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A Late Pleistocene clockwise rotation phase of Zakynthos (Greece) and implications for the evolution of the western Aegean arc

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Abstract

Palaeomagnetic measurements have been carried out on Eocene to Pleistocene sediments on the Ionian island of Zakynthos, NW Greece. Magnetostratigraphic constraints, biostratigraphic analyses of planktonic foraminifera and calcareous nannofossils provide a reliable time frame for these deposits. The results show that no significant rotation occurred between 8.11 and 0.77 Ma, but that Zakynthos underwent a 21.6º ± 7.4º clockwise rotation between 0.77 Ma and Recent. Thus, our data indicate a rapid rotational event, in contrast to continuous rotation since 5 Ma as previously postulated [Laj et al., Tectonophysics 86 (1982) 45–67]. We speculate this late Pleistocene tectonic rotation phase to be linked to rapid uplift in the Greek region which results from rebound processes caused by (African) slab detachment underneath the Ionian islands.

Keywords: palaeomagnetism; tectonics; rotation; Mediterranean region; Aegean Islands; Neogene

1. Introduction

The main part of Greece belongs to the Hellenides, an approximately NW–SE-running orogenic belt which forms the connection between the mountain chains of the Dinarides (northern Albania and former Yugoslavia) in the west and the Taurides (Turkey) in the east. The Hellenides are divided into a number of sedimentary facies belts or isopic zones [1] from internal (east) to external (west): Vardar, Pelagonian, Pindos, Gavrovo-Tripolitsa, Ionian and Pre-Apulian zone. These zones are separated by major NW–SE-striking thrusts on the Greek mainland and on the Ionian Islands. The geological evolution of the Hellenides is dominated by divergence and convergence of the African and Eurasian plates [1] and related processes like subduction, roll back followed by extension in the Aegean back-arc, and possibly an additional westward Anatolian push. During Mesozoic times, troughs and platforms developed between the foreland, Adria (the African promontory), and the internal oceanic part of the Neotethys. Subsequently, the oceanic part closed and the dif-

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ferent isopic zones were emplaced as well-defined thrust sheets. The timing and locus of emplacement migrated progressively towards the foreland [2]. The (outer) westernmost thrust zone, the Ionian thrust, was probably active during the Early Pliocene [3].

The current southern and western boundaries of the deforming Aegean region are formed by the subduction (Hellenic trench system) of the African slab underneath Eurasia, with Adria separating Greece from Italy. Tomography has shown that subduction occurred at both sides of Adria [4]. The seismic velocity structure reveals detachment of the (African) slab from the surface in northern Greece [4] and beneath the Calabrian arc in southern Italy [5]. According to Wortel and Spakman [6] the detachment of the slab started in the north and migrated southwards in time, causing temporal and spatial variations in the slab pull. Where the slab is just detached, a basin (deflection downward) can develop, succeeded by a period of rebound processes in which the area will be uplifted. Although other authors have used tomography data to propose a continuous slab in southern Italy and Greece [7,8] there is a growing number of studies, e.g. on migration of depocentres along the Apennines [9], that are consistent with the process of migration of slab detachment.

Over the last decades, palaeomagnetic studies have aided in the understanding of the Neogene geodynamic evolution of the Aegean arc (Fig. 1). Kissel and Laj [12] concluded that the curvature of the Aegean arc has been acquired by deformation during two major tectonic phases, an older one during the Middle Miocene and a younger one during the Plio–Pleistocene. They suggested, on the basis of palaeomagnetic results from the Ionian islands of Zakynthos, Kefallonia and Corfu, that the western part of the Aegean arc underwent a continuous clockwise rotation during the younger phase, from

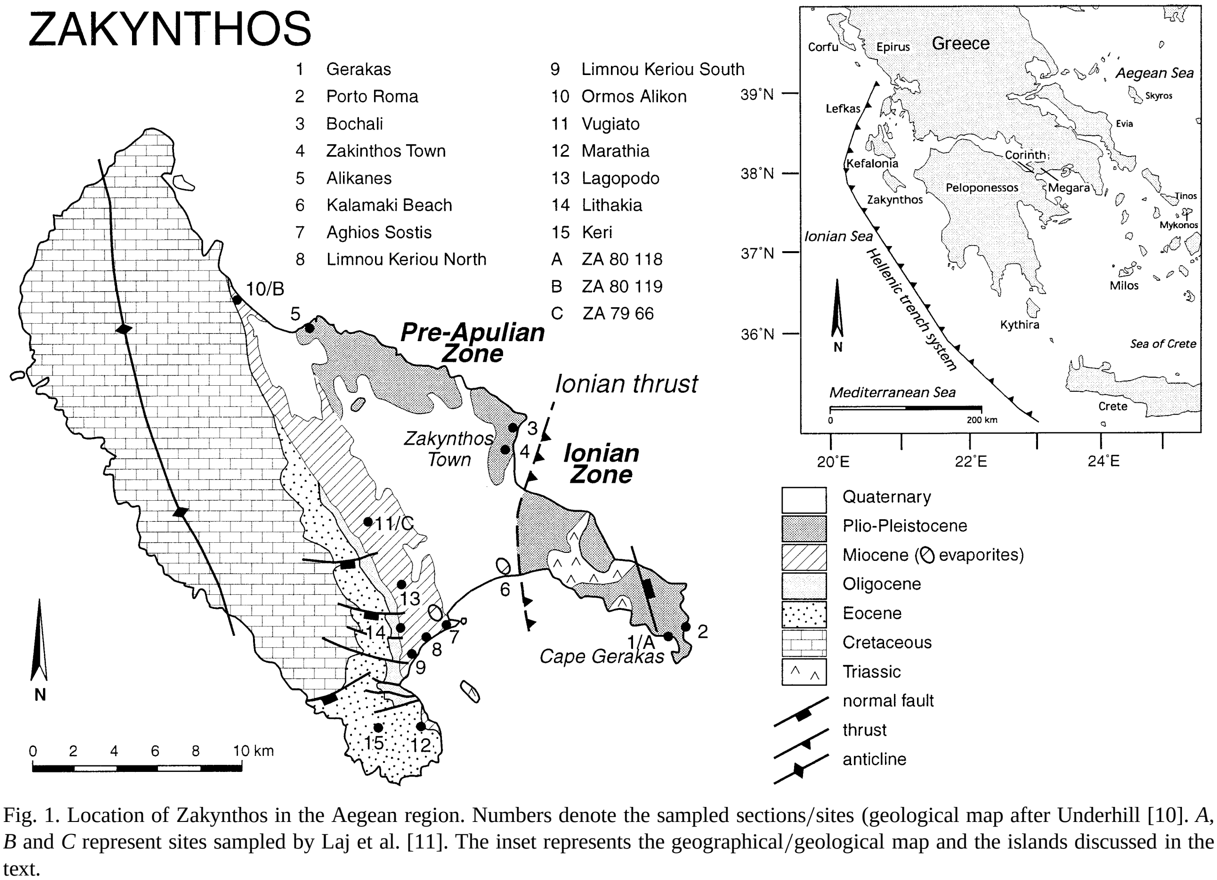

Fig. 1. Location of Zakynthos in the Aegean region. Numbers denote the sampled sections/sites (geological map after Underhill [10]. *A*, *B* and *C* represent sites sampled by Laj et al. [11]. The inset represents the geographical/geological map and the islands discussed in the text.

approximately 5 Ma to Recent, with an average rate of 5º/Ma [11]. The area of clockwise rotations extends further north, including the external Albanides, and ends at the Scutari-Pec transverse zone [13,14]. More to the centre of the Aegean region, on the Cycladic islands of Mykonos [15], Tinos [16], Evia and Skyros [17], comparable clockwise rotations are found. In western Turkey, forming the eastern part of the arc, anticlockwise rotations up to 45º were identified during the Middle Miocene [12]. Based on palaeomagnetic data from Crete and Rhodes [11,18], it was suggested that the central and eastern parts of the Aegean arc did not rotate since Tortonian respectively Pliocene times. The area of non-rotation (at least since 15 Ma) extends to the east including the Antalya region in southern Turkey [19]. Many geophysical modelling studies concerning the Aegean arc have used constraints derived from these palaeomagnetic data [20–22]. However, recent results from Crete indicate predominantly post-early Messinian anticlockwise (ac) rotations, in agreement with a tectonostratigraphic analysis [23]. These ac rotations are governed by rotations of fault-bounded blocks. Evidence for anticlockwise rotations in the central Aegean was also found on Naxos since the Middle Miocene [15] and on Milos since the Plio–Pleistocene [24], constraining the overall sense of rotation in the central part of the Hellenic arc.

