2001

The Palaeomagnetism of Lesbos, NE Aegean, and the Eastern Mediterranean Inclination Anomaly

Myrl E. Beck Jr.
Western Washington University, myrl.beck@wwu.edu

Russ R. Burmester
Western Washington University, russ.burmester@wwu.edu

Despina P. Kondopoulou

Artemios Atzemoglou

Recommended Citation

Beck Jr., Myrl E.; Burmester, Russ R.; Kondopoulou, Despina P.; and Atzemoglou, Artemios, "The Palaeomagnetism of Lesbos, NE Aegean, and the Eastern Mediterranean Inclination Anomaly" (2001). *Geology*. 21.
https://cedar.wwu.edu/geology_facpubs/21

Geophys. J. Int. (2001) **145,** 233–245

The palaeomagnetism of Lesbos, NE Aegean, and the eastern Mediterranean inclination anomaly

Myrl E. Beck, Jr,[1] Russell F. Burmester,[1] Despina P. Kondopoulou[2] and Artemios Atzemoglou[3]

[1] *Department of Geology, Western Washington University, Bellingham, Washington* 98225–9080, *USA. E-mail: beck@cc.wwu.edu*
[2] *Department of Geophysics, Aristotle University of Thessaloniki,* PO Box 352–1 *Thessaloniki,* 540 06, *Greece*
[3] *Institute of Geology and Mineral Exploration, Branch of Thessaloniki,* 546 26 *Thessaloniki, Greece*

Accepted 2000 November 2. Received 2000 October 31; in original form 2000 June 13

SUMMARY

Palaeomagnetic results for 44 sites in 16–22 Ma volcanic rocks from Lesbos, NE Aegean, yield a mean pole at 81.8°N, 178.1°E, $K=9.0$, $A_{95}=7.6°$. The mean direction for these sites ($D=4.3°$, $I=48.5°$, $k=10.8$, $\alpha_{95}=6.9°$) is $5.9° \pm 6.1°$ shallower than the reference direction for Miocene Lesbos calculated from Besse & Courtillot (1991). Combining these new data with previous work yields a mean inclination that is $5.6° \pm 4.7°$ too shallow. Experimental problems, magnetic anisotropy, the magnetic terrain effect, geomagnetic anomalies, and problems with the reference path all seem unable to account for this observation. Shallow inclinations are a common feature of the Aegean region: 17 of 18 palaeomagnetic studies on Cenozoic igneous rocks have returned an inclination that is shallower than expected. Northward motion of the Aegean block by ~500 km with respect to northern Europe would account for this observation.

Key words: Aegean, inclination, Lesbos, Miocene, palaeomagnetism.

1 INTRODUCTION

Palaeomagnetic studies of Cenozoic rock units from the eastern Mediterranean consistently find mean inclinations that are slightly too shallow when compared with reference directions calculated from the European curve of apparent polar wander (APW). This was recognized at least as early as 1986 (Westphal *et al.* 1986), and has been discussed by Van der Voo (1993), Westphal (1993), and Beck & Schermer (1994), among others.

Fig. 1 shows the locations of Lesbos and 18 palaeomagnetic studies of Tertiary igneous rocks in the Aegean region. Table 1 and Fig. 2 illustrate the shallow-inclination problem. Fig. 2 plots inclination anomalies versus age. Anomalies are inclinations observed in these rock units (I_0) less their 'expected' inclination (I_x), calculated from the European composite curve of apparent polar wander of Besse & Courtillot (1991). Observed inclination is less than expected in all but one study. The inclination anomalies are not large, but they are persistent. Because these studies are exclusively of igneous rock units, compaction and other causes of inclination-shallowing in sedimentary rocks are not relevant.

For only one entry in Table 1 is $I_0 > I_x$, and that is for four sites in extremely young (~2.5 Ma) volcanic rocks. All other studies have observed inclinations that are shallower than expected ($I_0 < I_x$). Updating the calculation given in Beck (1997), if the probability of obtaining a too-shallow inclination in a single study is 0.553 (appropriate for the average palaeolatitude and dispersion of Aegean palaeomagnetic results), then the probability of obtaining 17 too-shallow results in 18 attempts is 0.0002. Clearly the Eurasian APW path of Besse & Courtillot (1991) is not an adequate predictor for the Aegean.

Following Beck & Schermer (1994), if Aegean inclinations are systematically too shallow, one or more of the following must be true:

(1) experimental problems have biased the Aegean palaeomagnetic data set towards shallow inclinations;
(2) the reference path of Besse & Courtillot (1991) is wrong, at least for much of the Tertiary;
(3) the axial dipole hypothesis, universally used in palaeomagnetism to map directions into poles (and vice versa), for some reason did not apply when these rocks were magnetized;
(4) some tectonic process has caused the Aegean region to move northwards with respect to stable Eurasia.

Several of these possibilities were discussed in Beck & Schermer (1994). For instance, all available choices of APW path were tested, and all yielded the same pattern of anomalously shallow inclinations. The hypothesis of Westphal (1993), that the inclination anomalies were caused by an abrupt swing of the geomagnetic dipole away from the rotation axis, was also discussed. Such a large 'excursion' (18°) ought to be seen in APW paths for other continents, but is not found in the detailed record of North American APW. Systematic experimental error was discounted by Beck & Schermer (1994) because many

