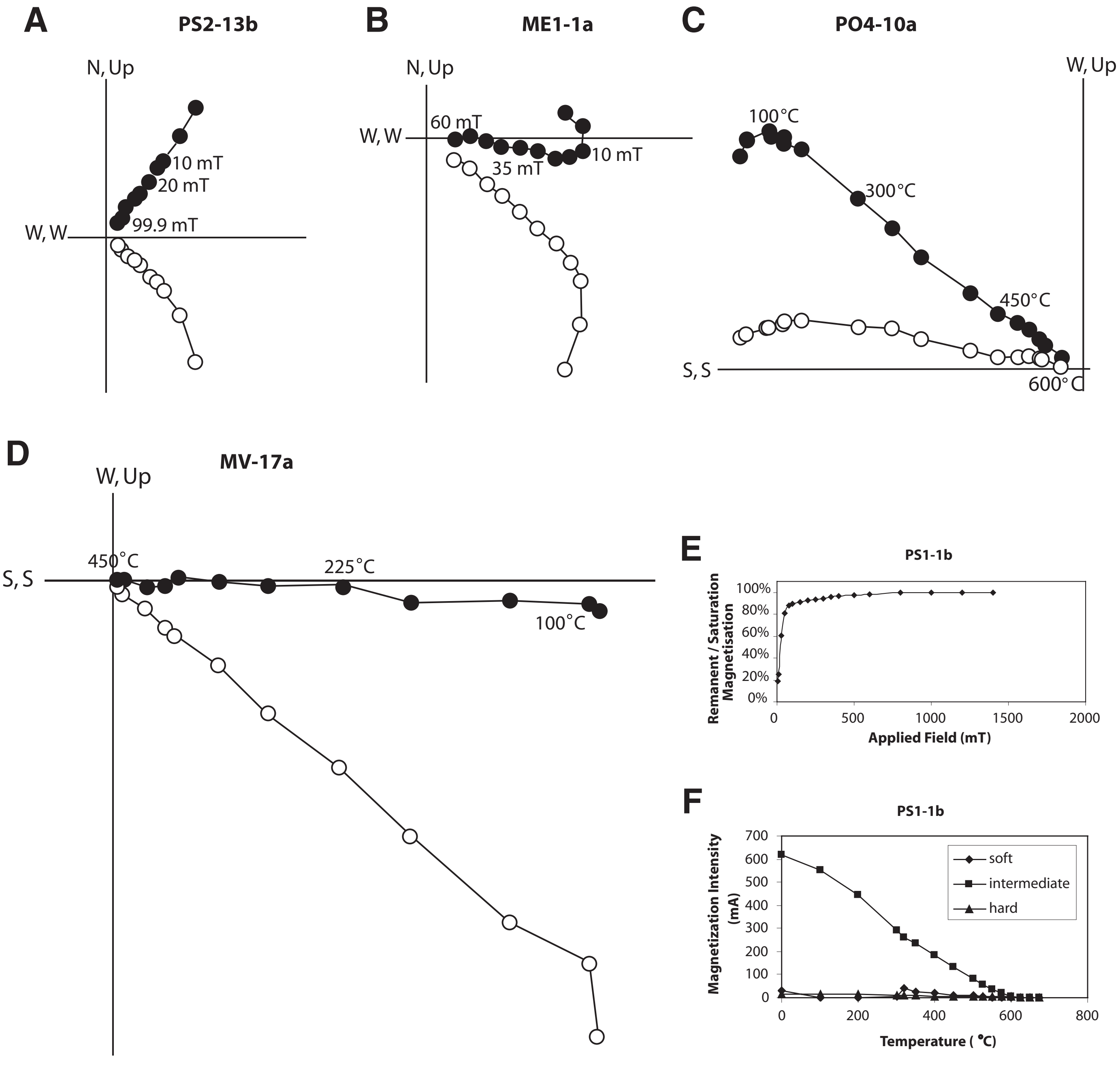


Figure 3. (A–D) Zijderveld plots showing typical demagnetization behavior from sites in (A) Upper Cretaceous limestone with initial magnetization M(r) = 1.85 mA/m; (B) Eocene limestone, M(r) = 0.40 mA/m; (C) Oligo-Miocene blue-gray marl, M(r) = 6.55 mA/m; and (D) Plio-Pleistocene blue gray marl, M(r) = 16.10 mA/m. Solid circles—horizontal projection of magnetization vector at a particular temperature or field (see labels on plots); open circles—vertical projection of the same. The distance of points from the origin indicates the magnitude of the magnetization, and consecutive points that lie in a straight line represent components of the magnetization vector. (E) Normalized isothermal remanent magnetization (IRM) acquisition curve. (F) Thermal demagnetization of IRM for a pink Upper Cretaceous limestone. Panel E illustrates that 90% of the saturation magnetization is acquired by the time the applied field has reached 100 mT, while panel F shows that the dominant component of magnetization is the intermediate coercivity component and that it is virtually eliminated by 600°.

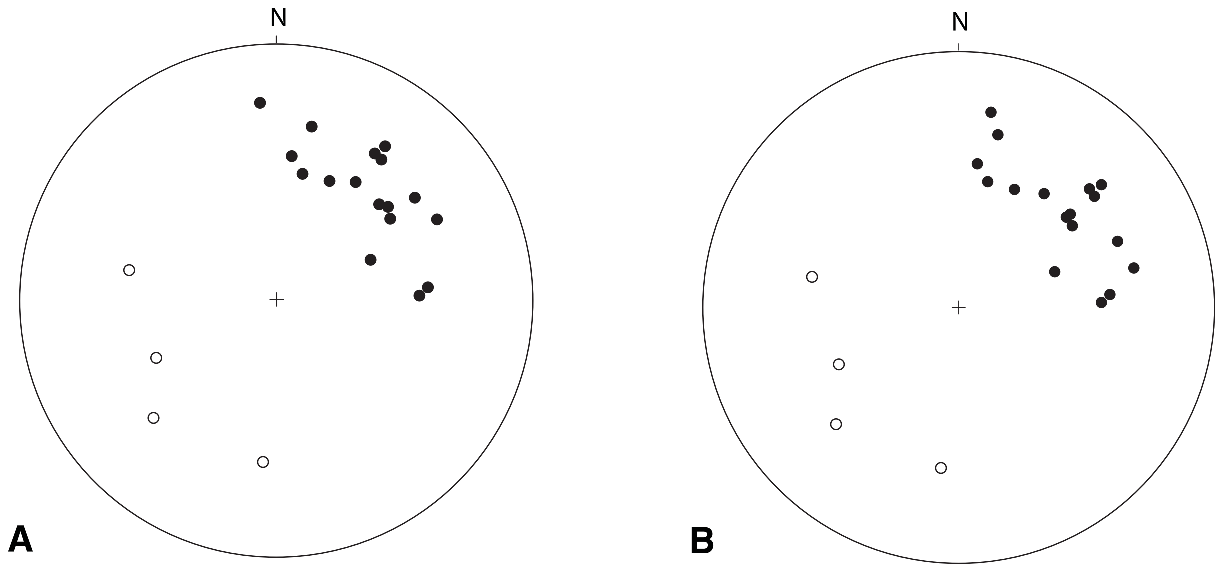


Figure 4. Stereographic projections showing the distribution of rotations inferred from this study within the Ionian zone relative to (A) present-day geographic North and (B) expected declinations predicted for each site using the paleo-positions of the African poles given by Besse and Courtillot (2002). Filled circles indicate that the inclination is positive, plotted in the lower hemisphere. Open circles indicate a negative inclination, plotted in the upper hemisphere.

