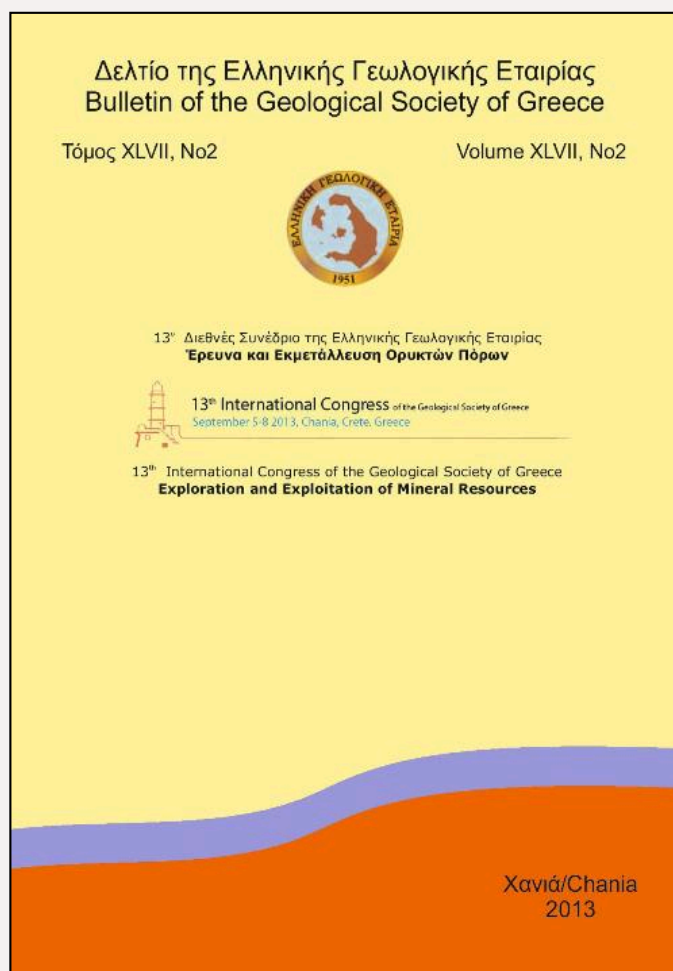


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A RE-ASSESSMENT OF THE SHALLOW PALEOMAGNETIC INCLINATIONS OF THE WESTERN CYCLADES, GREECE

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Abstract

Consistently shallow paleomagnetic inclinations measured in Early to Middle Miocene lacustrine and dacitic volcanic rocks of the Kymi-Aliveri basin have been cited as evidence for an anomalous geomagnetic field geometry or northward drift of the Aegean Sea region. We present new paleomagnetic data from the lacustrine beds that are instead not anomalously shallow and consistent with deposition near their present-day latitude as predicted by global apparent polar wander paths. Anomalously shallow inclinations and easterly declinations reported from the Oxyliothos volcanics are an artifact of an inappropriate tilt correction. The excessively shallow paleomagnetic inclinations reported from the deformed Middle Miocene plutons on Mykonos and Naxos are consistent with reorientation of an original thermoremanent magnetization acquired during cooling below 580°C by subsequent ductile strain at temperatures of 400-500°C. Magnetization overprints observed in these rocks may reflect the acquisition of a stable chemical remanent magnetization lying parallel to the transposed high-temperature magnetization as the result of low-temperature (<350°C) magnetization. We therefore find no convincing evidence for an anomalous Middle Miocene field geometry, northward drift of the Aegean, or back-tilting of the low-angle normal faults that constitute the North Cycladic Detachment System.

Key words: Tectonics, paleomagnetism, detachment, paleolatitude, Kymi-Aliveri basin.