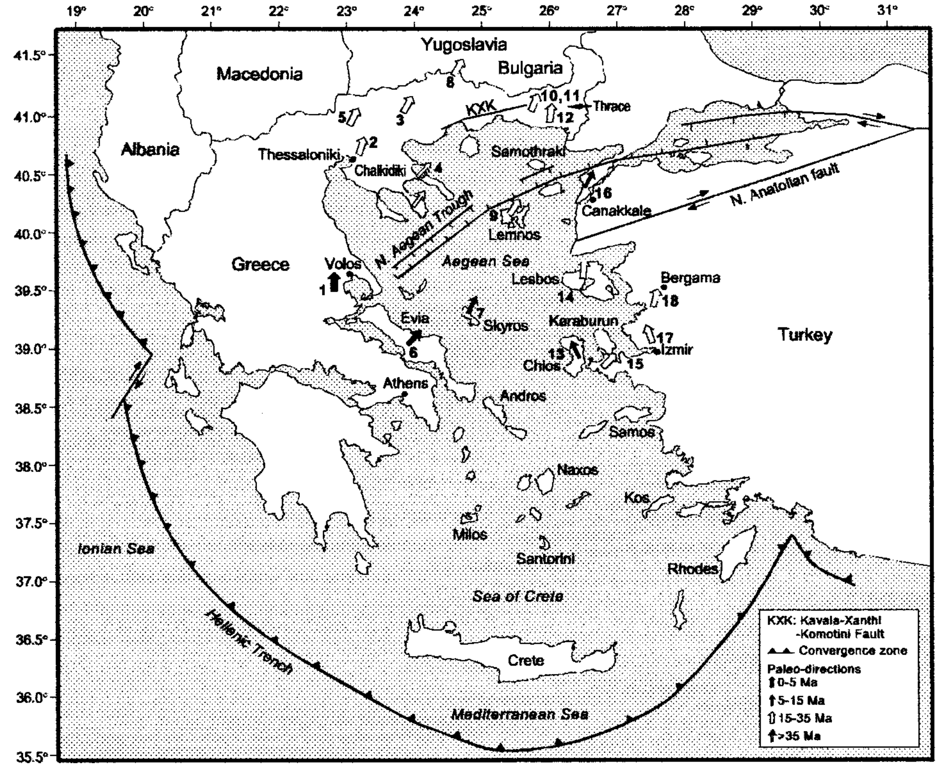

Figure 1. Location map for Lesbos and palaeomagnetic studies in 18 Tertiary igneous rock units of the Aegean region. Numbers refer to entries in Table 1. Arrows indicate observed declination and age.

of the studies involved were large, involved what appeared to be uncomplicated geological settings, and had been done with extreme care. Beck & Schermer (1994) concluded somewhat reluctantly that possibility number (4)—relative northward displacement—was the most likely.

However, there seem to be serious geological difficulties in accommodating so much northward displacement (~500 km). According to most investigators, Tertiary displacement in the Aegean has been southwards relative to Europe, not northwards (e.g. Angelier et al. 1982). For this reason we decided to

Table 1. Observed and expected inclinations for Cenozoic igneous rocks of the Aegean area.

Unit	Lon (°)	Lat (°)	Age	I_0 (°)	I_x (°)	ΔI_{95} (°)	Reference
1	23.0	39.0	2.5	59.0	56.1	8.5	Kissel *et al.* (1986b)
2	23.0	41.1	25	47.0	56.4	?	Westphal *et al.* (1991)
3	23.1	41.1	25	48.0	156.4	1.4	Pavlides *et al.* (1988)
4	23.8	40.2	35	31.0	55.2	7.5	Kondopoulou & Westphal (1986)
5	23.8	41.2	30	50.0	57.2	?	Kondopoulou (1986)
6	24.0	38.5	12.5	43.8	54.2	6.4	Kissel *et al.* (1986b)
7	24.5	38.9	15	45.5	54.4	6.4	Kissel *et al.* (1986b)
8	24.4	41.5	30	42.7	57.5	?	Atzemoglou *et al.* (1994)
9	25.2	39.8	20	48.0	54.9	9.6	Westphal & Kondopoulou (1993)
10	25.5	41.1	30	52.0	57.3	4.1	Spais (1987); Kondopoulou (1993)
11	25.9	41.1	30	46.0	57.3	3.5	Spais (1987); Kondopoulou (1993)
12	26.0	40.9	35	46.5	56.1	6.3	Kissel *et al.* (1986c)
13	26.1	38.2	15	37.0	153.8	0.1	Kondopoulou *et al.* (1993)
14	26.3	39.2	17.5	49.4	54.5	5.8	Kissel *et al.* (1986a); Kondopoulou & Lauer (1984)
15	26.5	38.4	20	51.0	153.6	3.0	Kissel *et al.* (1987)
16	26.6	40.0	12.5	54.0	55.9	3.8	Kissel *et al.* (1987)
17	27.0	39.0	17.5	52.0	54.4	7.2	Kissel *et al.* (1987)
18	27.1	38.9	17.5	39.0	154.3	5.9	Kissel *et al.* (1987)

Location (Lon, Lat) listed as E longitude and N latitude. Age rounded to nearest 2.5 Ma. I_0 is observed inclination; some entries recalculated. I_x is expected inclination, calculated from the composite Eurasian reference path of Besse & Courtillot (1991). ΔI_{95} is the combined 95 per cent error limits. Units: (1) Volos volcanics; (2) Thessaloniki volcanics; (3) Strymon volcanics; (4) Chalkidiki plutonics; (5) Serbomacedonian plutonics; (6) Evia volcanics; (7) Skyros volcanics; (8) Rhodope volcanics; (9) Lemnos volcanics; (10) Thrace volcanics and plutonics, southern area; (11) Thrace volcanics and plutonics, northern area; (12) Thrace volcanics and plutonics; (13) Chios volcanics; (14) Lesbos volcanics; (15) Karaburun, Turkey, volcanics; (16) Canakkale, Turkey, volcanics; (17) Izmir, Turkey, volcanics; (18) Bergama, Turkey, volcanics.

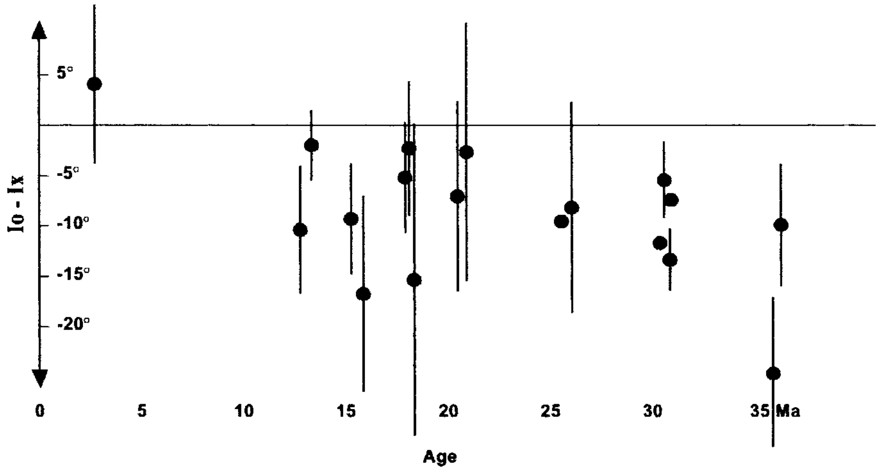

Figure 2. Inclination anomalies plotted versus age of rock unit at locations in Fig. 1. I_0 is observed inclination; I_x is inclination expected, calculated from the European curve of apparent polar wander of Besse & Courtillot (1991). Error bars are combined errors on I_0 and I_x. Data in Table 1.