Recently, accurate astronomical (polarity) time scales including a significantly improved biostratigraphic resolution [25–27] have allowed to constrain more precisely rotation phases in the central Mediterranean. In contrast to continuous deformation, e.g. as proposed for the western Aegean area, there is increasing evidence for short periods of rapid, pulsed tectonic rotations. For instance, in southern Italy, palaeomagnetic data indicate a large 25º anticlockwise tectonic rotation phase in Calabria that has taken place somewhere between 8.6 and 7.8 Ma [28]. During the Pliocene, a 10º clockwise rotation event occurred on Sicily around 3.21 Ma within some 80–100 ka [29], while a Pleistocene rotation phase has been documented in Calabria (15º clockwise) and the southern Apennines (23º anticlockwise) taking place between 0.8 and 0.7 Ma [30,31]. For this reason, we decided to examine in detail the timing and duration of tectonic rotations in the western Aegean area. We first selected the island of Zakynthos (Fig. 1) because it contains the most complete sedimentary record of the Ionian islands, with rocks ranging in age from Cretaceous to Pleistocene. The new dating techniques enable to accurately confine the age of the sediments and to determine more precise constraints on rotation phases, and thus on the geodynamics of the Aegean area.

2. Sections and sampling

The island of Zakynthos belongs partly to the Ionian and partly to the Pre-Apulian zone (Fig. 1); the latter zone comprises the eastern slope of the African promontory. These two zones are separated by the Ionian thrust, which runs east of Zakynthos town [10] and was emplaced in the Early Pliocene according to Sorel [3].

The sediments on Zakynthos range in age from Cretaceous to Pleistocene and occur in approximately parallel, linear zones running NW–SE (Fig. 1). A mountain belt, formed by Cretaceous limestones, dominates the western part of the island, the pre-Apulian zone. To the east, we encounter rhythmically bedded Eocene deposits, followed by Oligocene olistostromes embedded in Miocene (Aquitanian to Serravallian) pelagic limestones. Scattered outcrops of Tortonian age mainly consist of alternations of marls and sapropels. The southern part of Zakynthos encompasses a long and continuous Messinian section of marls and sandy turbidites, which at the top abruptly pass into steeply dipping (∼60º) evaporites related to the Messinian salinity crisis. These evaporites are overlain by Pliocene 'Trubi'-like marls, representing the basal Zanclean flooding of the Mediterranean. Younger Pliocene sediments are found along the northeast coast of the island and at the base of the 'Citadel section' near Zakynthos town. This section has previously been subjected to detailed studies as it contains the Plio–Pleistocene boundary [32,33]. The Pliocene part consists of alternating clays and silt/sandstones with some sapropelitic intercalations in the lower part; the sand content is increasing towards the top. The Pleistocene part (Citadel–Bochali sequence) consists of an alternation of open marine turbidites, which in turn are overlain by calcarenites.

The southeastern peninsula of Zakynthos is believed to belong to the Ionian zone and is predominantly formed by Triassic evaporites and Plio–Pleistocene sediments [10]. This part is separated from the Apulian zone by an area of intense deformation. Diapirism of Triassic evaporites, large-scale faulting and thrusting resulted in scattered and highly deformed outcrops of sediments in the western part of this peninsula. The southeastern part of the Ionian zone at Cape Gerakas contains well-exposed sections of Pliocene–Pleistocene marls, but clear signs of deformation (steeply (~40º) dipping layers, folding and normal faulting) caused by Late Pliocene to Quaternary diapiric intrusion, are observed [34]. These marls, immediately adjacent to the diapirs in SE Zakynthos, are steeply dipping and overturned ([34], field observations), and are overlain by an undeformed series of Pleistocene marls alternating with calcareous sandstones/calcarenites [35], resembling the earlier mentioned Citadel–Bochali sequence. A detailed stratigraphic study also revealed the Plio–Pleistocene boundary in this area [36].

For our study, fifteen sites and sections have been selected all over Zakynthos with ages ranging from Eocene to Pleistocene. All but two sections/sites consist of undeformed sediments with (slightly) inclined strata. The Messinian marls and evaporites at Kalamaki Beach and the Plio–Pleistocene marls at Cape Gerakas (one of the sites of Laj et al. [11]) were sampled despite their signs of deformation. We have also sampled the two other sites on Zakynthos (Fig. 1) used by Laj et al. [11]. A total of 609 cores was sampled and drilled with an electrical drill and generator. Preferentially, continuous sections were sampled — with three cores per level (for paleomagnetic, biostratigraphic and rock magnetic analysis) — formed by outcrops of more than 10 m stratigraphic thickness. This allows magnetostratigraphy to be used as an age constraint in addition to the detailed biostratigraphy. Individual outcrops were sampled with eight to fourteen cores per site. Mostly, fine-grained sediments (clays, marls) were sampled with a low sedimentation rate (typically 5 cm/ka) and over a sufficiently large interval, thus averaging out, to a large extent, secular variation. In addition, early post-depositional processes typically smooth out the finer-scale variations of the geomagnetic field [37].

Ages of sections are mainly obtained by recording foraminiferal and calcareous nannofossil species (caption to Fig. 2) of which last (common) occurrences (L(C)O) and first (common) occurrences (F(C)O) have been dated. Foraminifers have been analysed in washed residues of >125 μm; for calcareous nannofossils we have used smearslides. The sections/sites including the age diagnostic species are shown in Fig. 2 and described in Appendix A together with their Mediterranean chronostratigraphy and numerical ages [25,27,42]. Most sections have additional magnetostratigraphic constraints (Appendix A).