Περίληψη

Στις Μεσο-Μειοκαινικές λιμναίες αποθέσεις και τα δακτυκά ηφαιστειακά πετρώματα της λεκάνης Κύμης-Αλιβερίου έχουν παρατηρηθεί σταθερά μικρές εγκλίσεις σε παλαιομαγνητικές μετρήσεις οι οποίες έχουν αναφερθεί ως αποδεικτικό στοιχείο είτε για τοπική γεωμαγνητική ανωμαλία είτε για μετατόπιση προς βορρά της περιοχής του Αιγαίου. Παρουσιάζονται νέα δεδομένα μετρήσεων παλαιομαγνητισμού σε λιμναία στρώματα τα οποία δεν παρουσιάζουν μικρές εγκλίσεις και είναι συμβατά με απόθεση κοντά στο σημερινό γεωγραφικό πλάτος τους. Οι ιδιαίτερα μικρές εγκλίσεις και αποκλίσεις προς τα ανατολικά που έχουν αναφερθεί στις ηφαιστειακές διεισδύσεις του

Οξύλιθου είναι αποτελέσματα ακατάλληλης διόρθωσης ως προς οριζόντιο άξονα. Οι υπερβολικά μικρές παλαιομαγνητικές εγκλίσεις που έχουν αναφερθεί στα πλουτώνια σώματα της Μυκόνου και τη Νάξου, Μέσο-Μειοκαινικής ηλικίας παραμόρφωσης, είναι συμβατές με επαναπροσανατολισμό μιας αρχικής θερμο-παραμένουσας μαγνήτισης που προέκυψε κατά την ψύξη τους κάτω από 580°C την οποία ακολούθησε ιξωδοελαστική παραμόρφωση σε θερμοκρασίες 400-500°C. Δευτερεύουσες μαγνήτισεις που παρατηρήθηκαν στα πετρώματα αυτά αντικατοπτρίζουν, πιθανότατα, τη διαδικασία μίας σταθερής -χημικής προέλευσης-παραμένουσας μαγνήτισης, παράλληλα με την προϋπάρχουσα μαγνήτιση υψηλής θερμοκρασίας, ως αποτέλεσμα της δημιουργίας μαγνεμίτη σε χαμηλή θερμοκρασία (<350°C). Κατά συνέπεια δεν μπορούμε να βρούμε ικανοποιητικές αποδείξεις είτε για τοπική μαγνητική ανωμαλία ή μετακίνηση του Αιγαίου προς βορρά είτε για περιστροφή των μικρής κλίσης κανονικών ρηγμάτων που συνθέτουν το σύστημα αποκόλλησης των Βορείων Κυκλάδων.

Λέξεις κλειδιά: Τεκτονική, παλαιομαγνητισμός, ρήγμα αποκόλλησης, παλαιο-γεωγραφικό πλάτος, λεκάνης Κύμης-Αλιβερίου.

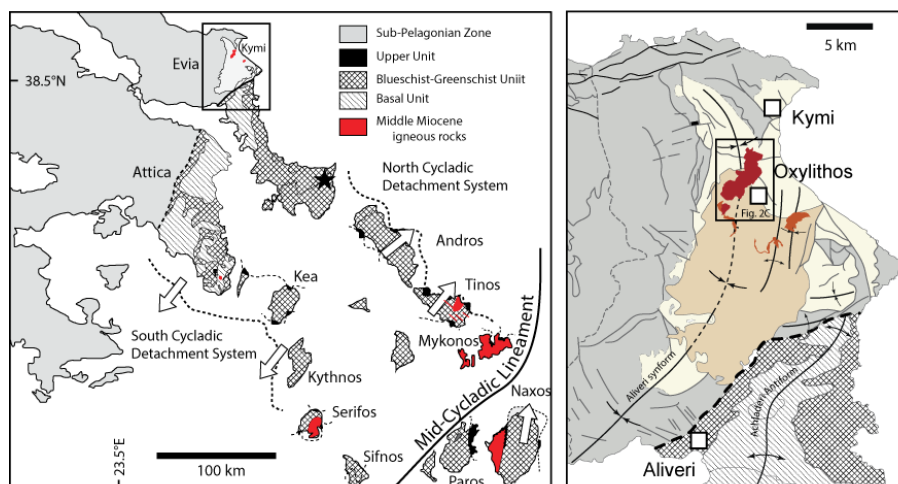


Figure 1 –Generalized geological maps of the western Cycladic archipelago and the Kymi-Aliveri basin. Box in left panel shows location of the Kymi-Aliveri basin, shown in detail in the right panel. Location of map in Fig. 2C is given by box in right panel. Star: site for which we have calculated an expected Miocene field geometry.