test possibility number (1), that the observed inclinations are too shallow because of experimental problems. We chose to re-study the palaeomagnetism of the northern Aegean island of Lesbos, because it has a large suite of volcanic rocks and had previously yielded an anomalously shallow inclination (Kissel *et al.* 1986a; Kondopoulou & Lauer 1984). As will be seen below, extensive re-sampling and detailed thermal and alternating field demagnetization of rocks from 50 sites ($\sim$400 individually orientated samples) scattered over the central part of the island yielded a result that differs from previous mean directions by $<2°$. Thus an early conclusion of this study is that experimental problems do not account for the pervasive inclination anomaly.

2 GEOLOGY OF LESBOS

Fig. 3 is a simplified geological map of Lesbos. According to Fytikas *et al.* (1984), Zouros & Fytikas (1997), and Pe-Piper & Piper (1993), the volcanic rocks we sampled are 16–22 Ma, with a strong concentration of dates at about 16–18 Ma. 'Basement', consisting of Late Palaeozoic and Early Mesozoic metamorphic rocks, with some peridotite and serpentine, is exposed only on the eastern part of the island; in Fig. 3, basement is combined with some small exposures of post-volcanic sedimentary rocks. Neogene volcanic rocks occupy the northwestern two-thirds of the island and lie on the basement with angular unconformity.

Structure within the volcanics is simple. Dips are small [$0° - 25°$, with a strong concentration (56 per cent) of 10° or less]. Two systems of active faults cross at least the central part of the island, with trends of NE–SW and NW–SE (Fytikas *et al.* 1999). Whether these faults are rotational is unknown.

As discussed below, one of the problems encountered in this study is whether to treat the measured dips as tectonic (and thus correct for tilt), or original (and thus use the *in situ*—uncorrected—direction). Fig. 4 is a plot of poles to 'bedding' for all sites sampled in this study. The distribution is nearly circular: the elongation is 1.5, and the probability of it being drawn from a circular distribution is estimated at 33 per cent (Beck 1999). The mean inclination of the set of poles-to-bedding is 88.6°, which indicates that there is no preferred direction of tilt, and also predicts that the mean tilt-corrected and *in situ* directions for the collection will be very similar. The

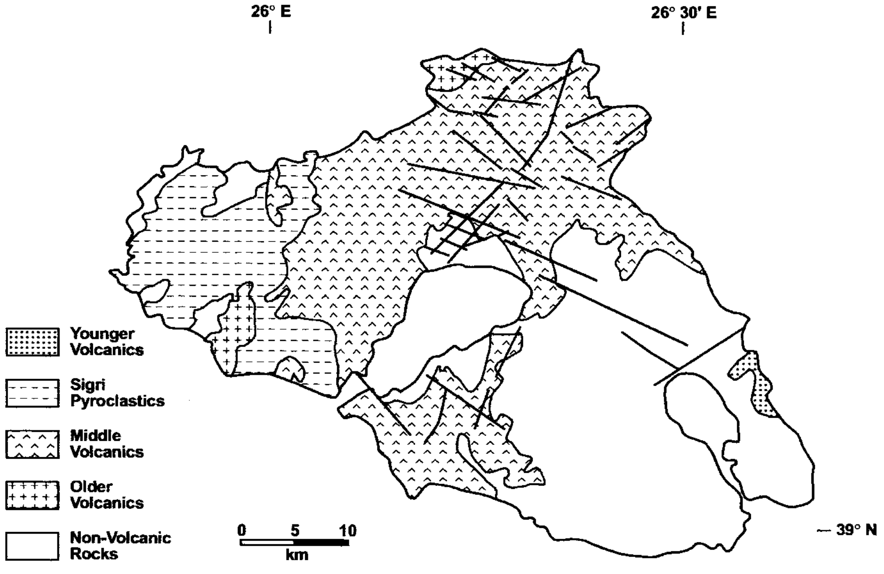

Figure 3. Simplified geological map of Lesbos after Fytikas *et al.* (1984), Pe-Piper & Piper (1993), Zouros & Fytikas (1997), and Fytikas *et al.* (1999).

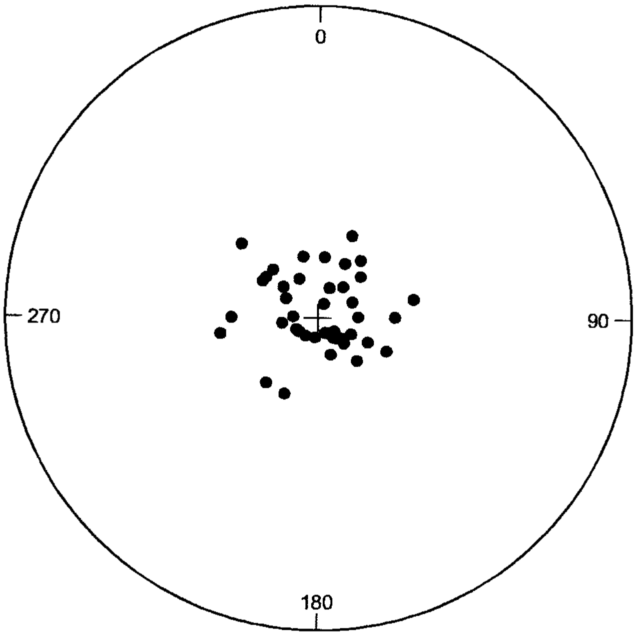

Figure 4. Equal-area plot of poles to bedding for all sites sampled in this study. The distribution is nearly circular with a mean only 1.4° from vertical, which indicates that there is no preferred direction of tilt.

set of poles-to-bedding, although nearly circular, is slightly elongate towards the southeast (106°). Thus, if the dips are tectonic, a vague 'regional' tilt axis of ~16° is indicated.