3. Palaeomagnetic results

3.1. Analysis of the natural remanent magnetisation (NRM) and isothermal remanent magnetisation (IRM)

The natural remanent magnetisation (NRM) was measured on a 2G Enterprise DC SQUID cryogenic magnetometer using progressive stepwise thermal demagnetisation with temperature increments of 30 or 50ºC, from room-temperature to the limit of reproducible results. The demagnetisation results (Figs. 3 and 4) show that often a small viscous and laboratory-induced component is removed at 100ºC, while occasionally a relatively small secondary present-day field component exists which is typically removed at ~200ºC. As a rule, steps below ~200ºC are never used to determine characteristic components because of possible overlap of blocking temperature spectra (e.g. Fig. 3b). Demagnetisation at temperatures higher than 200ºC reveals two types of demagnetisation behaviour related to intensities and different maximum unblocking temperatures. In general, samples with a relatively low NRM intensity have a characteristic remanent magnetisation (ChRM) which is completely removed at 360–400ºC (Fig. 3d,f,i and Fig. 4a–h). Demagnetisation at temperatures higher than 360–390ºC results in randomly directed magnetisations because of alteration (oxidation) of iron sulphides (typically pyrite), which is commonly observed in this type of marls and clays. In high NRM intensity samples the ChRM is usually only completely removed at 580–620ºC (Fig. 3a–c,e,g,h and Fig. 4i), but also here disturbing magnetisations may occur at temperatures above 360–390ºC, depending

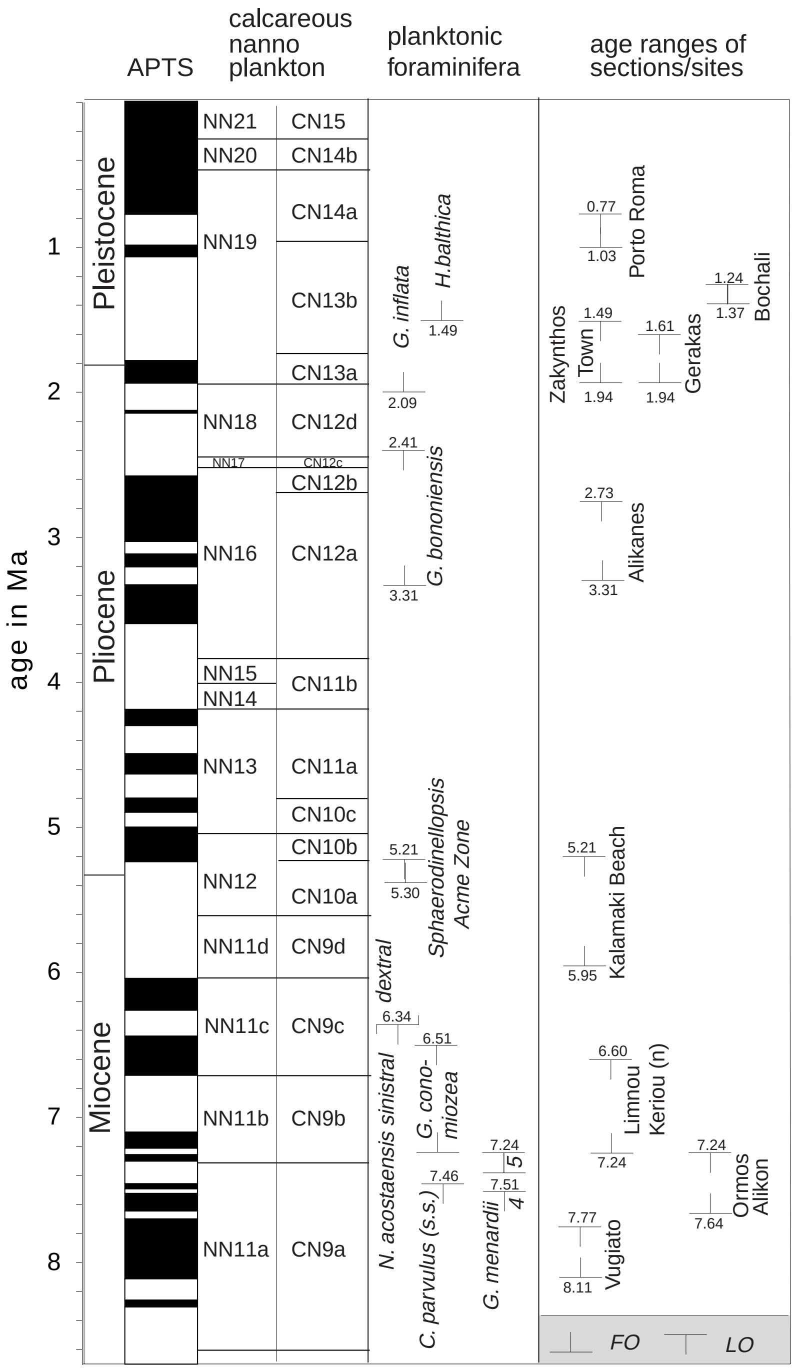

Fig. 2. Astronomical polarity time scale (APTS) of Lourens et al. [27] for the Pliocene and Hilgen et al. [25] and Krijgsman et al. [38] for the Miocene with calcareous nannoplankton zones [39,40] and planktonic foraminifera [25–27,41] biochronology. *FO* (*LO*) indicates first (last) occurrences and *s.s.* small sized. The sections/sites from Zakynthos are correlated on the basis of magnetostratigraphy, planktonic foraminifera, calcareous nannoplankton and polarities. For details see Appendix A.