TABLE 3. SUMMARY OF PALEOMAGNETIC RESULTS

Site	Age	N/R	Latitude (°N)	Longitude (°E)	ή/n	D_B (°)	I_B (°)	k_B	$\alpha_{95\ B}$	D_A (°)	I_A (°)	K_A	$\alpha_{95\ A}$	S/D
MV	Pl	12/0	37.68	21.00	12/14	358.8	54.5	38.81	7.1	11.7	48.2	38.81	7.1	334/12
BAY	Pl	15/0	37.68	21.00	15/38	358.2	48.1	43.56	5.9	6.1	42.8	44.6	5.8	–
GER	Pl	14/0	37.68	21.00	14/27	10.9	55.7	43.78	6.1	24	47.7	43.78	6.1	340/13
KAL	Pl	10/0	37.68	21.00	10/12	2.8	45.3	37.01	8.0	11.5	31.4	36.09	8.2	–
PM1	M	6/0	39.34	20.33	6/13	22.1	56.2	174.02	5.1	66.6	57.1	174.02	5.1	046/28
KM1	M	4/0	39.17	20.64	4/9	358.7	50.4	218.68	6.2	33.8	43.7	218.68	6.2	005/32
PM4	M	11/0	39.55	20.63	11/12	37.6	71.8	29.59	8.5	46.9	44.3	29.59	8.5	324/28
PO4	M	0/6	39.41	20.35	6/12	216.8	–5.9	213.79	4.6	184.7	–37.0	213.79	4.6	180/74
PE1	Ep	3/12	39.53	20.56	15/19	0.9	–77.7	12.70	11.2	281.7	–41.1	31.10	7.0	–
ME1	Ep	14/0	38.84	20.95	14/16	88.7	–10.6	7.90	15.1	88.0	43.5	40.64	6.3	–
AE1	Ep	8/3	39.26	20.98	11/11	25.0	61.7	119.75	4.2	54.3	44.5	119.75	4.2	002/27
IE4	Ep	0/11	39.89	20.73	11/11	232.2	–44.8	72.78	5.1	244.5	–47.0	72.78	5.1	069/12
PE3	Eg	7/4	39.55	20.55	11/12	58.7	72.2	38.15	7.5	50.0	42.6	38.15	7.5	314/30
IE1	Ep	0/12	40.03	20.44	12/13	221.6	–48.2	71.29	5.2	226.3	–34.2	71.29	5.2	335/15
PE2	Eg	2/4	39.53	20.55	6/12	109.3	72.7	49.33	9.6	85.0	40.4	49.33	9.6	341/35
PS3	K	17/0	39.41	20.51	17/17	25.3	61.4	22.60	7.7	53.4	33.2	50.7	5.1	–
FS1	K	10/0	39.53	20.33	10/10	22.1	39.9	81.91	5.4	35.2	27.3	81.91	5.4	356/23
FS2	K	11/0	39.55	20.32	11/12	54.8	74.2	29.59	8.5	63.2	30.5	29.59	8.5	337/44
IS1	K	14/0	39.69	20.68	14/14	39.8	45.5	45.69	5.9	36.7	32.0	45.69	5.9	292/14
PS1	K	9/0	39.44	20.25	9/11	339.2	47.7	121.33	4.2	355.3	23.7	121.33	4.2	300/32
PS2	K	10/0	39.43	20.50	10/12	16.0	46.4	131.55	4.2	33.8	31.6	131.55	4.2	351/26

Note: For Age refer to the codes given in Table 2. N/R—ratio of the number of samples of normal polarity to the number of those of reversed polarity; ή/n—ratio of the number of samples used to determine mean site magnetization to the total number of samples demagnetized; D—declination; I—inclination; k—precision parameter; α_{95}—angle of 95% confidence. Subscripts B and A denote, respectively, directions before and after applying a correction for tilted bedding. S/D—mean strike (90° counterclockwise of dip) and dip of site bedding where applicable.

However, detailed inspection of the results shows that there is considerable dispersion among site mean directions across the Ionian zone, indicating a range of declinations from little or no rotation to over 90° clockwise rotation (Fig. 4A). By considering site location as well as sense and magnitude of rotation, we have identified three areas (Fig. 2) in which vertical-axis rotations deviate significantly from the regional average obtained in this study and from the averages obtained by previous workers (cf. Table 1):

i. The Igoumenitsa region. We identified no significant rotation relative to present-day geographic North, reinforcing the results obtained by Horner (1983).
ii. The Saloniki region. Large rotations of over 90° were observed in Eocene pink and gray limestones.
iii. The Lefkada-Vonitsa region. Large rotations of ~90° were observed in Eocene pink limestones, confirming the large rotations recognized in the area (Horner and Freeman, 1983; Marton et al., 1990; Birch, 1994).

The effects of applying the correction for expected direction to these anomalous regions, and to all other parts of the Ionian zone, are described later, as is the regional significance of these effects. However, the Saloniki region (Area ii) is not discussed in detail in this article because appraisal of this area is pending additional paleomagnetic results.

Reappraisal of Paleomagnetic Data from the Ionian Zone

Data. The results re-evaluated in this section are from (1) Laj et al. (1982), (2) Horner (1983), (3) Horner and Freeman (1983), (4) Kissel et al. (1985), (5) Marton et al. (1990), (6) Birch (1994), (7) Duermeijer et al. (1999), and (8) this study. These data are referred to the African polar wander path of Besse and Courtillot (2002), with expected directions and inferred rotations calculated for each site individually (see Table 4 for representative expected directions). Only results with $\alpha_{95} < 15°$ have been used, except in cases in which the results are from a cluster of sites of the same age, in the same formation and structure, and show a similar remanence to a well-defined local mean vector.

Figure 4B shows the mean paleomagnetic vectors from all sites in this study after correction for expected declination. These results still imply a net clockwise rotation of the Ionian zone, with a mean D = 47.8°, I = 42.6°, and $\alpha_{95} = 9.2°$; individual rotations now range from insignificant to over 100° clockwise. Figure 5 shows the corrected rotations inferred from this study and the re-evaluated results from the studies numbered 2–7 in the previous paragraph.