3 PALAEOMAGNETIC PROCEDURES

In all we sampled 50 sites, each consisting of eight or more separately orientated samples. Samples were drilled and orientated *in situ*; core azimuths were measured with both sun and magnetic compass. We used a GPS unit to obtain site locations, which subsequently were used to convert directions to virtual geomagnetic poles (VGPs). Flows, dykes, ashflow tuffs, and volcanic sediments were sampled. Attitudes were measured at each site. Attitudes in contiguous fine-grained sedimentary rocks were preferred for structural data, but where these were absent we used flow tops or platy parting in lava flows. Table 2 summarizes the basic field data.

In the laboratory, each sample was cut into specimens and the natural remanent magnetization (NRM) of at least one specimen per sample was measured on a fluxgate spinner magnetometer. From a plot of NRMs, two or more specimens per site were selected for pilot demagnetization by the alternating field (a.f.) method (using a two-axis reciprocating tumbler), and by the thermal (T) method. Later stages of the study employed a non-tumbling a.f. demagnetizer and a cryogenic magnetometer, located in the new shielded room of the Pacific Northwest Palaeomagnetism Laboratory. Guided by results of the pilot demagnetizations, the rest of each site was demagnetized by the method that appeared the more promising. T and a.f. were used together on a few sites. In general, one specimen per sample was demagnetized, in five or more steps, to 10 per cent or less of its original intensity. Principal component analysis (Kirschvink 1980) was used to determine the characteristic remanent magnetic (ChRM) direction for each specimen. Nearly all samples responded well to magnetic cleaning: the maximum angular deviation (MAD) of Kirschvink (1980) for most specimens was <5°. Site-mean directions of magnetization were calculated by the method of Fisher (1953). In general, within-site scatter was small: 74 per cent of the values of α_{95} (radius of circle of 95 per cent confidence) were <5°. Fig. 5 shows examples of the behaviour of typical Lesbos samples during magnetic cleaning.

Table 2. Locations, structural data and lithologies for Lesbos volcanic rocks.

Site	Lon (°)	Lat (°)	BedAz (°)	Dip (°)	Rock type
01	26.213	39.379	270	5	andesite flow
02	26.300	39.375	350	23	rhyolite flow
03	26.249	39.361	200	5	andesite flow
04	26.263	39.362	200	5	andesite flow
05	26.306	39.351	260	8	dyke with perlite margin
06	26.306	39.351	260	8	welded tuff
07	26.343	39.364	135	7	rhyolite flow
08	26.321	39.365	135	7	andesite flow
09	26.317	39.374	135	7	rhyolite flow
10a	26.181	39.250	90	11	dyke in 10b
10b	26.181	39.250	90	11	clasts in breccia
11	26.172	39.251	90	11	intrusion into breccia
12	26.272	39.363	120	15	rhyolite flow
13	26.300	39.365	335	11	rhyolite flow
14	26.109	39.257	115	15	andesite flow
15	26.065	39.262	40	18	andesite flow
16	26.051	39.246	30	8	andesite flow
17	26.031	39.237	315	10	two dykes
18	26.031	39.237	315	10	andesite flow
19	26.034	39.235	340	40	lahar?
20	26.262	39.239	260	15	andesite flow
21	26.285	39.267	225	5	andesite flow
22	26.313	39.299	90	5	andesite flow
23	26.302	39.323	115	10	rhyolite flow
24	26.322	39.349	70	10	andesite flow
26	25.957	39.156	225	5	andesite flow
27	26.015	39.105	230	5	andesite flow
28	26.199	39.363	305	8	dyke in andesite flow
29	26.224	39.348	200	5	andesite flow
30	26.017	39.236	305	15	andesite flow
31	26.020	39.234	305	15	andesite flow
32	26.011	39.243	305	15	chilled andesitic intrusion
33	26.004	39.283	125	25	andesite flow
34	25.987	39.246	155	10	dyke similar to 30
35	26.033	39.208	215	5	dyke
36	26.030	39.215	200	5	andesite flow
37	26.120	39.288	30	15	andesite flow
38	26.167	39.191	135	6	andesite flow
39	26.136	39.152	130	8	andesite flow
40	26.118	39.136	120	6	rhyolite flow
41	26.091	39.118	80	25	rhyolite flow
42	26.083	39.135	135	15	basalt flow
43	26.058	39.150	25	22	welded tuff
45	25.983	39.148	110	10	andesite flow
46	25.938	39.172	270	20	dacite dyke
47	25.973	39.227	140	5	welded tuff
48	26.047	39.250	50	15	andesite flow
49	26.235	39.317	350	15	dacite flow
50	26.253	39.317	320	15	mafic dyke

Location (Lon, Lat) listed as E longitude and N latitude. BedAz and Dip are the azimuth and plunge of the dip vector.

Rocks from the northeast part of the area retain both polarities of remanence (Figs 5a and b). Magnetite is the