1. Introduction

Paleomagnetic data have formed the basis for a number of regional paleogeographic reconstructions of the greater Aegean Sea region (e.g., Kissel and Laj, 1988; van Hinsbergen et al., 2005; Bradley et al., 2013). The utility of this method in resolving regional rotations, translations, and tilting of crustal blocks is largely dependent on the validity of the geocentric axial dipole (GAD) hypothesis, which states that adequately sampled rock units that acquired remnant magnetizations over thousands of years will retain a remanence directed toward geographic north with an inclination given by the dipole formula $\tan(I) = 2\tan(\lambda)$, where I is the paleomagnetic inclination and λ is latitude. Assuming a GAD field, a site located in Central Greece (star in Figure 1) should have experienced a time-averaged magnetic inclination of $56.5 \pm 2.5^\circ$ during Middle Miocene time [accounting for global plate motion using either the African or European apparent

polar wander (APW) paths of Torsvik et al., 2008]. This is essentially indistinguishable from their present latitude, and implies that they have been mostly stationary since this time. However, paleomagnetic inclinations reported from rocks of Miocene and younger age in the Aegean region range from 25 to 50°, thus exhibiting a systematic inclination shallowing (Beck and Schermer, 1994). This has led to suggestion that the local time-averaged geomagnetic field was different from the GAD model (Morris and Anderson, 1996; Avigad et al., 1998), that the Aegean region was actually ~500 km south of its present position in Miocene time (Beck and Schermer, 1994; Beck et al., 2001; Aidona et al., 2008; Kondopoulou et al., 2011), or that the paleomagnetic data exhibit systematic shallow biases (Krijgsman and Tauxe, 2004; Tauxe et al., 2008).

With respect to the latter, small amounts of inclination shallowing can be attributed to a variety of factors. Shallow inclinations in sedimentary rocks can result from processes of grain settling and subsequent compaction flattening, as in the case of the Miocene marine rocks of Crete (Krijgsman and Tauxe, 2004; Tauxe et al., 2008). Small datasets ($N < 20$ site mean directions) are statistically biased toward shallow inclinations by up to ~5° (Krijgsman and Tauxe, 2004), as are rapidly-cooled igneous rocks that temporally under sample paleosecular variation. The use of unit vectors instead of total vectors (which require paleointensity data) for calculation of mean directions can result in artificial shallowing of several degrees as a purely mathematical effect (Creer, 1983).

However, these mechanisms are insufficient to account for the large amount of inclination shallowing observed at several critical localities. In particular, shallow inclinations reported from Early to Middle Miocene lacustrine and volcanic rocks of the Kymi-Aliveri basin on the island of Evia and Middle Miocene plutons and dykes on the nearby islands of Tinos, Mykonos, and Naxos (Figure 1) have been considered as strong evidence for a systematic Aegean shallow inclination bias (Morris and Anderson, 1996; Avigad et al., 1998). These rocks were deposited or emplaced during development of the North Cycladic Detachment System, which consists of a set of closely related, northeastward-dipping low-angle normal faults that accommodated exhumation of deep-seated metamorphic rocks to Earth's surface (Lister et al., 1984; Jolivet et al., 2010).

Because paleomagnetism of pre-, syn-, and post-detachment igneous rocks can uniquely constrain aspects of the kinematics of late-stage exhumation and subsequent regional block rotation, resolution of the shallow inclination problem in this region is of critical importance. Here, we address this problem by re-examining the paleomagnetic data from the Kymi-Aliveri basin and the islands of Tinos, Mykonos, and Naxos.



Figure 2. A) Tilt-corrected specimen-level characteristic remanence directions from the Kymi Formation. Gray band shows the expected magnetic inclination of $56.5 \pm 2.5^\circ$ at the time of deposition. B) Field photographs of silt-poor (top) and silt-rich (bottom) facies of the Kymi Formation. C) Correction of reversed-polarity mean inclination from 49.3° to 52.1° by the elongation-inclination method (Krijgsman and Tauxe, 2004) assuming sedimentary compaction as the origin of the anomalously shallow remanence. Dashed lines bracket the 95% confidence interval for the corrected inclination.