Overall, relative to the African poles, the clockwise rotations of all sites are greater than those relative to present-day geographic North. However, significant variations exist. A detailed analysis of the spatial and temporal patterns in these rotations was carried out, and the results are now described.

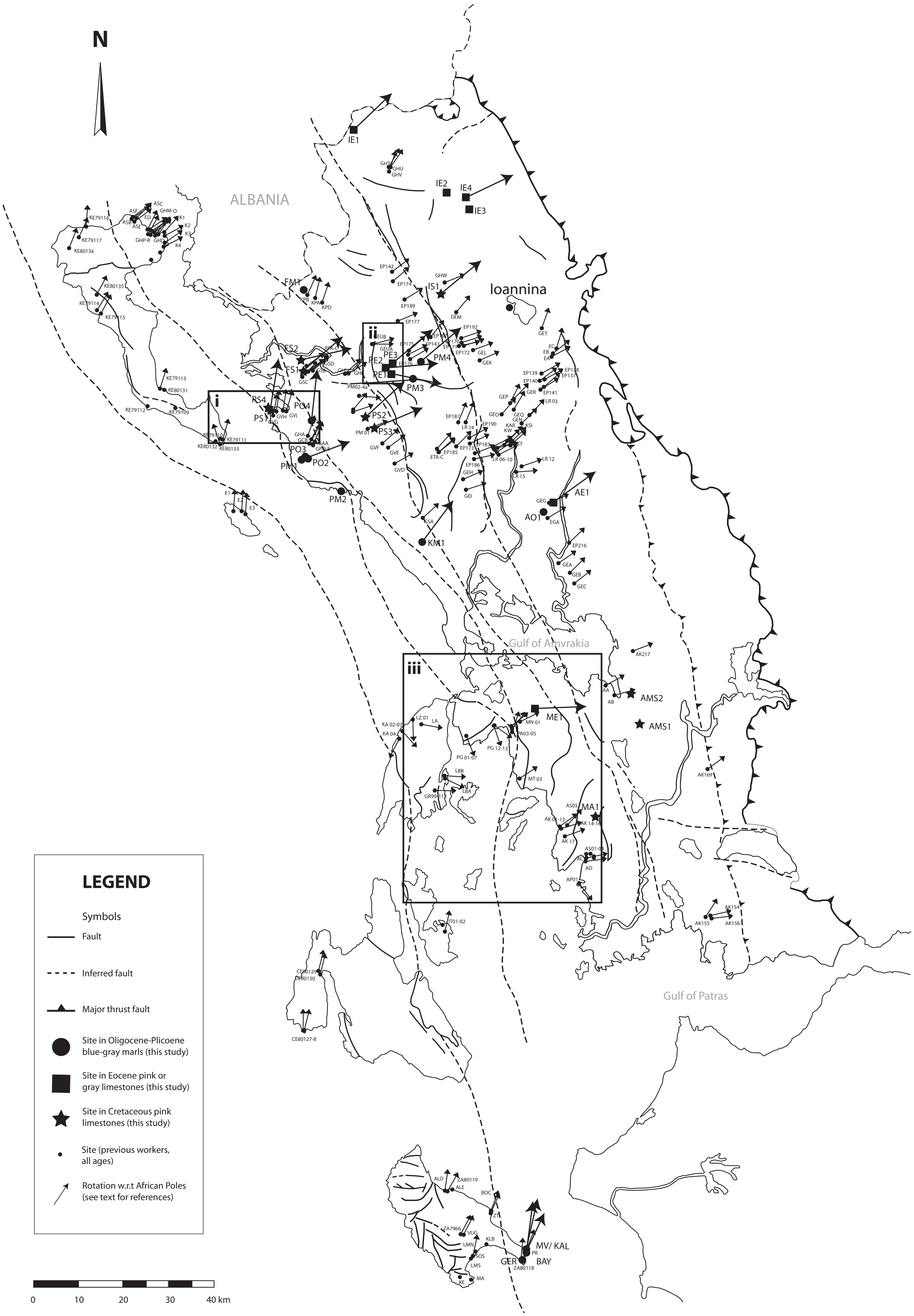
Rotation versus Strike of Bedding. In a study of the Betic-Rif arc, Platt et al. (2003) demonstrated that analyses of the relationships between structural trends and the amount of vertical-axis rotation in a thrust belt can be successfully used to determine the belt's original geometry. Timings of rotation can be established by observing the relationship between kinematics and the amount of rotation (Allerton, 1998).

In the absence of detailed kinematic data from the Ionian zone, we have made a preliminary appraisal of the overall relationship between the amount of rotation and regional bedding strike (Fig. 6). This method differs from the conventional tectonic correction discussed earlier in that it is not a correction to the paleomagnetic data. Rather, it is a comparison of the amount of rotation, inferred by tectonically corrected paleomagnetic data from a site, with the regional trend of the structure (e.g., anticline) to which the site belongs. This allows an assessment of whether variations in structural trends are primary or whether structures have been rotated into their present configurations. For paleomagnetic data from this study, our own structural measurements were used for the strike of bedding. However, for sites from other studies that did not include detailed structural data, bedding strike was determined from maps and our own

TABLE 4. EXPECTED DECLINATIONS AND INCLINATIONS IN THE IONIAN ZONE

Age	Pleistocene	Pliocene	Upper Miocene	Lower Miocene	Oligocene	Upper Eocene	Lower Eocene	Paleocene	Upper Cretaceous	Lower Cretaceous	Middle Jurassic	Late Jurassic
Expected declination (°)	358.7	358.1	357.4	356.9	358.4	359.9	357.5	352.7	346.0	331.4	332.8	337.2
Expected inclination (°)	55.7	55.5	54.8	53.4	50.7	47.4	45.0	43.1	41.4	34.5	38.5	43.0

Note: Expected directions are calculated for a representative site location of 39.5° N, 20.5° E, using Besse and Courtillot's (2002) apparent polar wander path for Africa.


N
ALBANIA
Ioannina
Gulf of Amvrakia
Gulf of Patras
i
ii
iii
IE1
IE2
IE3
IE4
IS1
FM1
FS1
FS2
PS1
PS2
PS3
PS4
PO2
PO3
PO4
PM1
PM2
PM3
PM4
PE1
PE2
PE3
KM1
AE1
AO1
ME1
MA1
AMS1
AMS2
MV/ KAL
GER
BAY
LEGEND
Symbols
Fault
Inferred fault
Major thrust fault
Site in Oligocene-Plicoene blue-gray marls (this study)
Site in Eocene pink or gray limestones (this study)
Site in Cretaceous pink limestones (this study)
Site (previous workers, all ages)
Rotation w.r.t African Poles (see text for references)
0
10
20
30
40 km

field data, by establishing a mean strike for the structures that the sites belonged to on a scale of tens of kilometers. Although this method must have introduced some scatter, we feel that it is the most reliable method of obtaining accurate structural measurements for the majority of sites.