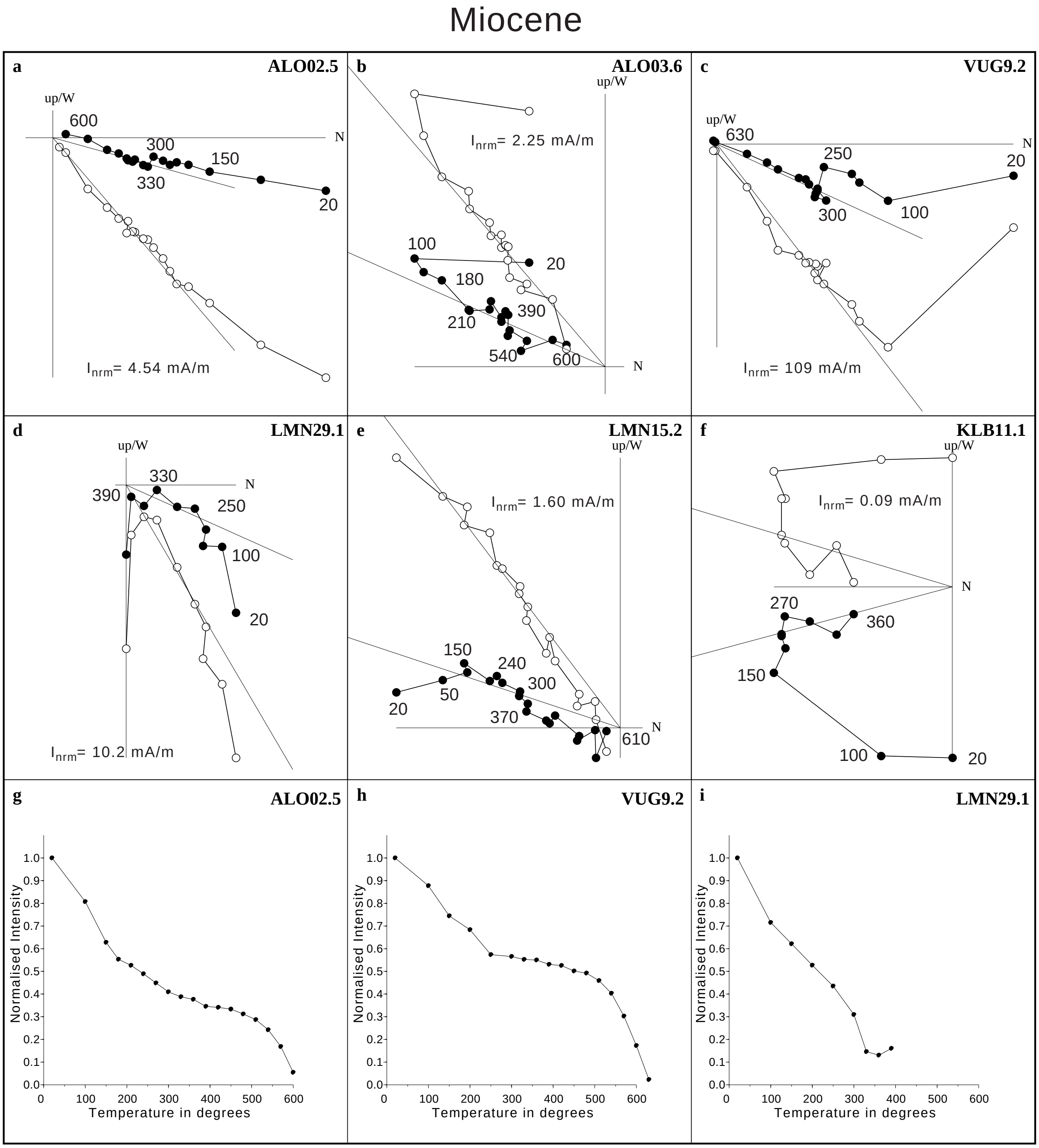

Fig. 3. Orthogonal projections of stepwise thermal demagnetisation diagrams (corrected for bedding tilt) from Miocene sediments on Zakynthos. Closed (open) circles represent the projection of the NRM vector endpoint on the horizontal (vertical) plane. Values denote demagnetisation steps in ºC. Codes can be found in Table 1; line represents the interpreted result. The initial NRM intensities (I_{nrm}) are given. Some normalised intensity plots are also given (g–i).

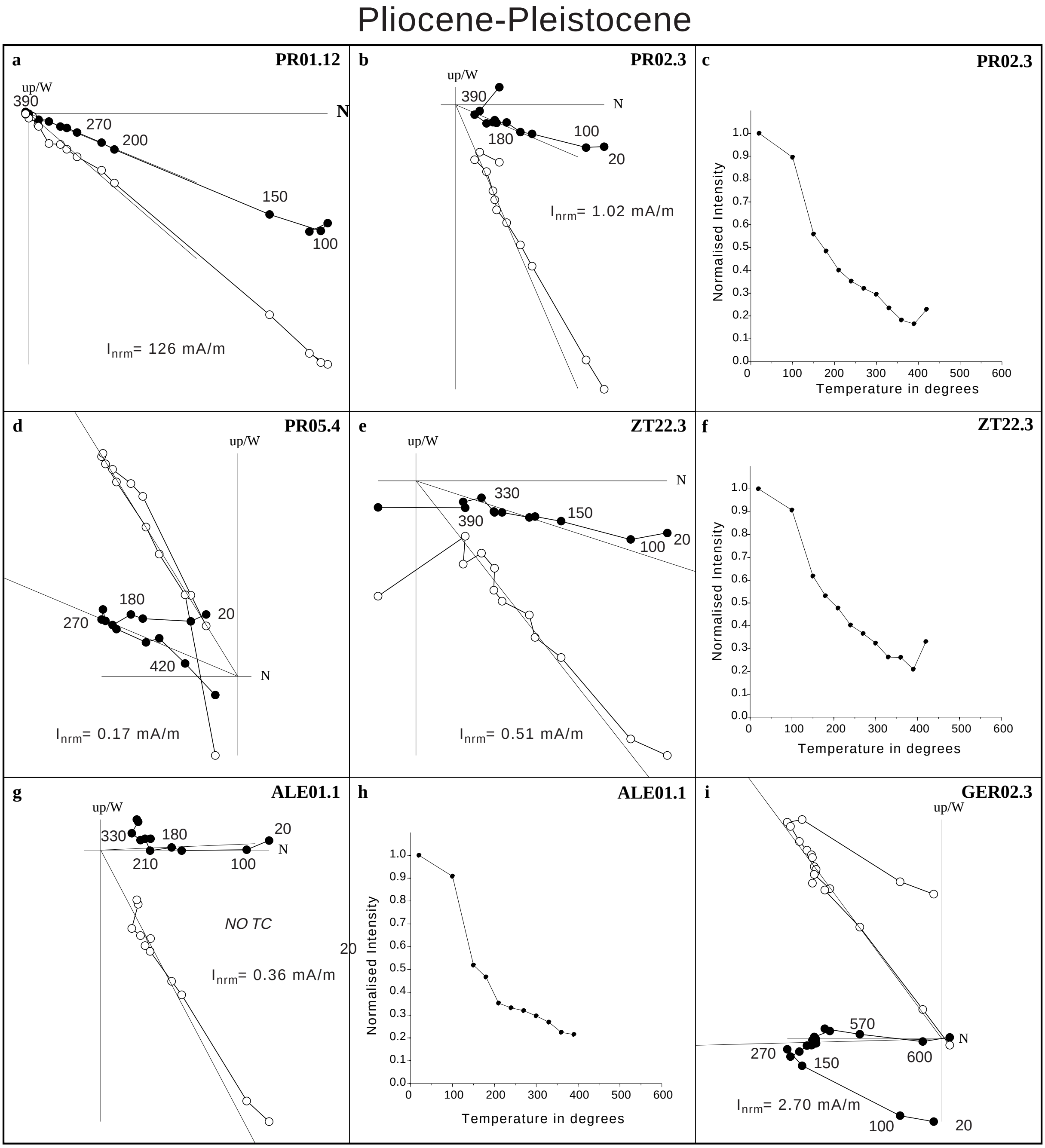

Fig. 4. Orthogonal projections of stepwise demagnetisation diagrams (corrected for bedding tilt) from Plio–Pleistocene sediments on Zakynthos. See also caption to Fig. 2; no tc (g) means without tectonic tilt correction. Some normalised intensity plots are also given (c, f, h).

on the presence of iron sulphides. Since this may cause an apparent decay of the ChRM passing the origin (e.g. Fig. 3e), we have in such cases conservatively used only the data points below ∼390ºC. Samples with a large present-day overprint or unstable samples were not used. As the outcrops are monoclinal, the fold-test could not be performed. The reversal-test was positive for Ormos Alikon and Limnou Keriou (Classifications B and C, respectively). For the Porto Roma site the reversal test was negative, but this is commonly observed in these types of sediments [43]. Although Scheepers and Langereis [44] devised a method to correct the non-antipodality between normal and reversed polarity, it appears that simply averaging normal and reversed directions yields essentially the same result.

We performed some rock magnetic tests to identify the dominant carriers of the remanence, including acquisition of a three-component [45] isothermal remanent magnetisation (IRM) and subsequent demagnetisation of this IRM. The IRM was induced in a pulse magnetiser and was measured on a digitised spinner magnetometer based on a Jelinek JR3 driver unit. The IRM was induced in three orthogonal directions using fields of 75 mT, 200 mT and 2 T. All samples, both normal and reversed, are characterised by the dominance of a low-coercivity mineral (Fig. 5A,B) and the magnetisation is carried by magnetic minerals with coercivities below 200 mT, mostly below 75 mT (Fig. 5C,D). The relatively low-intensity samples (0.2–0.8 mA/m) show a maximum blocking temperature around 570ºC, indicating the presence of magnetite, but iron sulphides are likely present as well as can be seen from the inflexion at ~350ºC (Fig. 5C,D). The ChRM in these low-intensity samples was removed at 360–400ºC; the ChRM at higher temperatures could not be measured. The relatively high-intensity samples (3–55 mA/m) have a maximum blocking temperature between 600 and 650ºC, suggesting (partly) oxidised magnetite as the dominant carrier of the NRM (Fig. 5D).