2. The Kymi-Aliveri Basin

The Kymi-Aliveri basin consists of a basal sequence of Early to Middle Miocene lacustrine marls, siltstones, and sandstones (Figure 2) that pass upward into and are locally unconformably overlain by Middle Miocene fluvial/alluvial conglomerates (Bradley et al., 2013). The Middle Miocene Oxyliothos dacites were intruded into (and perhaps locally erupted onto; Pe-Piper and Piper, 1994) this sequence. The Kymi-Aliveri basin developed synchronously with the main period of exhumation of rocks to shallow crustal levels along low-angle normal faults in the adjacent Attic-Cycladic Complex, and is bounded to the southeast by the South Evia-North Attica Fault (Fig. 1) (Xypolias et al., 2003; Papanikolaou and Royden, 2007; Papanikolaou and Papanikolaou, 2007; Jolivet et al., 2010; Soukis and Stockli, 2012).

The close association between a thick succession of well-exposed sediments and coeval volcanics makes the Kymi-Aliveri basin an attractive location for paleomagnetic sampling (Kissel et al., 1986; Morris, 1995; Bradley et al., 2013). Pioneering paleomagnetic studies in the Kymi-Aliveri basin yielded consistent paleomagnetic directions from both the Kymi Formation and the Oxyliothos volcanics (Kissel et al., 1986; Morris, 1995). All sites in these studies exhibited mean inclinations of $\sim 40\text{--}45^\circ$ after tilt correction, well below the expected inclination of 56.5° . Notably, these studies sampled only reversed-polarity intervals of the Kymi Formation (Kissel et al., 1986; Morris, 1995). In order to test whether the reported shallow inclinations were due in part to shallow biases of reversed-polarity directions, we intensively sampled ~ 750 m of stratigraphic section of the Kymi Formation. The samples were analysed in the MIT Paleomagnetism Laboratory, with details of the analytical procedures, demagnetization characteristics, quality criteria, and stability tests presented in Bradley et al. (2013).

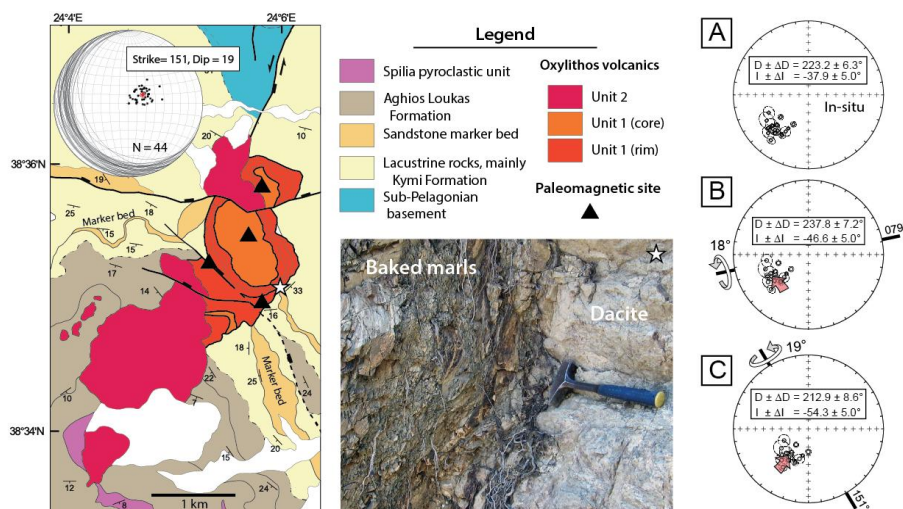


Figure 3. Paleomagnetism of the Oxyliothos dacites. White star on map indicates location of photograph showing intrusive contact between dacite and lacustrine marls. A) In-situ paleomagnetic data from Unit 1 (Kissel et al., 1986; Morris, 1995; Bradley et al., 2013). B) Tilt correction proposed by Kissel et al. (1986) and Morris (1995). C) Tilt correction using the orientation of the youngest beds intruded by the dacites (stereonet at upper left of figure).