Figure 6 illustrates the variation of strike with rotation across the entire study area. There is a broad scatter of results, with no simple relationship clearly evident. This lack of correlation implies that at least part of the rotation was acquired prior to the folding and thrusting events that produced the structures that dominate the Ionian zone. If this pre-tectonic rotation had affected the entire zone in a consistent manner, one would expect the data presented in Figure 6 to fall on a straight line with zero slope. However, the degree of scatter in the data suggests that this was not the case, and although part of the rotation must have preceded folding and thrusting, the amount of rotation must have varied spatially. In addition, the rotations of Miocene-age and younger data clearly either are contemporary with or postdate the folding and thrusting. A more detailed study of the rotations of individual structures may help to resolve these issues.

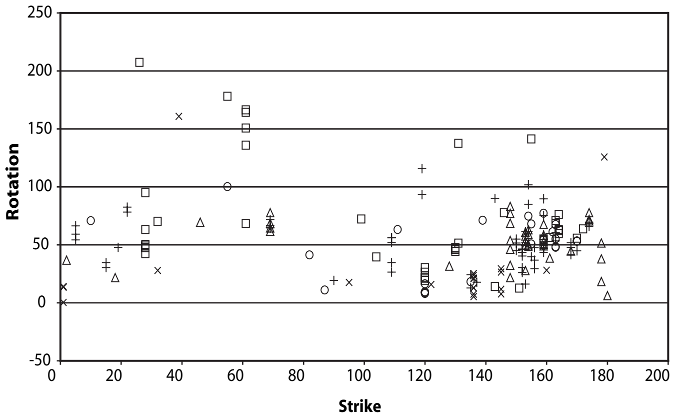


Figure 6. Plot of rotation versus strike for all sites in the study area. The symbols indicate the ages of magnetization: squares—Lower Jurassic; circles—Tithonian–Santonian; crosses—Paleocene–Eocene; triangles—Oligo-Miocene; x's—Plio-Pleistocene.

The Igoumenitsa Region (Area i) and the Rotation of Individual Thrust Sheets. After correction, the data for the Igoumenitsa region (Area i in Figs. 2 and 5) show a significant difference from the uncorrected values in this area. This region now appears to have undergone a clockwise rotation of up to 19° since the upper Santonian (Fig. 5). Four Jurassic sites in the region, ranging in age from Toarcian to Bathonian, show clockwise rotations ranging from 22° to 30°. Site PO4 (Figs. 2 and 5), the youngest site within this region, shows a rotation of 6° relative to the Oligocene African pole (Besse and Courtillot, 2002), and the inclination is 14° shallower than expected. The inclination error is slightly large, but of a magnitude similar to those of sites of the same age and lithology from elsewhere in the Ionian zone (e.g., Kissel et al., 1985) when taken relative to the African pole used in this study. Kissel et al. (1985) found this error to be due to the presence of a planar sedimentary fabric, and this cause is favored in this study, based on preliminary measurements of anisotropy of magnetic susceptibility. However, in the last decade there has been much debate on the commonly observed shallow bias in paleomagnetic inclinations in the Mediterranean region (e.g., Beck and Schermer, 1994; Krijgsman and Tauxe, 2004), with widely divergent alternative solutions proposed, including the presence of a large nondipole component of the Earth's main field and major northward drift, as well as inclination flattening. It may be possible to test the cause of the inclination error observed at site PO4 using a statistical method that relates the dispersion of paleomagnetic vectors due to secular variation to latitude and to inclination by means of a flattening factor (e.g., Krijgsman and Tauxe, 2004).

Site PM1, in Miocene blue-gray marls, shows a clockwise rotation of 70° that, on inspection of Figure 5, appears to be in complete contrast with the small 6° rotation indicated by PO4. However, this site was actually in a tectonic window, and thus belongs to the underlying Corfu thrust sheet (Fig. 1).

The results from Jurassic sites in this region imply some degree of pre-Cretaceous rotation, but it cannot be defined from these results due to their scatter. The remaining results suggest that the Igoumenitsa area has undergone a clockwise rotation of ~16°, commencing, at the earliest, in the upper Santonian, and continuing post-Oligocene, with 6° of the rotation occurring since, at the earliest, the Oligocene.

In contrast to the results from Area i (Figs. 2 and 5), those from the northern part of the Igoumenitsa thrust sheet and the neighboring Corfu and Paramythia thrust sheets (Fig. 1) show large average clockwise rotations relative to the African poles. These are 45° and 57°, respectively, for the latter two thrust sheets (Fig. 7). Sites from northeastern Corfu on the northern part of the Igoumenitsa thrust sheet exhibit a mean clockwise rotation of 47°. Figure 7 illustrates the mean rotations of the individual thrust sheets identified in Figure 1, not taking into account the positions of sites within a thrust sheet or their ages. This figure shows that there is a general westward decrease in the mean rotation of thrust sheets. This can be seen very clearly in Figure 8, which shows how the magnitude of rotation decreases linearly with distance from the Pindos thrust, along a section taken from the Pindos thrust to the Ionian Sea in approximately the direction of thrusting (Line 1, Fig. 1).

The Lefkada-Vonitsa Region (Area iii) and Rotations within Thrust Sheets. The apparently straightforward relationship between magnitude of rotation and proximity to the fore-

Figure 5. Map of the Ionian zone showing site locations and rotations relative to the African poles given by Besse and Courtillot (2002) for the Neogene, Oligo-Miocene, Paleocene–Eocene, Upper Cretaceous, Lower Cretaceous, and Lower–Middle Jurassic. Large symbols indicate results from this study, small symbols results from studies referred to in the text. Boxes i–iii as in Figure 2.

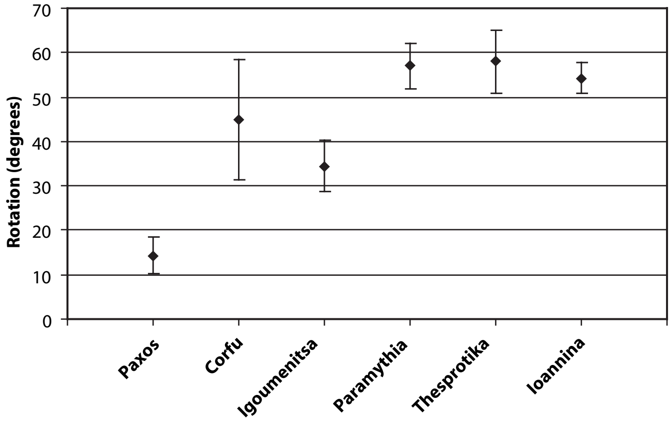


Figure 7. Plot showing the mean rotation of each of the thrust sheets defined in Figure 1.

land is confused by differential rotations within thrust sheets that, when averaged over entire thrust sheets, can give misleading information. This can be seen by comparing Figures 8 and 6. Figure 7 shows a mean clockwise rotation of 45° of the Corfu thrust sheet, sandwiched between the Igoumenitsa thrust sheet and the Paxos zone, both of which show far less rotation on average. However, it can be seen in Figure 5 that data on the mean rotation of the Corfu thrust sheet is made up of data that define two rather disparate subsets, separated geographically by the Gulf of Amvrakia.