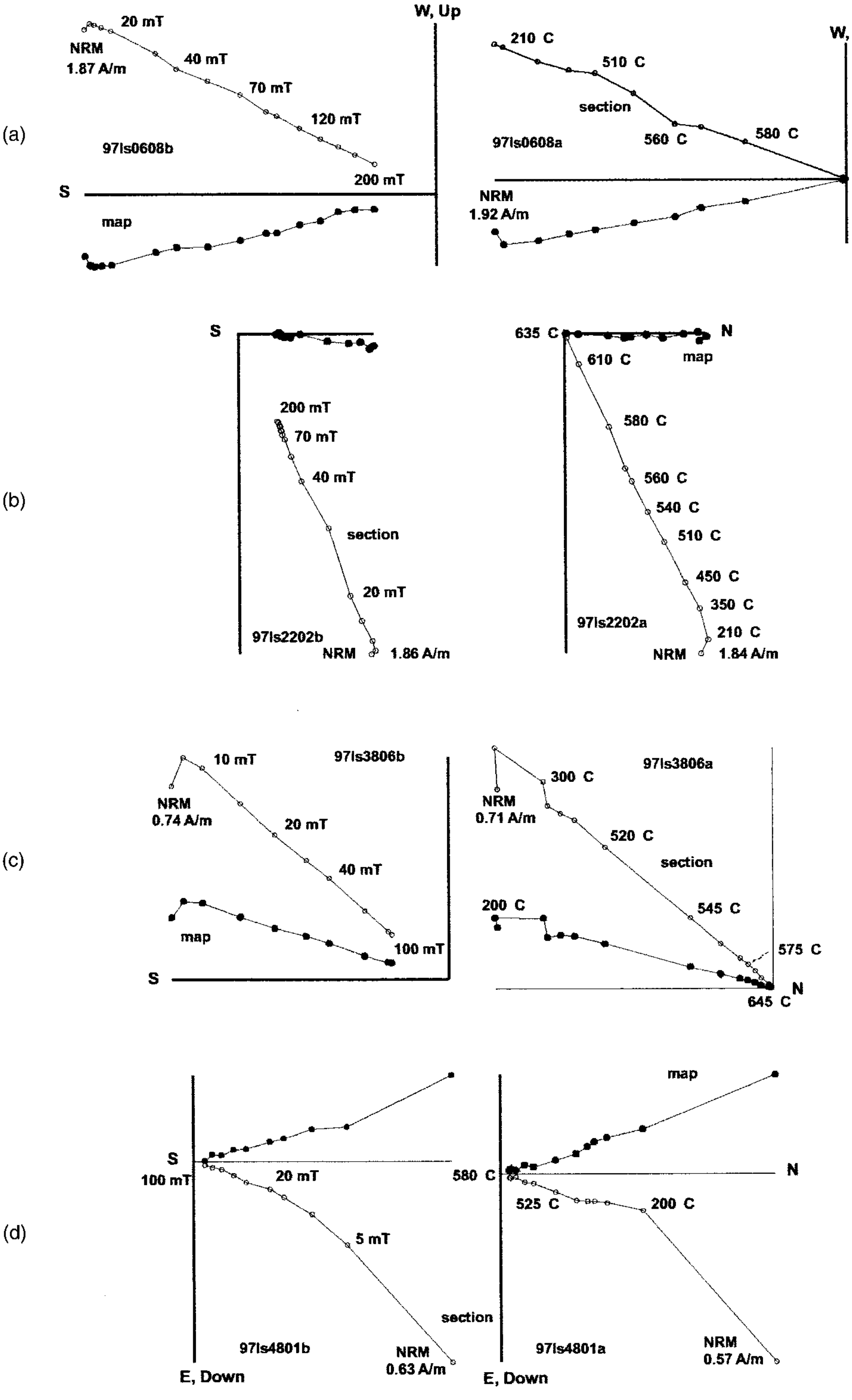

Figure 5. Orthogonal projections for representative samples. (**a**) Ash flow tuff from the northeast part of the area carries an essentially single-component reverse magnetization. Demagnetization at 70–200 mT suggests that fine-grained magnetite carries much of the remanence. (**b**) Andesite flow from the northeast part of the area carries a nearly single-component normal-polarity magnetization. Resistance of about 25 per cent of the remanence to a.f. demagnetization and unblocking of 25 per cent above 580 °C suggest that ~25 per cent of the remanence is carried by haematite. Colinearity of demagnetization paths from a.f. and above 580 °C suggests that both minerals were magnetized in the same magnetic field. (**c**) Andesite flow from the southern part of the area carries a reverse-polarity magnetization, with little overprint; ~5 per cent of the remanence is carried by haematite. (**d**) Andesite flow from the western part of the area carries a normal-polarity magnetization. This sample has atypically low coercivity and unblocking temperature spectra yet has useful linear decay towards the origin after the initial erasure of an overprint with a slightly different direction.

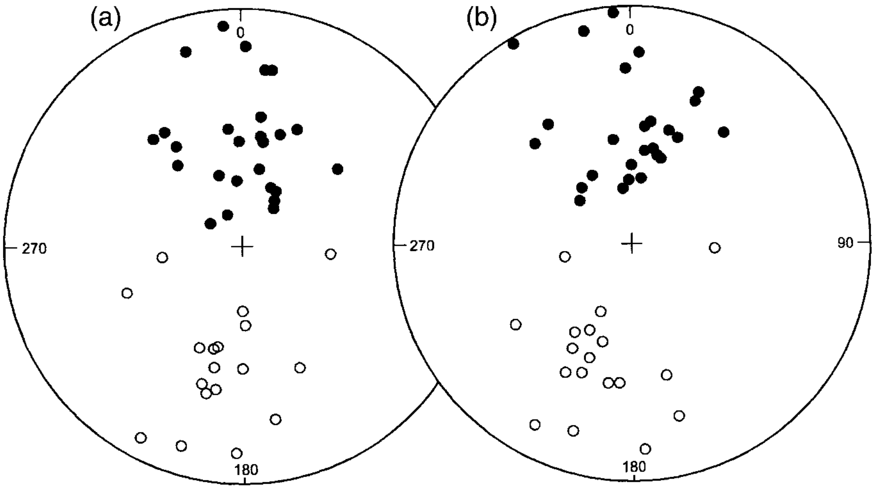

Figure 6. Equal-area projection of site-mean directions (a) not corrected for tilt, and (b) corrected for tilt. Hollow/solid symbols indicate upper/lower hemisphere. Data in Table 3.

dominant carrier of remanence, with haematite accounting for 5 per cent typically, 20 per cent rarely and 40 per cent in one site, judging from the proportion of remanence unblocked above 580 °C. The similarity of demagnetization paths above 580 °C and those from a.f. demagnetization suggest that both magnetite and haematite were magnetized in the same magnetic field. Some sites also exhibited high coercivities with unblocking of remanence continuing to 200 mT, the highest field our equipment could attain. This is consistent with the presence of very fine-grained magnetite. Linear demagnetization paths suggest that there is little anisotropy; otherwise we would expect to see effects of gyromagnetic remanence in the non-tumbling demagnetization (Dankers & Zijderveld 1981).

Both polarities of remanence are also recorded in the southwest, but rocks carrying them are less intermixed than in the northeast. Reverse polarity magnetizations dominate the southern part of the area. Magnetizations are typically weaker and less stable to laboratory demagnetization (Fig. 5c). Hematite carries 5 per cent of the remanence in some sites. Normal polarity overprints are common, but are typically removed by 20 mT or 500 °C. Magnetizations from the western part of the area have normal polarity. The example shown in Fig. 5(d) has nearly the lowest unblocking spectra of any site, yet still displays demagnetization paths towards the origin after the lowest stability fraction is demagnetized.