Out of 311 accepted characteristic remanence directions, the reversed-polarity directions are on average 7.2° shallower than those with normal polarity (Figure 2A). In the Kymi-Aliveri basin, the

normal-polarity intervals are characterized by carbonate-rich marls and lacustrine limestones, while the reversed-polarity intervals exhibited higher silt content (Figure 2B), suggesting that enhanced compaction of silty beds could explain the shallow bias of the reversed-polarity dataset. Application of the elongation-inclination method (Krijgsman and Tauxe, 2004; Tauxe et al., 2008) to the reversed-polarity directions yields an elongation-corrected mean inclination of 52.1° (+6.0, -3.5), bracketing the expected Middle Miocene inclination (Figure 2C). Alternatively, the shallow nature and higher dispersion of reversed-polarity specimens may reflect incomplete thermal cleaning of a modern normal-polarity viscous overprint from the reversed-polarity specimens (Parés and van der Voo, 2013). The normal-polarity magnetization of the Kymi Formation therefore appears to be most closely representational of the ambient field direction during deposition. This interpretation is supported by observation of similar effects in large paleomagnetic datasets with depositional paleolatitudes that are independently known from plate reconstructions (Tauxe et al., 2008).

The Oxyolithos intrusive dacites yielded highly consistent site-mean directions (Figure 3A) in three separate studies (Kissel et al., 1986; Morris, 1995; Bradley et al., 2013). These dacites do not exhibit bedding or paleohorizontal indicators. Kissel et al. (1986) and Morris (1995) applied a tilt correction to these directions based on the attitude of southward-dipping marls exposed along the nearby Kymi-Platana road. Application of this correction to the combined dataset yields an anomalously shallow mean inclination similar to that of the reversed-polarity data from the Kymi Formation and a large inferred clockwise vertical-axis rotation of $\sim 58^\circ$ (Figure 3B). Based on new geological mapping, we instead find that the dacites are intruded into and slightly postdate the lacustrine section, invalidating this tilt correction. We propose an alternative tilt-correction that restores to horizontal the youngest beds intruded by the dacites (Figure 3). Application of this correction to the combined dataset yields a mean inclination of $54.3 \pm 5^\circ$ and an inferred clockwise vertical-axis rotation of $32.9 \pm 8.6^\circ$, consistent with the magnetization of the slightly older Kymi Formation (Figure 3C). We therefore find no evidence from the sedimentary rocks or volcanics of the Kymi-Aliveri basin for a Middle Miocene Aegean inclination anomaly.

3. Paleomagnetism of Northwestern Cycladic Igneous Rocks

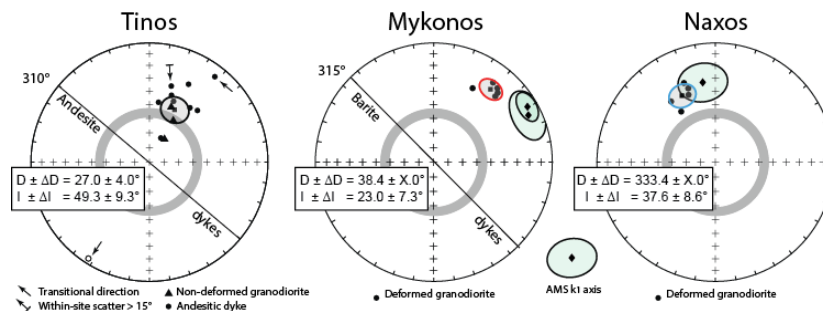


Figure 4. Summary of published paleomagnetic and magnetic fabric data from the islands of Tinos, Mykonos, and Naxos. Data are from Morris and Anderson (1996), Avigad et al. (1998), and Denèle et al. (2012). Gray bands show the expected Middle Miocene inclination.

From 15-10 Ma, a variety of plutons and dykes were intruded into the Attic-Cycladic Complex (Bolhar et al., 2010; Jolivet et al., 2010). On Tinos, a syn-detachment 14.73 ± 0.22 Ma granodiorite (s.l.) pluton and a set of 11.55 ± 0.43 Ma post-detachment dacitic dykes are exposed (Avigad et al., 1998; Bolhar and Ring, 2010). On Mykonos and Naxos, ~ 13.4 -11 Ma granodiorite (s.l.) plutons are also exposed (Bolhar et al., 2010; Brichau et al., 2008).