North of the Gulf of Amvrakia, rotations generally range from ~4° to ~32° clockwise. The obvious exception to this trend is the aforementioned rotation of 70° at site PM1 (Figs. 2 and 5). However, this site shows an inclination that is ~7° larger than that expected, which implies an original position ~8° farther north than expected relative to the Oligo-Miocene African pole, some degree of horizontal-axis rotation about more than one axis, the imposition of a magnetic fabric, or remagnetization. Southward drift of the Ionian zone since the Miocene is not evidenced in other paleomagnetic results or in paleogeographic reconstructions of the eastern Mediterranean (e.g., Robertson and Dixon, 1984). Horizontal-axis rotation about more than one axis would lead to an erroneous tectonic correction, because phases of tilting cannot be distinguished in the absence of detailed kinematic data, so the application of a simple tectonic correction based on the current bedding dip, as used in this study, would lead to an incorrect interpretation of the original magnetization. Based on our field observations, we believe that any significant differential rotation due to distinct phases of folding is unlikely, because the sediments at the site are relatively undisturbed and form continuous, fairly gently dipping beds. However, we noted the presence of very small-scale enechelon normal faults with apparent displacements on the order of a few millimeters to 1 or 2 cm. Therefore, we cannot rule out the possibility that this site underwent a second phase of tilting related to normal fault activity.

Figure 9 illustrates the principal susceptibility axes of sediments at PM1 plotted relative to bedding. These results describe an oblate susceptibility ellipsoid characterized by a clustering of minimum (K_{min}) susceptibility axes perpendicular to bedding and by intermediate (K_{int}) and maximum (K_{max}) axes defining a plane approximately parallel to bedding. These results indicate a moderate planar sedimentary fabric with a mean anisotropy factor of K_{max}/K_{min} = 1.04 and no significant lineation, for K_{max}/K_{int} = 1.007. Based on these results, we believe that the inclination steepening at site PM1 is not due to the presence of a strong magnetic fabric.

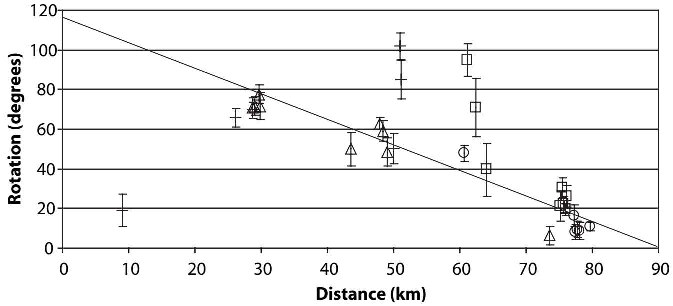


Figure 8. Plot showing the variation of rotation with distance from the Pindos thrust, along Line 1 (Fig. 1), approximately oriented in the direction of thrusting. The symbols represent the ages of magnetization: squares—Lower Jurassic; circles—Tithonian–Santonian; crosses—Paleocene–Eocene; triangles—Oligo-Miocene.

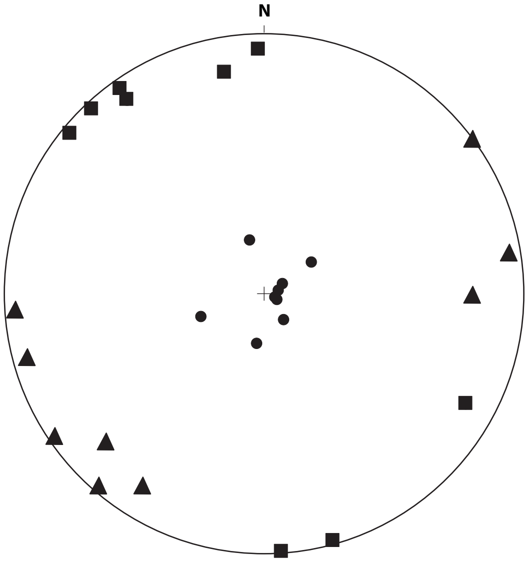


Figure 9. Stereonet illustrating the principal susceptibility axes of samples from site PM1 relative to bedding, i.e., the perimeter of the stereonet is parallel to bedding, and the center defines the perpendicular to bedding. The symbols represent susceptibility axes (K): squares—K_{max}; triangles—K_{int}; circles—K_{min}.

The explanation we favor for the results from site PM1 is that of post-tilting remagnetization. If the pre-tilt-corrected magnetization vector of this site is viewed relative to the Plio-Pleistocene African pole (Besse and Courtillot, 2002), the magnitude of rotation is in good agreement with other results from the northern parts of the Corfu thrust sheet, at ~23°, and the inclination is <1° steeper than the predicted field. This inclination anomaly is within the errors on the magnetization direction from this site ($\alpha_{95} = 5.1°$). A mechanism for overprinting during the Pliocene might be provided by fluid circulation during thrust sheet emplacement (e.g., McWhinnie et al., 1990). An exposure at the northern end of Arilla Beach in Epiros (cf. Fig. 3 for location) clearly shows deformed Triassic evaporites emplaced above Pliocene clastics by the sole thrust of the Igoumenitsa thrust sheet, constraining activity on this fault to be no older than Pliocene age. If remagnetization of the underlying sediments occurred during movement on this fault, it would be reasonable to refer the magnetization vector to the Plio-Pleistocene African pole as we have done. However, this conjecture is speculative and should be viewed only as a possible solution to the problem of the discrepancy between the observation at PM1 and the situation in the rest of the northern Corfu thrust sheet. Detailed rock magnetic study may resolve the issue if different phases and conditions of magnetic mineral growth can be identified and dated.

South of the Gulf of Amvrakia, the magnitude of clockwise rotations on the Corfu thrust sheet is generally much larger than to the north, as is the array of magnitudes, ranging from ~5° rotation of lower Pleistocene sediments on Zakynthos to ~207° locally, in Toarcian sediments on Lefkada. Figure 10A shows the relationship between the magnitude and age of rotations on the southern part of the Corfu thrust sheet. This shows a clear increase in the magnitude with age and an apparent decrease in rotation rate with age.