Although all pilots showed encouraging demagnetization behaviour, not all sites collected proved useful. Sites 25 and 44 disintegrated during thermal demagnetization. Sites 28 and 41 were eliminated because they had too much scatter ($\alpha_{95} > 15°$). Sites 11, 14, 29 and 50 yielded reasonably tight clusters (low within-site scatter), but were eliminated because they had conspicuously streaked distributions. In addition, sites 11 and 50 lacked demagnetization paths trending towards the origin. These sites probably retain two inseparable components of remanent magnetization. On the other hand, sites 10 and 49 were found to consist of subsets with distinct directions, so these were subdivided. This left 44 sites for use in further calculations.

4 PALAEOMAGNETIC RESULTS

Tables 3 and 4 list site-mean directions and VGPs from this study, and Figs 6 and 7 illustrate their distributions. Table 5 summarizes mean directions and VGPs for the entire suite.

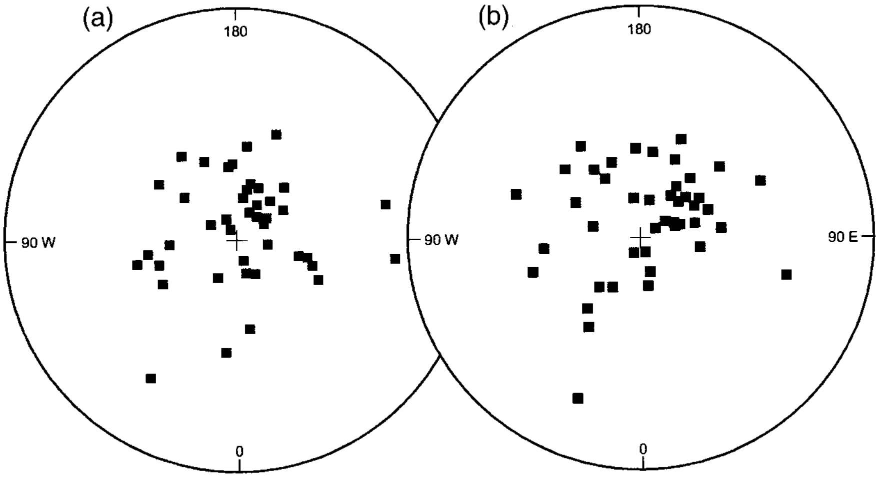

Figure 7. Equal-area projection of north virtual geomagnetic poles from site-mean directions (a) not corrected for tilt, and (b) corrected for tilt. Data in Table 4.

Table 3. Site mean directions and statistics.

Site	D_g (°)	I_g (°)	D_s (°)	I_s (°)	N	R	k	α_{95} (°)	Min	Max	T	L
01	261.1	−63.5	259.2	−68.4	8	7.977	304.3	3.1	20	100	a,t	o
02	27.3	67.8	9.7	47.3	8	7.962	184.2	4.1	20	620	a,t	o
03	197.5	−19.3	197.4	−24.3	8	7.978	318.2	3.1	20	100	a	o
04	208.2	−15.9	208.4	−20.8	7	6.985	400.0	3.0	480	580	t	c
05	192.1	−41.7	185.0	−44.3	9	8.975	320.0	2.9	20	100	a	o
06	169.8	−31.1	165.0	−30.7	7	6.964	166.7	4.7	500	635	t	o
07	203.1	−54.1	212.7	−56.2	11	10.980	500.0	2.2	580	635	t	o
08	342.1	64.8	351.1	70.8	8	7.953	148.9	4.5	20	100	a	o
09	99.0	−60.6	89.9	−65.9	8	7.979	333.3	3.0	500	660	t	o
10a	180.1	−69.0	206.5	−66.4	6	5.996	1250.0	1.9	530	645	t	c
10b	195.9	−55.5	209.6	−51.2	6	5.933	74.6	7.8	30	625	a,t	o
11	215.1	−55.4	225.8	−48.2	9	8.794	38.8	8.4	30	100	a	c
12	194.3	−40.3	207.5	−42.7	5	4.992	500.0	3.4	25	100	a	o
13	247.8	−49.4	235.1	−44.1	9	8.921	101.3	5.1	30	600	a,t	c
					8	7.958	166.7	4.3				c
14	11.4	17.3	16.4	20.2	10	9.728	33.1	8.5	20	200	a	o
15	19.0	49.2	24.0	32.1	10	9.973	333.3	2.6	20	100	a	o
16	355.5	8.2	355.9	1.6	10	9.944	160.7	3.8	20	80	a	c
17	326.9	48.8	325.1	39.0	6	5.992	625.0	2.7	480	625	t	c
18	305.9	76.8	309.7	66.9	11	10.980	500.0	2.3	20	90	a	o
19	325.9	41.8	329.5	2.6	5	4.973	148.1	6.3	20	100	a	c
20	181.7	−18.0	176.5	−20.4	8	7.951	142.9	4.6	30	540	a,t	o
21	12.4	53.5	8.2	57.6	10	9.979	428.6	2.3	20	90	a	o
22	356.1	67.8	8.3	67.6	9	8.977	347.8	2.7	500	635	t	o
23	321.9	54.4	330.4	63.0	8	7.974	269.2	3.4	520	660	t	o
24	154.9	−46.0	165.3	−46.0	8	7.992	875.0	1.9	410	660	t	c
26	25.8	45.1	23.9	49.8	10	9.952	187.5	3.5	20	100	a	c
27	320.7	41.6	316.3	41.5	7	6.978	272.7	3.6	20	100	a	o
28	150.9	−62.3	145.7	−54.9	7	6.678	18.6	14.4	40	580	a,t	c
29	204.1	−15.9	204.2	−20.9	5	4.914	46.5	11.3	560	655	t	o
30	334.6	78.4	318.2	64.3	8	7.934	106.1	5.4	20	90	a	o
31	39.5	73.2	356.9	68.5	7	6.982	333.3	3.3	20	100	a	o
32	31.2	68.2	359.5	62.9	6	5.983	294.1	3.9	100	585	a,t	o
33	10.0	26.5	24.2	34.3	9	8.962	210.5	3.5	30	100	a	o
34	10.0	51.3	19.2	59.0	7	6.946	111.1	5.8	20	100	a	o
35	9.0	44.7	6.6	49.1	8	7.963	189.2	4.0	30	100	a	o
36	353.3	48.9	350.4	53.3	7	6.985	400.0	3.0	20	100	a	c
37	13.0	63.1	18.5	48.5	10	9.956	204.5	3.4	25	130	a	o
38	196.4	−42.4	201.6	−45.0	8	7.987	538.5	2.4	30	100	a	o
39	194.1	−56.5	206.1	−59.2	8	7.964	194.4	4.0	520	625	t	o
40	193.4	−49.4	200.4	−50.8	8	7.991	777.8	2.0	480	645	t	o
41	155.3	−35.0	173.9	−37.4	7	6.335	9.0	21.2	500	630	t	o
42	179.7	−49.8	196.6	−58.9	8	7.983	411.8	2.7	30	300	a,t	o
43	178.2	−64.5	189.4	−43.9	8	7.989	636.4	2.2	480	645	t	o
45	359.3	54.1	13.4	56.5	7	6.994	1000.0	1.9	540	630	t	c
46	8.5	26.7	358.1	27.9	8	7.971	241.4	3.6	25	90	a	c
47	1.5	17.3	2.7	21.0	10	9.898	88.2	5.2	30	100	a	o
48	344.4	16.4	347.6	9.8	10	9.952	187.5	3.6	30	100	a	o
49a	34.8	70.5	16.5	58.1	6	5.973	185.2	4.9	20	90	a	o
49b	51.6	47.6	39.8	39.1	4	3.990	300.0	5.2	20	100	a	c
50	230.9	−40.6	218.3	−39.2	8	7.904	72.9	6.5	480	575	t	c