Remanent magnetizations for the Tinos pluton and dykes are characterized by final unblocking temperatures of $\sim 580^\circ\text{C}$ and little unblocking below 500°C , indicating that low-Ti titanomagnetite

dominates the magnetic remanence (Avigad et al., 1998). In contrast, paleomagnetic remanence at Mykonos and Naxos is dominated by a component with low unblocking temperatures ($< \sim 350^\circ\text{C}$) and a subordinate component with high unblocking temperatures of up to 580°C , carried by low-Ti titanomagnetite (Morris and Anderson, 1996). The published mean inclinations for Tinos, Mykonos, and Naxos are $41.9 \pm 9.9^\circ$, $23.0 \pm 7.3^\circ$, and $37.6 \pm 8.6^\circ$, respectively (Morris and Anderson, 1996; Avigad et al., 1998) (Figure 4). These authors argued that such shallow inclinations, which are statistically distinguishable from the expected Middle Miocene inclination of $56.5 \pm 2.5^\circ$, should be interpreted in the context of the $\sim 42^\circ$ mean inclination reported for the contemporary rocks of the Kymi-Aliveri basin under the assumption of a regional inclination anomaly. Our revision of the paleomagnetism of the Kymi-Aliveri basin invalidates this correction, exacerbating rather than mitigating the shallow inclination problem in the western Cyclades.

The published mean inclination of $41.9 \pm 9.9^\circ$ at Tinos depends strongly on two sites exhibiting nearly equatorial inclinations. These specific sites incorporate only 3 out of 6 (for site T1) and 2 out of 5 (for site T4) specimens (Avigad et al., 1998), the lowest ratios of analyzed to utilized specimens in the dataset. Furthermore, site T1 exhibits a nearly reversed polarity, but its mean direction is not antipodal to the cluster of normal-polarity sites, suggesting that it records a transitional direction. Exclusion of T1 and T4 as well as the site with greatest scatter (T13; Fisher 95% confidence interval $\alpha_{95} = 19.5^\circ$) yields a revised mean inclination of $49.3 \pm 9.9^\circ$. As the confidence interval for this inclination overlaps with the expected magnetic inclination for a Middle Miocene GAD (Figure 4), inference of an anomalous shallow inclination depends on inclusion of the three lowest-reliability sites, suggesting that the inferred shallow inclination could be an artefact of the small number of analysed samples and sites.

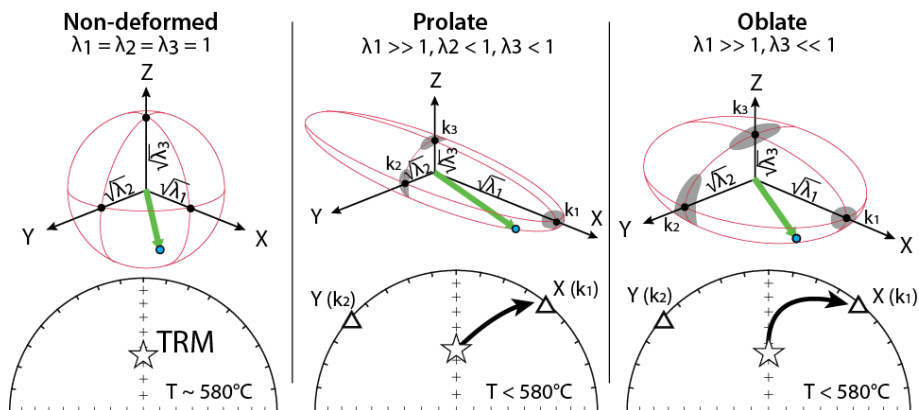


Figure 5. Transposition of a primary thermal remanent magnetization (TRM; open star) acquired during cooling below 580°C by oblate or prolate coaxial strain at temperatures of $350\text{--}500^\circ\text{C}$ (after Borradaile, 1997). Green arrow: paleomagnetic remanence direction.

The simplest way to explain shallow paleomagnetic inclinations within extensional terranes is by back-tilting of fault-bounded blocks. This mechanism requires minimum back-tilting of Tinos, Mykonos and Naxos by 7.2° , 33.5° and 18.9° , respectively. However, the similar strike of vertical andesite dykes on Tinos and barite dykes on Mykonos indicate that there has been little relative vertical-axis rotation or differential tilting between the footwalls of those islands since ~ 11 Ma (Avigad et al., 1998). The difference in magnetic inclination of $\sim 26.3^\circ$ between coeval rocks at Tinos and Mykonos cannot be explained solely by block tilting.