In fact, this trend of larger rotations south of the Gulf of Amvrakia also appears to be present on the Paramythia and Thesprotika thrust sheets (Fig. 5), in the Lefkada-Vonitsa region (Area iii, Figs. 4 and 6) and also affects the whole of Zakynthos. Figure 10B illustrates the relationship between the magnitude of rotation and the age of magnetization in that part of the study area south of the Gulf of Amvrakia (including sites in Paxos zone sediments). The plot shows a linear increase rather than a decreasing rotation rate, with ages from the present day back to

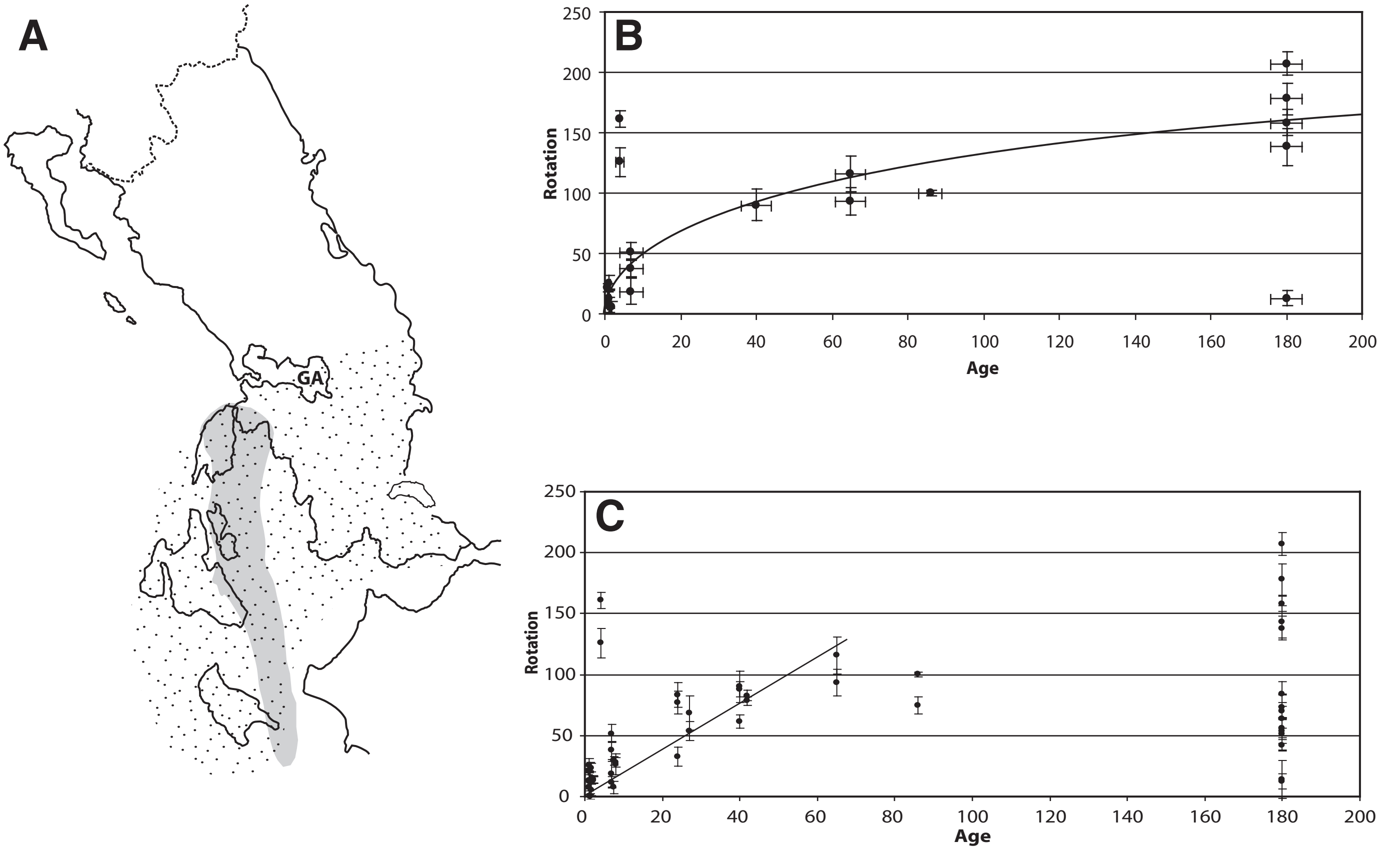


Figure 10. (A) Sketch map showing the regions referred to in panels B and C. GA—Gulf of Amvrakia. (B) Plot showing the variation in magnitude of rotation with age on the Corfu thrust sheet, south of the Gulf of Amvrakia (solid shaded region only in panel A). (C) Plot showing variation in magnitude of rotation with age in the study area, south of the Gulf of Amvrakia (solid shaded and stippled regions in panel A).

the middle Eocene (ca. 42 Ma), at a rate of ~2° per million years. However, beyond the Eocene, the story becomes more complicated. Upper Cretaceous data (ca. 65–85 Ma) show a decrease in rotation with age, implying a relative counterclockwise rotation between the Cretaceous and the Eocene. Following this, there is a large gap in the data between 85 and 180 Ma. This is due in part to unconformities and in part to a lack of magnetically suitable lithologies in this age range. Toarcian sediments in this region exhibit a huge range of rotations (Fig. 10B), from ~13° to over 200° clockwise. Because these large variations are not seen in younger lithologies, the broad range is probably due to local rotations that occurred prior to pelagic sedimentation in the Ionian zone. It may be that these local variations are partly associated with subsidence and extension during the transition from platform to pelagic sedimentation during the Middle Jurassic. Due to a lack of data (only four sites in Cretaceous sediments) and the large scatter of Toarcian data, it was not possible to assess the rate, sense, and amount of rotation of this region prior to the Eocene. Although these results are inconclusive, it is possible that there may have been some relative counterclockwise rotation of this region between the Eocene and the Jurassic, based on the smaller amounts of overall rotation observed at pre-Eocene sites.