The characteristic directions of the magnetisations were determined by least squares fitting (principal component analysis) through selected data points. For each section or site, average ChRM-directions were calculated using Fisher statistics (Fig. 6; Table 1). The distribution of the ChRM directions on Zakynthos can be seen in Fig. 7; the errors are calculated using $R/\Delta R$ and $F/\Delta F$ (Table 1). Directions before and after tilt corrections have essentially the same precision parameter (k); low k values are typically seen in low-intensity samples.

4. Discussion

Our palaeomagnetic data of all sampled late Neogene sections on Zakynthos, in both the pre-Apulian and Ionian zones, show no significant differences in rotation. Since the ages of the sediments range from Tortonian (8.11 Ma) to Pleistocene (1.03–0.77 Ma), it must be concluded that no differential rotations took place between 8.11 Ma and 0.77 Ma. Thus, the overall 22º clockwise rotation (Table 1) must have occurred since 0.77 Ma.

The results of three sites, however, are questionable. The Alikanes section shows magnetisations largely removed at low (200ºC) temperatures and is a classic example of overprinting, which is confirmed by the present-day field direction before tilt correction (Fig. 6e; Table 1). At Gerakas, the marls are steeply dipping and overturned caused by Late Pliocene to Quaternary diapirism [34]. Although the large error makes the small clockwise rotation of Gerakas not incompatible with other results (Table 1), we feel that including this result is not warranted. At Kalamaki Beach, the (late) Messinian evaporites reveal anticlockwise rotations. Because of the observed deformation in these evaporites in the vicinity of the Ionian thrust, we do not regard this result as representative. Therefore, we prefer not to include the results from Alikanes, Cape Gerakas and Kalamaki Beach.

Our new results have considerable implications for the geodynamic evolution of the western Aegean arc. A previous tectonic reconstruction for the northwestern part of Greece was made by Kissel and Laj [12], based on combined palaeomagnetic data from the Ionian islands of Zakynthos, Kefallonia and Corfu. They suggested that all three islands were subjected to a continuous rotation starting at 5 Ma, with an average rate of 5º/Ma. This scenario was predominantly based on (9) results from Corfu, whereas fewer results were obtained from Zakynthos (3) and from Kefallonia (4). Kissel and Laj [12] thus considered the Ionian islands as a structural unity, and they argued that this is supported by structural data from Mercier et al. [46].

We sampled the Laj et al. [11] sites from Zakynthos and re-dated them. It appears that our ages of these sites are significantly younger. The reason for this difference cannot be determined because no age diagnostic fossils are given in Laj et al. [11].

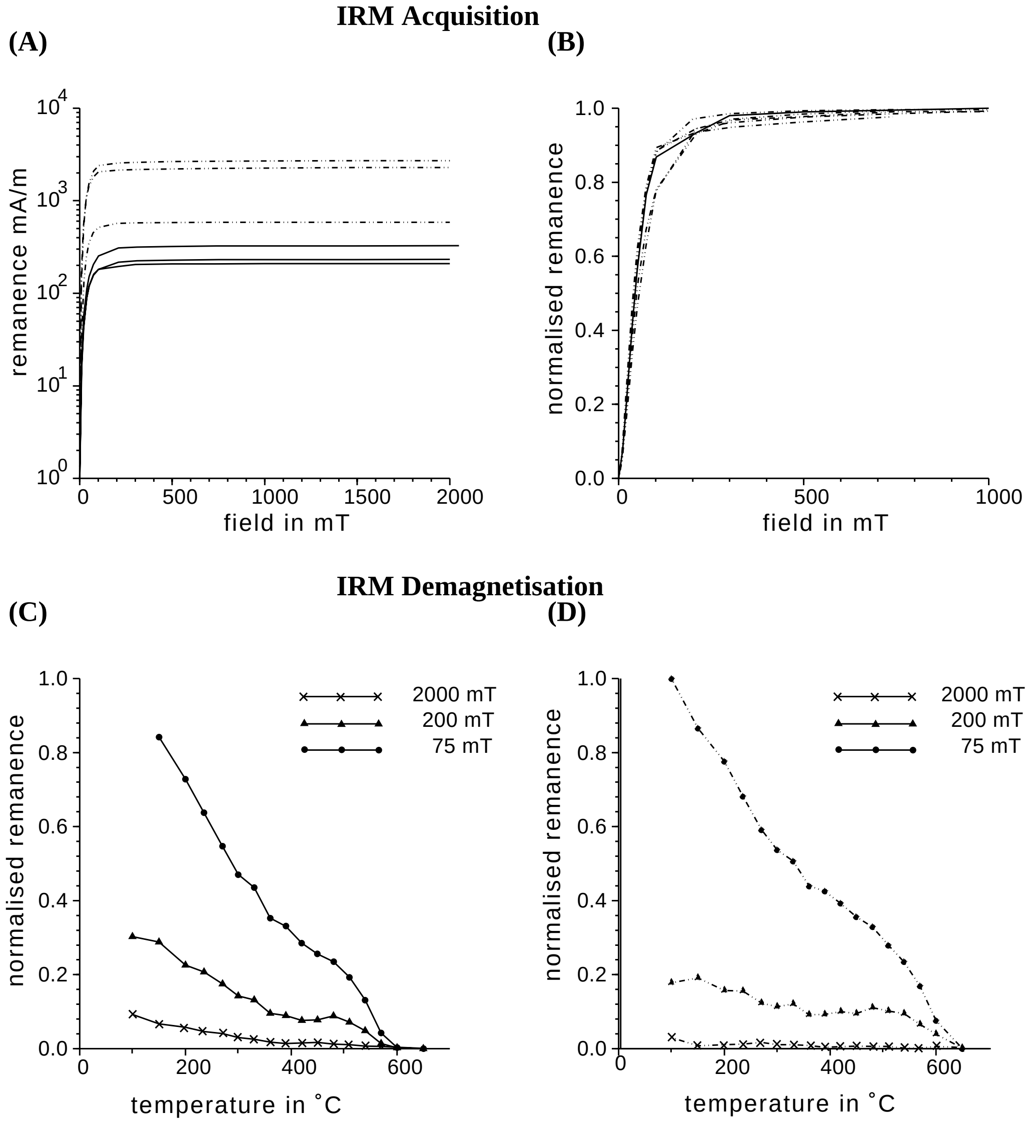

Fig. 5. Examples of absolute (A) and normalised (B) IRM acquisition of samples from Zakynthos. Solid (dotted) lines represent relatively low- (high-) intensity samples. Stepwise thermal demagnetisation of the normalised three-component IRM of a low- (C) and high- (D) intensity sample indicates magnetite, respectively maghemite as the main carriers of the ChRM.