D_g, I_g, D_s, I_s are declination and inclination of uncorrected and corrected mean directions calculated giving unit weight to N samples. R, k and α_{95} are statistics from Fisher (1953). Min, Max are minimum and maximum levels of demagnetization in mT (for a) and °C for t. T: type of magnetization used—a, alternating field; t, thermal; a,t, both used on same specimen. L: type of line fit used—O, line forced through origin; C, free line (Kirschvink 1980).

4.1 Preliminary observations

From Figs 6 and 7 and Table 5 the following observations are noted.

(1) Scatter is greater than usually encountered in palaeomagnetic studies of areas with similar palaeolatitude.

(2) The distributions are very nearly circular.

(3) Because dips are small no fold test is possible, although uncorrected directions and poles are slightly less scattered than corrected directions and poles.

(4) Normal and reverse subsets are statistically antiparallel; the reverse-polarity subset has a more easterly declination than

Table 4. VGPs from uncorrected and corrected site-mean directions.

Site	Uncorrected		Corrected	
	E. Lon (°)	N. Lat (°)	E. Lon (°)	N. Lat (°)
01	261.8	−32.3	255.1	−36.0
02	76.4	67.8	167.1	76.4
03	353.6	−56.7	351.5	−59.2
04	339.8	−49.8	337.1	−51.9
05	349.0	−71.6	7.4	−76.0
06	50.7	−65.7	60.4	−63.7
07	303.5	−71.0	291.7	−64.3
08	331.7	75.0	8.6	73.1
09	147.0	−30.8	157.2	−28.2
10a	206.4	−76.8	260.5	−68.8
10b	305.5	−77.0	304.1	−64.9
11	291.8	−62.2	296.8	−51.3
12	345.6	−69.6	320.3	−62.7
13	283.4	−34.9	295.5	−42.4
14	184.5	57.9	174.8	57.7
15	140.8	71.9	155.6	59.8
16	213.8	54.6	212.6	51.4
17	286.9	61.3	276.3	55.7
18	353.7	50.0	329.3	53.4
19	278.5	57.5	249.9	43.0
20	22.9	−60.0	33.4	−61.1
21	140.2	78.8	122.9	83.5
22	14.2	78.2	97.2	61.5
23	300.2	59.5	319.2	67.5
24	94.0	−66.0	76.3	−72.9
26	138.4	65.1	132.3	68.7
27	283.2	53.6	286.7	50.2
28	136.7	−67.9	118.9	−62.6
29	345.2	−52.0	342.6	−54.3
30	8.0	58.3	322.6	58.9
31	64.7	58.3	17.3	77.3
32	76.5	65.2	22.0	84.9
33	184.0	63.2	182.6	58.1
34	154.8	79.1	107.9	75.2
35	173.0	75.1	336.5	84.3
36	238.4	79.1	328.9	70.1
37	83.2	79.0	143.3	71.9
38	338.0	−69.9	324.7	−68.0
39	302.4	−78.7	285.4	−69.9
40	331.0	−75.9	314.5	−71.7
41	80.3	−60.9	43.9	−71.1
42	27.8	−81.5	288.5	−77.2
43	196.3	−82.7	301.5	−67.9
45	213.3	85.5	122.9	79.3
46	187.0	63.8	210.4	65.6
47	203.0	59.6	200.4	61.5
48	234.5	56.1	227.3	53.9
49a	71.2	62.2	113.4	77.2
49b	114.0	46.5	131.3	52.1
50	301.3	−44.3	312.6	−53.3

Table 5. Mean directions and palaeomagnetic poles for Neogene volcanic rocks from Lesbos, Greece.

Directions Calculation	N	Dec (°)	Inc (°)	E	δ (°)	k	α_{95} (°)
Corrected for tilt	44	5.9	49.4	1.402	25.2	10.7	6.9
Not corrected for tilt	44	5.0	51.7	1.594	24.7	11.1	6.8
Preferred	44	4.3	48.5	1.375	25.1	10.8	6.9
Preferred – 38	38	6.0	46.3	1.871	20.8	15.5	6.1
Lesbos	71	5.9	48.9			12.8	4.9

VGPs Calculation	N	Lon (°)	Lat (°)	E	Δ (°)	K	A_{95} (°)
Corrected for tilt	44	162.7	82.4	1.577	28.2	8.6	7.8
Not corrected for tilt	44	173.4	84.7	1.207	27.9	8.8	7.7
Preferred	44	178.1	81.8	1.637	27.7	9.0	7.6
Preferred – 38	38	177.0	79.1	1.662	20.9	15.3	6.1

N, number of sites used in calculation. Dec/Inc, mean declination and inclination. Lon/Lat, east longitude and north latitude of mean pole. E, elongation of data set. δ/Δ, angular standard deviation for directions/VGPs; k/K, Fisher (1953) precision parameter for directions/VGPs. α_{95}/A_{95}, 95 per cent confidence limit on directions/VGPs. For the 'Preferred' calculations, see text. 'Lesbos' is combination of directions given by Kissel *et al.* (1986a), Kondopoulou *et al.* (1984), and this paper.

the normal-polarity subset, but the two are indistinguishable at 95 per cent confidence by the test of McFadden & Lowes (1981).