Rotation and Age. The timings and rates of rotations in key areas have already been discussed in previous sections. However, we also performed a brief analysis of the distribution of rotations observed within the five main age groups, namely: (1) Plio-Pleistocene, (2) Oligo-Miocene, (3) Paleocene-Eocene, (4) Cretaceous, and (5) Jurassic. The results are presented in Figure 11 and show ~29° clockwise rotation between the Miocene and the Plio-Pleistocene and no significant rotation between the Jurassic and the Miocene when the results are averaged over the entire study area. The stereonets in Figure 11 (A–E) show the distribution of rotations that contributed to the mean rotation for each age. The Plio-Pleistocene sites show good clustering, although this is partly due to a bias in sampling, for suitable sediments of this age are found only in more external parts of the Ionian zone. Sites of all other ages show a very scattered distribution, particularly the Cretaceous and Jurassic sites. Horner and Freeman (1983) and Horner (1983) have shown that this

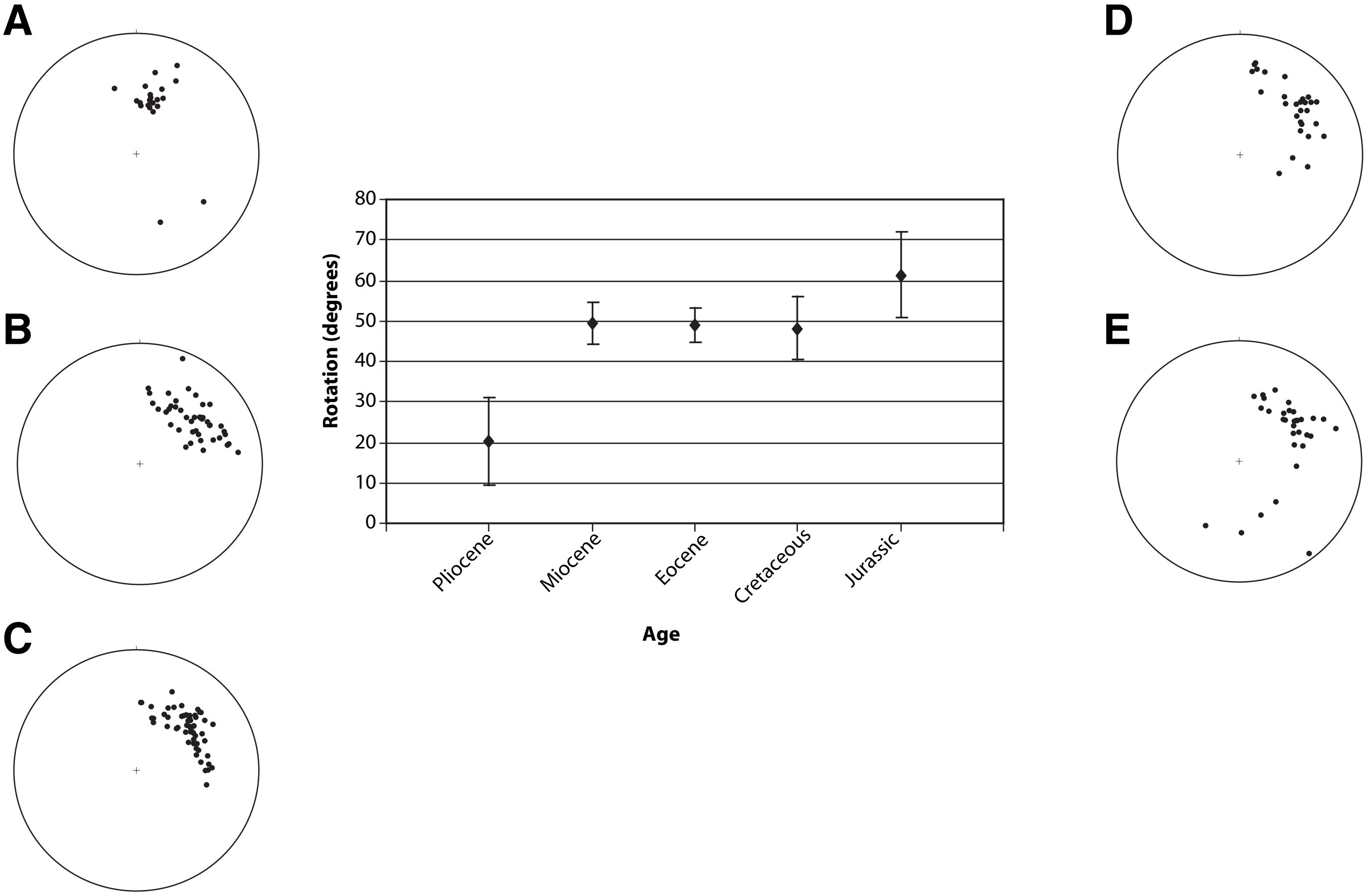


Figure 11. Graph and stereonets showing, respectively, mean rotations and distribution of rotations relative to the African poles, for (A) Pliocene, (B) Oligo-Miocene, (C) Paleocene–Eocene, (D) Cretaceous, and (E) Jurassic sediments from the Ionian zone and most of the external Paxos zone.

scatter of paleomagnetic directions can be significantly reduced by applying a correction for local fold axis trend to produce a reliable estimate for the overall rotation of the Ionian zone. However, the results presented in previous sections of this article show that these variations can be important in themselves in distinguishing the evolution of different parts of the thrust belt.

SUMMARY AND CONCLUSIONS

Overall, the new paleomagnetic results presented in this study are in agreement with the results of previous studies, providing evidence of a large clockwise rotation of the Ionian zone. However, our reappraisal of previous results and detailed analysis of the spatial and temporal distribution of both these and our new results has implications for the evolution of the Ionian zone and the relationship of vertical-axis rotations to thrusting. In general, these results further support the hypothesis of van Hinsbergen et al. (2005) of a large clockwise rotation of a broad region of Greece. However, while these authors dismiss local variations in the degree of rotation as due to local tectonic features, we feel that these variations deserve further study in their own right, for they may allow a deeper understanding of the mechanisms accommodating regional-scale rotation.

Based on a smaller degree of overall clockwise rotation of most sites of Cretaceous and earlier age, we suggest that parts of the Ionian zone may have undergone some degree of counterclockwise rotation beginning, at the earliest, in the Upper Cretaceous. The questions about the amount of rotation and the extent of the zone affected are not resolvable based on these results. However, a fairly widespread counterclockwise rotation predating the main folding and thrusting events in the Ionian zone would help to explain the lack of correlation between magnitude of rotation and strike (Fig. 6). Any counterclockwise rotation must have come to an end by, at the latest, the Paleocene, and may have been associated with a transition from relative sinistral shear to convergence between Eurasia and Africa and with opening of the north Atlantic (Robertson and Dixon, 1984).

We present evidence of differential rotations between thrust sheets, with paleomagnetic data showing a general southwestward, or forelandward, decrease in the magnitude of rotation (Fig. 8). In particular, evidence from Oligocene sediments on the Igoumenitsa thrust sheet implies that at least the mainland part of this thrust sheet (Fig. 1) has undergone only ~6° clockwise rotation since the Oligocene, in contrast to data from Oligo-Miocene sediments from more internal parts of the Ionian zone, which exhibit rotations of around 50°–75°. The overall implication is that rotations may have occurred during thrusting.