Our larger number of sample localities and accurate age constraints clearly reveal a different tectonic evolution at least for the island of Zakynthos. A continuous rotation during the last 5 Ma seems no longer tenable, since our new palaeomagnetic data indicate that a significant clockwise rotation of ~22º occurred between 0.77 Ma and the Recent, while no rotational motions occurred between at least 8.11 and 0.77 Ma (Fig. 8). Our different geodynamic scenario for Zakynthos need not be surprising, because Zakynthos (and Kefallonia) are separated from Corfu by the important Kefallonia Fault Zone. Moreover, Corfu does not overlie the Hellenic subduction zone, in contrast to Zakynthos and Kefallonia. It may thus have experienced a tectonic evolution quite different from that of Zakynthos. Although the rotation

Table 1
Results from NRM analysis from the different sections on Zakynthos

Site/Section	CODE	N	D_{notc} (°)	I_{notc} (°)	k	α_{95} (°)	D_{tc} (°)	I_{tc} (°)	k	α_{95} (°)	rot. (°)	R (°)	ΔR (°)	F (°)	ΔF (°)	Age (Ma)
Porto Roma[1]	PR	20	12.1	62.0	135.7	2.8	20.0	59.2	98.4	3.3	20 c	14.5	5.6	−6.1	3.2	1.03–0.77
Bochali[1]	BOC	8	193.5	−58.2	65.3	6.9	199.5	−50.2	65.3	6.9	20 c	14.0	8.9	2.9	5.8	1.37–1.24
Zakynthos Town[1]	ZT	41	21.8	63.8	43.2	3.4	22.3	54.5	43.6	3.4	22 c	16.8	5.1	−1.4	3.3	1.94–1.44
Gerakas	GER	8	137.2	−55.2	12.9	16.0	187.9	−54.1	20.9	12.4	8 c	2.4	17.3	−1.0	10.1	1.94–1.61
ZA 80 118[*]	A	10	–	–	–	–	184.0	−57.0	84.5	4.8	4 c	−1.5	7.4	−3.9	4.3	1.8–1.61
Alikanes	ALE	18	358.7	55.0	225.2	2.3	341.5	58.9	204.3	2.4	–	−6.8	3.8	−1.9	2.6	3.31–2.73
Kalamaki Beach	KLB	11	143.2	−19.3	27.3	8.9	169.2	−22.6	27.3	8.9	11 ac	−16.3	8.0	30.5	7.4	5.95–5.21
Aghios Sostis	SOS	9	–	–	–	–	–	–	–	–	–	–	–	–	–	Messinian
Limnou Keriou (north)[2]	LMN	23	176.4	−58.2	44.9	4.6	199.2	−47.4	47.7	4.4	19 c	13.7	5.6	5.7	4.0	7.24–6.60
Linmou Keriou (south)	LMS	4	–	–	–	–	–	–	–	–	–	–	–	–	–	Tortonian
Ormos Alikon[2]	ALO	25	170.6	−58	30.1	5.4	195.1	−40.5	34.1	5.0	15 c	9.6	5.7	12.6	4.4	7.64–7.24
ZA 80 119[*]	B	7	–	–	–	–	206.8	−39.8	248.0	3.5	27 c	21.3	4.2	13.3	3.3	7.64–7.24
Vugiato[2]	VUG	14	350.3	70.2	22.3	8.6	23.9	50.3	20.9	8.9	24 c	18.4	11.4	2.8	7.4	8.11–7.70
ZA 79 66[*]	C	15	–	–	–	–	25.3	44.9	76.6	4.1	25 c	19.8	5.1	8.2	3.8	8.11–7.70
Marathia	MA	8	–	–	–	–	–	–	–	–	–	–	–	–	–	Serravalian
Lagopodo	LAG	20	–	–	–	–	–	–	–	–	–	–	–	–	–	early Middle Miocene
Lithakia	LIT	7	–	–	–	–	–	–	–	–	–	–	–	–	–	early Middle Miocene
Keri	KE	7	–	–	–	–	–	–	–	–	–	–	–	–	–	Eocene
Mean																
[1]Pleistocene		3	–	–	–	–	20.6	54.6	312.4	7.0	21 c	15.1	9.9	−1.5	5.9	1.94–0.77
[2]Miocene		3	–	–	–	–	19.1	46.1	189.5	9.0	19 c	13.6	10.6	7.0	7.4	8.11–6.60
All		8	–	–	–	–	21.6	48.4	128.0	4.9	22 c	16.1	6.3	4.7	4.3	8.11–0.77

[*]Laj et al. [11] (redated).

Corrected and uncorrected for bedding tilt; ages are indicated. N = number of specimens; D, I = site mean ChRM declination and inclination; k = Fisher's precision parameter; α_{95} = 95% cone of confidence; rot. = sense of rotation, (a)c = (anti)clockwise with a 0° reference direction; $\alpha_{95}/\cos(I)$ = error (see Fig. 6).

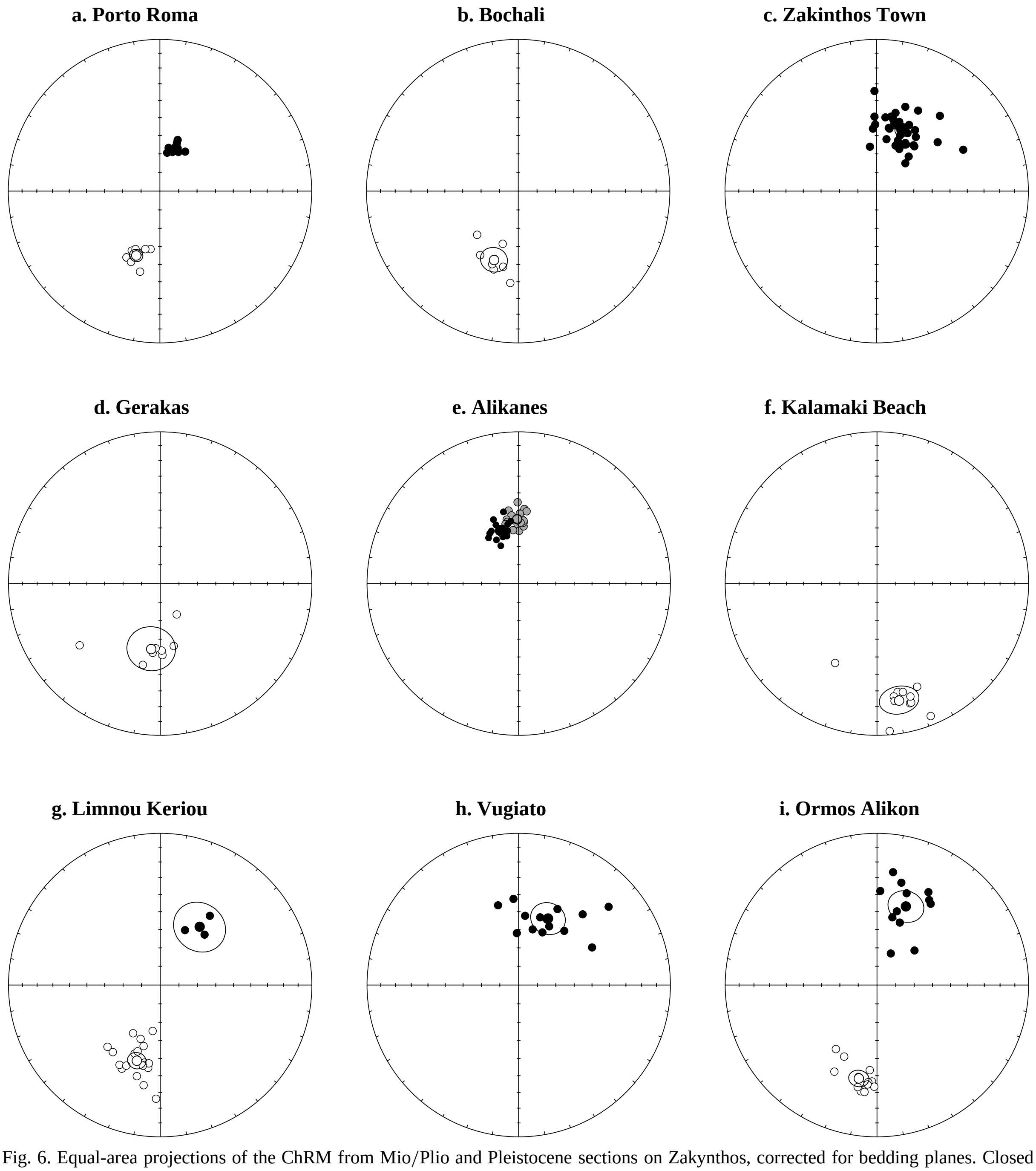

Fig. 6. Equal-area projections of the ChRM from Mio/Plio and Pleistocene sections on Zakynthos, corrected for bedding planes. Closed (open) circles represent downward (upward) projections. Ellipses denote α_{95}. The grey circles (Alikanes) indicate the ChRM results before bedding plane correction and are indistinguishable from the present-day field direction.