We therefore seek an alternative model for the origin of shallow inclinations at Mykonos and Naxos. All sites at these localities were drilled within rocks exhibiting a pronounced non-

magmatic foliation and a well-developed mineral lineation. This lineation parallels the principal (k_1) axis of the anisotropy of magnetic susceptibility tensor measured at each paleomagnetic drill site (Figure 4; Morris and Anderson, 1996). The tectonic fabrics record crystal-plastic deformation at temperatures down to $\sim 350^\circ\text{C}$, well below the $560\text{--}580^\circ\text{C}$ blocking temperature of low-Ti titanomagnetite (Lee and Lister, 1992). Temperatures of mylonitization of $400\text{--}500^\circ\text{C}$ have been observed in other metamorphic core complexes where syn-detachment plutonic rocks that are lithologically and structurally comparable to the Tinos and Mykonos plutons (e.g., Singleton and Mosher, 2012). Any primary thermoremanent magnetization acquired by cooling of low-Ti titanomagnetite grains below 580°C during initial post-crystallization cooling would therefore have significantly predated the cessation of ductile deformation.

Paleomagnetic remanence vectors carried by robust, elongate magnetic grains can rotate as passive lines under ductile deformation due to grain reorientation (Borradaile, 1997), with the mean remanence vector following an arcuate path toward the intermediate strain axis before converging on the maximum elongation direction (Figure 5A-C). While this effect has not to our knowledge been described in granite mylonites, the basic physical principles are closely analogous to well-studied examples (Borradaile, 1997). The magnitude and sense of angular deflection of a magnetization originally acquired in the expected (GAD) local field direction can therefore be estimated from finite strain measurements, assuming that strain was dominantly coaxial and that the axes of the anisotropy of magnetic susceptibility tensor measured at the paleomagnetic drill sites represent the finite strain axes. This approach requires knowledge of the paleo-north direction independent of the magnetization directions of the Cycladic plutons. Realignment of footwall lineations across the Mid-Cycladic Lineament (Walcott and White, 1998) requires $\sim 50^\circ$ of relative vertical-axis rotation between Mykonos and Naxos (Philippon et al., 2011). As the region northwest of the Mid-Cycladic Lineament is known to have rotated by $\sim 25^\circ$ clockwise since Middle Pliocene time (Bradley et al., 2013), the region to the southeast, including the island of Naxos, must have rotated counter-clockwise by $\sim 25^\circ$.

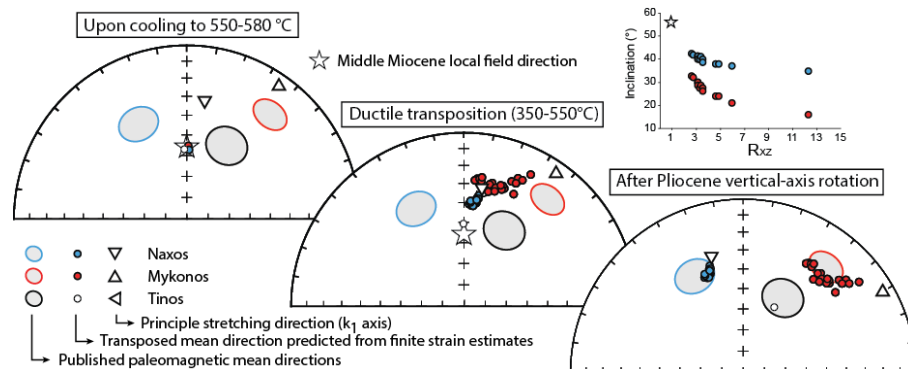


Figure 6. Hypothesized evolution of the paleomagnetic remanence of Tinos, Mykonos, and Naxos, accounting for ductile deflection of a primary thermoremanent magnetization using the strain ellipsoids measured on Naxos (Koukouvelas and Kokkalas, 2003) oriented by the principal axes of the magnetic susceptibility tensors measured at the paleomagnetic drill sites on both Naxos and Mykonos (Morris and Anderson, 1996).