However, the pattern of forelandward decreasing rotation is disturbed by regional rotations that appear to affect multiple thrust sheets. Considering first the Igoumenitsa thrust sheet, discussed earlier, the Toarcian to Eocene sites on the northernmost part of this thrust sheet (northeastern Corfu, Fig. 5) show a clear average clockwise rotation of 47°, α_{95} = 5.1°, around 30° greater than the rotations of sites of the same age on the mainland part of this thrust sheet (Area i, Fig. 5).

Clockwise rotations of up to 28° relative to the Pliocene African pole (Besse and Courtillot, 2002) are observed on western and southern Corfu (Fig. 5) and interpreted to be of early Zanclean (ca. 5 Ma) age (Laj et al., 1982). This latter region falls on the Corfu thrust sheet, which underlies the Igoumenitsa thrust sheet (Fig. 1). We tentatively interpret data from Miocene marls on the same thrust sheet in mainland Greece (PM1, Figs. 2 and 5) as having a post-tilting magnetization of Pliocene age that indicates a rotation of ~23°. Based on these results, we postulate that between Corfu and the Gulf of Amvrakia (Fig. 1) the Corfu thrust sheet has undergone a consistent clockwise rotation on the order of 25°–30° since the early Pliocene. In addition, we propose that the Igoumenitsa thrust sheet rotated consistently until at least Oligocene times, but that the northern part of this thrust sheet (northeastern Corfu) has moved with the Corfu thrust sheet since the early Pliocene. This hypothesis is based on the similarity of rotations observed over the whole of Corfu and the lack of any significant difference in rotation between sediments of Toarcian age and those of Pliocene age after subtracting the 16° rotation of the central part of the Igoumenitsa thrust sheet (Area i) from the rotations observed in northeastern Corfu.

An important implication of the previous discussion is that what was interpreted by Kissel et al. (1985, and references therein) as a period of no rotation of the entire Ionian zone between ca. 12 and 5 Ma could equally be interpreted simply as a lack of rotation in the most external part of the Ionian zone until ca. 5 Ma. However, this solution presents several problems. First, there must have been some mechanism that decoupled Corfu from mainland Greece and caused the northern part of the Igoumenitsa thrust sheet to move with the Corfu thrust sheet. Second, the central portion of the Igoumenitsa thrust sheet shows ~16° rotation loosely dated as post-Cretaceous but most likely much later than this, whereas the underlying Corfu thrust sheet exhibits a clockwise rotation of ~30° since the Pliocene.

GPS data from the northeast Ionian Sea (Kahle et al., 1993; Peter et al., 1998) show disparities between the trajectories of Corfu and northwest mainland Greece both relative to Eurasia and relative to a regional trend. In the latter case, GPS velocities on Corfu and in the northern Ionian Sea are oriented to the NNE and show a marked increase, from ~16 mm/yr on Corfu to ~36 mm/yr on the southernmost tip of the “heel” of Italy. This implies a clockwise rotation of Corfu and regions farther north relative to Epiros (Fig. 1). Concerning a mechanism accommodating these differential rotations, a key may be provided by kinematic analysis of major faults on Corfu and an analysis of structures in northern Epiros that show a pronounced change in strike just south of the Albanian border.

The relative rotation between Corfu and the central Igoumenitsa thrust sheet clearly is not a result of thrusting, for the deformation cuts across at least two thrust sheets and may even relate to the large clockwise rotations observed in the Saloniki region (Area ii, Figs. 2 and 5). Therefore, the fact that the Corfu thrust sheet underwent rotation while parts of the overlying Igoumenitsa thrust sheet remained relatively unrotated may imply that this deformation was partially accommodated on the thrust fault between these two thrust sheets simply because it presented a zone of weakness.

The other major feature complicating the pattern of rotations observed in the Ionian zone is a zone of very large clockwise rotations observed south of the Gulf of Amvrakia (Fig. 5). These large rotations appear to have affected not only mainland Greece south of the Gulf of Amvrakia, but also the islands of Lefkada, Kefallonia, and Zakynthos. We assume that Ithaki, with its position between Lefkada and Kefallonia, has undergone a rotation similar to that of these islands, but only one successful site exists on this island, showing an overall clockwise rotation of ~13° since, at the most, Toarcian times.

We show that this rotation has occurred since, at the earliest, Priabonian (ca. 40 Ma) times. The data fit a linear trend that indicates rotation at a rate of ~2°/m.y. since the Priabonian (Fig. 10). However, this rate should be treated with caution as an average rate, for there are gaps in the data from ca. 7–24 Ma and from ca. 25–40 Ma. Consequently, although the rotations of ~85° and ~60° are shown in Figure 10 to have begun around 40 and 24 Ma, respectively, these should be regarded as maximum ages.

Some degree of differential rotation is also likely to have occurred between individual thrust slices of the Ionian zone south of the Gulf of Amvrakia, but this has been difficult to assess for two reasons. First, there is a bias in sampling, with most of the samples from this region located in the more external domains; this bias is mainly due to a lack of magnetically suitable lithologies elsewhere. Second, this pattern, which we would expect to show a forelandward decrease in rotation, is heavily disrupted by a later pattern of rotations that show an increase in rotation toward the west. As suggested by Birch (1994) and later by van Hinsbergen et al. (2005), we believe that on the mainland, Lefkada, Kefallonia, and Ithaki, this westward increasing rotation is related to activity on and propagation of the Kefallonia fault zone and facilitated by the presence of large volumes of evaporites underlying this part of the Ionian zone (Jenkins, 1972; Graham, 1987). However, Duermeijer et al. (1999) present convincing evidence that the rotation of Zakynthos island, between 25° and 30° relative to the Plio-Pleistocene African pole (Besse and Courtillot, 2002), has occurred rapidly in the last 0.77 m.y. and that no significant rotation occurred on Zakynthos prior to this since, at the latest, the late Tortonian (ca. 8 Ma).

Zakynthos has a unique position when compared to the other Ionian islands in that it sits above the African slab, adjacent to the Hellenic arc (Le Pichon and Angelier, 1979). Duermeijer et al. (1999) proposed that the rotation observed on this island was related to rebound processes associated with detachment of the African slab underneath Zakynthos. However, GPS data presented by McClusky et al. (2000) show that Zakynthos has no significant motion relative either to Anatolia or to the southern Aegean, suggesting that it is in a zone that accommodates the distinct effects of Anatolian extrusion and southern Aegean extension. We propose that the interaction of these two motions may provide an alternative mechanism for the observed rapid clockwise rotation.

In summary, the results of this study provide insight into the tectonic evolution of the Ionian zone since the Early Jurassic. We show that clockwise rotations observed in this isopic zone are related, to some extent, to Miocene-Pliocene thrusting, but that this pattern is somewhat distorted by superimposed rotations resulting from regional forces and the complex interaction of plate motions in the eastern Mediterranean.

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