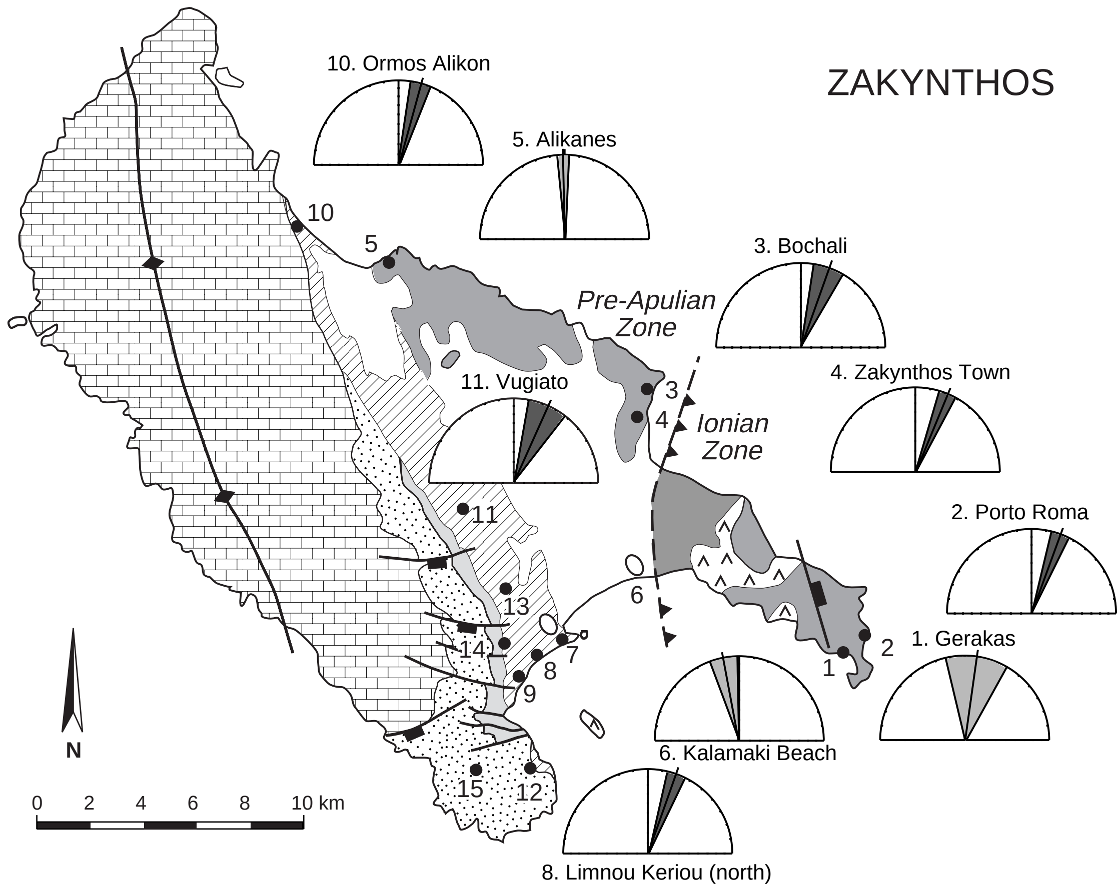

Fig. 7. Locality mean ChRM declinations on Zakynthos; shaded segment represents the statistical error $\alpha_{95}/\cos(I)$ (Table 1). See also caption to Fig. 1.

phase might have been influenced by local tectonics, considerable evidence is present suggesting a more regional cause, as outlined below.

The tomographic studies of Spakman [4] have shown that the African slab (Adria) is subducting in the west underneath Italy, and in the east underneath Greece. These studies have also shown that the African slab is detached both underneath Calabria in southern Italy and beneath the southern Peloponessos in Greece [47]. After slab detachment, rebound processes can cause rapid uplift in the internal zones caused by stretching of the shallow remainder of the slab [48]. This scenario is used by Sorel et al. [49] to explain the Pleistocene uplift of the Ionian islands, and which consequently would date the detachment in the Ionian region at that period [4]. In addition, much of the relief of southern Greece has developed only in the last million years [50]. As detachment proceeds, the gravitational pull of the detached part of the slab is transferred to the undetached part. This leads to an increase in the effective slab pull exerted by the undetached slab. A more pronounced outward migration of the trench, relative to the situation where only the roll-back process is active, is expected above the undetached slab [48] which then may result in rotations.

Furthermore, detailed studies of present-day and past stress fields in the Aegean [20] revealed a temporal change in the orientation of tensional stress — from NE–SW to NNW–SSE in the northern Aegean region — during the Late Pleistocene (post-Calabrian and pre-Milazzian) [51], i.e. roughly between 0.8 and 0.3 Ma. Numerical modelling of stress patterns by Meijer and Wortel [52] indicated that this change in orientation is likely caused by lateral mi-

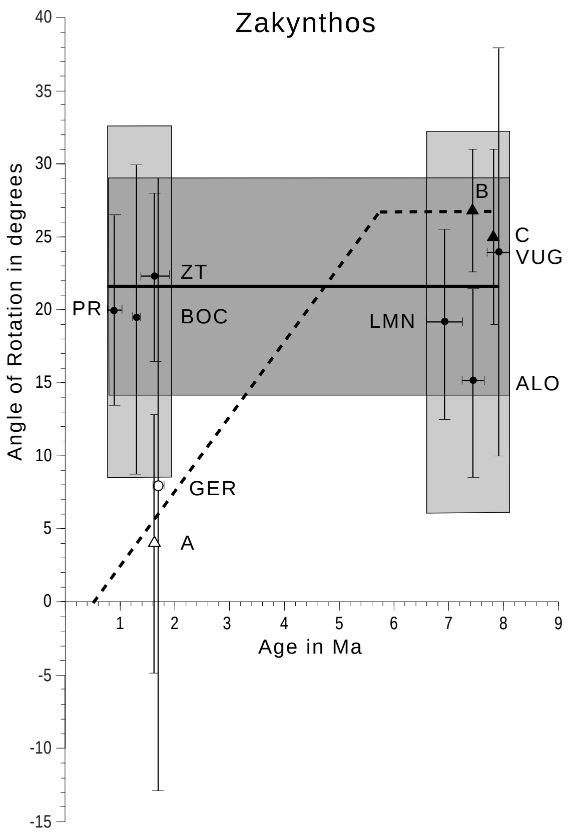

Fig. 8. Locality mean ChRM declination versus age on Zakynthos; codes are according to Table 1. Closed symbols indicate reliable results, open symbols are disregarded (see text for discussion). Circles are derived from this study, triangles from Laj et al. [11]. Vertical bars indicate error ($\alpha_{95}/\cos(I)$), horizontal bars denote age range. Light shaded rectangles give $\alpha_{95}/\cos(I)$ of Miocene and Pleistocene localities. The thick line and the dark shaded rectangle shows the mean rotation and the error $\alpha_{95}/\cos(I)$. Dotted thick line is the interpretation of Laj et al. [11] for the Ionian islands, indicating 5º/Ma starting around 5 Ma.

gration of slab detachment [6] on the eastern side of Adria. Our clockwise rotation phase on Zakynthos occurred after 0.77 Ma, corresponding to this change in stress regime. Hence, we prefer a scenario in which slab detachment and the subsequent rebound causes uplift and a change in stress regime, which in turn causes rotations.