For the case of Naxos, we adopt the 23 finite strain measurements of Koukouvelas and Kokkalas (2003), with the k_1 and k_3 axes of Morris and Anderson (1996) taken as the maximum and minimum elongation directions, respectively, of the finite strain ellipsoid. The resulting average remanence direction is $\sim 005^\circ/41^\circ$ (a flattening of 15.5°), which restores to a present-day remanence direction of $340^\circ/41^\circ$ after accounting for post-Miocene counter-clockwise rotation of 25° (Figure 6). Finite strain data are not presently available for the Mykonos pluton. If we assume

that the style and intensity of strain in the Mykonos pluton is similar to that at Naxos, but with the direction of maximum elongation oriented toward the k1 and k3 axes measured at Mykonos (Morris and Anderson, 1996; Denèle et al., 2011), we predict a deflected remanence direction of $015^{\circ}/30^{\circ}$ and, after accounting for post-Miocene clockwise rotation of 25° , a present-day remanence direction of $040^{\circ}/30^{\circ}$ (Figure 6). Because the largest amount of flattening and rotation of the remanence occurs at relatively low strain (strain ratio $RXZ < 2$; Figure 5F), the magnitude of the predicted deflection does not depend strongly on the details of the finite strain, so long as a stretching lineation is present and significant flattening has occurred (Figure 6, inset at upper right).

Ductile transposition of magnetizations acquired by cooling below 580°C in the expected ambient geomagnetic field can therefore explain the relative magnitude of inclination shallowing observed at Mykonos (25.5° lower than expected) and Naxos (15.5° lower than expected), as well as the more easterly declination of the remanence at Mykonos compared with Tinos.

However, our proposed model fails to explain strong demagnetization of specimens from Naxos and Mykonos at temperatures $<350\text{--}400^{\circ}\text{C}$. If this temperature range represents blocking temperatures, then magnetization must have postdated mylonitization. These magnetizations were originally attributed to monoclinic pyrrhotite, which demagnetizes upon heating to $\sim 320^{\circ}\text{C}$ (Grønvold and Haraldsen, 1952). However, to date no iron sulfides have been petrographically identified within the Mykonos or Naxos plutons. An alternative magnetic carrier is cation-deficient titanomaghemite, which undergoes inversion to hematite upon heating to $\sim 350^{\circ}\text{C}$, resulting in demagnetization in the same temperature range as pyrrhotite-bearing rocks (O'Reilly, 1983). Low-temperature ($<350^{\circ}\text{C}$) oxidation of fine-grained, acicular titanomagnetite can result in the production of intimately overgrown secondary titanomaghemite bearing a stable chemical remanent magnetization parallel to that of the original titanomagnetite grain (Heider and Dunlop, 1987). We suggest that after cooling through the brittle/ductile transition at temperatures of $\sim 300\text{--}350^{\circ}\text{C}$, low-temperature oxidative alteration led to growth of fine-grained titanomaghemite that acquired a remanence parallel to the already rotated high-temperature paleomagnetic remanence, which is now the primary paleomagnetic signal. In contrast, the dykes and plutonic rocks of Tinos, where sampled, were not penetratively strained or altered and therefore preserve both their igneous magnetic mineralogy and primary remanence direction.

4. Conclusions

Early to Middle Miocene sedimentary and volcanic rocks exposed in the Kymi-Aliveri basin and on the island of Tinos preserve paleomagnetic inclinations that are consistent with emplacement near their present-day latitude. Standard interpretation of the remanence directions at Mykonos and Naxos requires large fault-block tilts incompatible with independent structural constraints. We suggest an alternative interpretation of ductile transposition of a primary thermal remanent magnetization carried by low-Ti titanomagnetite followed by low-temperature maghemitization. This model can explain the progressive flattening and rotation toward the mylonitic stretching direction of paleomagnetic remanences at Mykonos and Naxos. Based on this new interpretation, the paleomagnetic data from the Central Greece and the western Cyclades do not require anomalous field geometries, significant northward drift of Aegean, or back-tilting of the low-angle normal faults of the North Cycladic Detachment System (Avigad et al., 1998). Our proposed model can and should be directly tested by coupled microstructural, rock magnetic, and paleomagnetic studies of deformed footwall plutons, as exemplified by the recent study of Zananiri et al. (2013) of the deformed Symvolon and Vrontou plutons of northern Greece.

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