The Pleistocene rotational phase on Zakynthos appears to have been rapid since it must have taken place some time during the last 0.77 Ma. A similar young and rapid Pleistocene tectonic rotation phase was found in southern Italy. In Calabria, the Calabro–Peloritan block underwent a 15º clockwise rotation between 0.8 and 0.7 Ma [31], whereas the southern Apennines experienced a time-equivalent 23º anticlockwise rotation [30,31]. Concurrently (0.9–0.7 Ma), uplift in Calabria (southern Italy) occurred which Westaway [53] related to slab detachment. Thus it appears that on both sides of the Adriatic platform a similar process of slab detachment, rebound, uplift and tectonic rotations occurred.

5. Conclusions

Our palaeomagnetic data show that during the last 8 Ma, the geodynamic evolution of the Ionian island of Zakynthos is marked by no significant rotational movements during Tortonian (8.11 Ma) to Pleistocene (0.77 Ma) times. A well-defined and rapid tectonic event occurs younger than 0.77 Ma causing a 22º clockwise rotation of the island. The Early Pliocene emplacement of the Ionian thrust did not result in any differential rotations of the island.

We link the clockwise rotation of Zakynthos to Late Pleistocene uplift in (mainland) Greece [50], related to rebound processes resulting from (African) slab detachment underneath the Ionian islands [6,52]. A similar process of slab detachment, rebound, uplift, and subsequent rotations is also found in southern Italy. This implies that rotations may ultimately be linked to slab detachment.

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Appendix A

Lithakia	
Age:	late Early to early Middle Miocene
Geographical coordinates:	37º42′N/20º49′E
Lithology:	blue laminated limestones
Cores:	3 sites/26 cores
Fossil content:	*H. ampliaperta* and *H. heteromorphus* (pre-*Orbulina* age)
Magnetostratigraphy:	undetermined
Lagopodo	
Age:	late Early to early Middle Miocene
Geographical coordinates:	37º44′N/20º47′E
Lithology:	scattered outcrops of laminated limestones/marls
Cores:	5 sites/39 cores in marls
Fossil content:	*H. ampliaperta* and *H. heteromorphus* (pre-*Orbulina* age)
Magnetostratigraphy:	undetermined
Marathia	
Age:	Serravalian
Geographical coordinates:	37º40′N/20º51′E
Lithology:	~30 m blue marls
Cores:	4 sites/32 cores in marls
Fossil content:	*H. walbersdorfensis* and *H. orientalis*
Magnetostratigraphy:	undetermined
Vugiato (= ZA 79 66)	
Age:	8.11–7.77 Ma
Geographical coordinates:	37º46′N/20º46′E
Lithology:	25 m clays with 16 intercalated sapropels
Cores:	15 levels/38 samples in clays
Fossil content:	*D. pentaradiatus*, *H. stalis*, left coiled *N. acostaensis*, small-sized *C. parvulus* and *G. menardii* 4
Magnetostratigraphy:	normal
Ormos Alikon (=ZA 80 119)	
Age:	7.64–7.24 Ma
Geographical coordinates:	37º52′N/20º44′E
Lithology:	60 m clay and sapropel alternations
Fossil content:	*Globorotalia menardii* 4, small-sized *C. parvulus* (in the lower part) and *G. menardii* 5 (in the upper part) and *M. convallis*, *D. brouweri*, *D. pentaradiatus*, and *H. brouweri*.
Magnetostratigraphy:	normal (first 17 m), reversed (next 30 m), normal (13 m)
Limnou Keriou South	
Age:	early Tortonian
Geographical coordinates:	37º41′N/20º50′E
Lithology:	5 m marly clays with 4 intercalated sapropels
Cores:	1 site/4 levels/12 cores in the marly clays
Fossil content:	*Neogloboquadrina acostaensis*, small-sized *Catapsydrax parvulus* without keeled globorotaliids, *Discoaster calcaris* and *Discoaster hamatus*
Magnetostratigraphy:	undetermined
Limnou Keriou North	
Age:	7.24 – 6.60 Ma
Geographical coordinates:	37º42′N/20º51′E
Lithology:	~300 m blue clays and sand alternations
Cores:	1 site/31 levels/97 cores in blue clays
Fossil content:	sinistral *N. acostaensis*, *G. conomiozea* group and *R. rotaria*
Magnetostratigraphy:	250 m reversed, followed by 50 m normal

Appendix A (continued)

Kalamaki Beach	
Age:	5.95–5.21 Ma
Geographical coordinates:	37º44′N/20º53′E
Lithology:	125 m evaporites alternating with clays, followed by 10 m marls/sapropel
Cores:	5 levels/15 cores in clays between evaporites and 35 cores in marls/sapropels
Fossil content:	*Reticulofenestra rotaria* in evaporitic part and high relative abundances of *Sphaeroidinellopsis* and dextral *N. acostaensis* in the Trubi part (*Sphaerodinellopsis* Acme Zone).
Magnetostratigraphy:	evaporitic part and base of marls (first 3.5 m) is reversed, top marls normal
Alikanes	
Age:	3.31–2.73 Ma
Geographical coordinates:	37º51′N/20º47′E
Lithology:	10 m blue clays and sand alternations
Cores:	2 sites/20 cores in clays
Fossil content:	*N. acostaensis, G. ruber*, *G. bononiensis* and *Discoaster tamalis*
Magnetostratigraphy:	overprinted
Gerakas (=ZA 80 118)	
Age:	1.94–1.61 Ma
Geographical coordinates:	37º42′N/20º58′E
Lithology:	~60 m of laminated clays and sandy alternations
Cores:	8 levels/28 cores
Fossil content:	absence of *H. balthica* and *G. inflata* in the basal, presence of *Sphaeroidinella* and of *D. asymmetricus* (reworked)
Magnetostratigraphy:	normal (first metre) followed by reversed
Zakynthos Town	
Age:	1.94–1.49 Ma
Geographical coordinates:	37º47′N/20º54′E
Lithology:	200 m clay, sapropel alternations with occasional sand layers
Cores:	22 levels/64 cores mostly in clays (top of section was not reached)
Fossil content:	*Discoaster triradiatus*, *G. inflata* and no *H. balthica*
Magnetostratigraphy:	normal (first 50 m) followed by reversed
Bochali	
Age:	1.37–1.24 Ma
Geographical coordinates:	37º48′N/20º54′E
Lithology:	scattered outcrops of sandy clay and sand alternations
Cores:	4 sites/43 cores in clays
Fossil content:	large-sized *Gephyrocapsa*, *G. inflata*, *H. balthica* and 100% right coiled neogloboquadrinids.
Magnetostratigraphy:	reversed
Porto Roma	
Age:	1.03–0.77 Ma
Geographical coordinates:	37º42′N/20º59′E
Lithology:	outcrops of blue clays in between calcarenites along the coast
Cores:	11 levels/54 cores
Fossil content:	the presence of *P. lacunosa*, *G. inflata* and *H. balthica* together with less than 15–20% left coiled neogloboquadrinids (in the middle/upper part of the section).
Magnetostratigraphy:	normal (first 10 m), reversed (next 5 m) followed by a calcarenite and 10 m of reversed clay, again calcarenite with 10 m normal clay.

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