(5) Because dips are small and random there is no significant difference between uncorrected means and corrected means.

(6) The expected inclination for 17.5 Ma at Lesbos calculated from the reference path of Besse & Courtillot (1991) is 54.4°. This is some 5° steeper than the observed inclination in the Lesbos volcanic rocks. Several of these observations are discussed below.

4.2 Scatter

The angular standard deviation of VGPs for the Lesbos volcanics is approximately 25°. The mean Lesbos inclination (I_0) is $\sim 50°$, which corresponds to a palaeolatitude of $\sim 30°$. Judging from the scatter in lavas of <5 Ma (Merrill *et al.* 1998, Fig. 6.14) one should find $\delta \sim 14°$ at latitude 30°; from Merrill & McElhinny (1983, Fig. 6.17), for the period 5–45 Ma the angular standard deviation at a latitude of 30° should be roughly 19°. Thus the scatter observed in Lesbos volcanic rocks is anomalously large.

Much of the scatter probably represents faulty tilt corrections; as is well known, obtaining reliable structural data in volcanic terranes can be difficult. However, inappropriate tilt corrections cannot be the entire answer; as shown in Table 5, sets of GPS for tilt-corrected directions, *in situ* directions, and a combination of the two (discussed below) all have anomalously large scatter. Possibly the Lesbos volcanics were erupted at a time when the ratio of non-dipole to dipole geomagnetic intensity was abnormally high, but we cannot know for sure.

4.3 Shape

Beck (1999) discussed the use of Bingham statistics to characterize the elongation of a data set (directions or VGPs): elongation (E) is defined as k_2/k_3, where k_2 and k_3 are the second and third eigenvalues of the distribution (Onstott 1980). Beck (1999) found that fairly large and uncomplicated data sets from cratonic areas have $E<3$ or so, with most around $E=1.5$.

Poles were found to be marginally more circular (less elongate) than directions. In the same study, some distributions from zones of active strike-slip faulting were found to be highly elongate ($E>3$, ranging up to $E\sim10$), probably reflecting internal deformation during or after magnetization. Lesbos data sets by these standards appear to be internally undeformed. The uncorrected VGP set in particular is extremely circular (Table 5).

4.4 Are the dips primary or tectonic—and does it matter?

As mentioned earlier, the gentle dips found in most Lesbos Neogene volcanics preclude a formal fold test. From Table 5, scatter is very slightly less for the uncorrected sets (directions and VGPs) than for the corrected sets. This tends to suggest that most of the dips are primary. The fact that the uncorrected VGP set has an extremely circular distribution also suggests that most dips are primary. However, almost certainly some post-magnetization tilting (folding or block faulting) has occurred, although perhaps not much.

It probably is impossible to separate original and tectonic tilts for these volcanic rocks in any effective manner, but we made an attempt. On the assumption that dips of 15° and over are unlikely to be completely original, we made another calculation in which tilt-corrected directions were used for sites for which dips were $\geq15°$, and *in situ* directions for the rest. This is our 'preferred' set (Fig. 8). The mean direction of this set is shallow by $5.9°\pm6.1°$ with respect to a reference direction calculated from Besse & Courtillot (1991) for a point near the centre of Lesbos (39.1°N, 26.3°E).

We performed one other calculation, identified in Table 5 as 'Preferred – 38'. This calculation (both directions and VGP) excludes sites 1, 9, 13, 15, 18, and 42. These sites have VGPs that are more than 39° from the mean. The angular dispersion that one would expect to find for a palaeolatitude of 30° is about 19.5°, from work cited earlier. Thus these six sites differ from the mean by more than twice the angular standard deviation. This calculation yields an even shallower distribution ($F=8.1°\pm5.6°$).

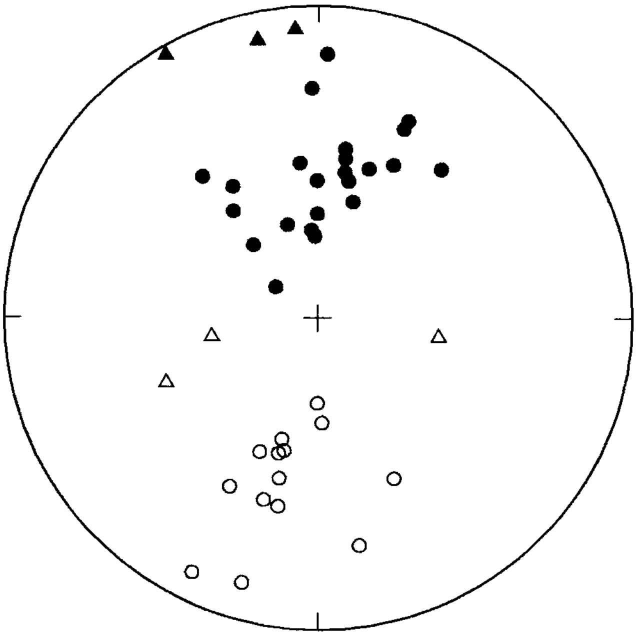

Figure 8. Equal-area plot of 'preferred' site-mean directions. Directions indicated by triangles are $>2\delta$ from the mean. See text.

5 COMPARISON WITH EARLIER RESULTS

Kissel *et al.* (1986a) reported results for 17 sites in the Lesbos volcanics and obtained a mean direction of $D=6.0°$, $I=49.5°$ ($N=17$, $k=24.7$). This is 1.5° from our preferred direction. Results by Kondopoulou & Lauer (1984) are similar: $D=12.5°$, $I=49.0°$ ($N=10$, $k=11$). It is difficult to evade the conclusion that the mean inclination of the Lesbos volcanics is $<50°$, or about 5° shallower than predicted by the Besse & Courtillot (1991) reference path.

6 COMBINED RESULTS

The three results of the last section (Kissel *et al.* 1986a; Kondopoulou & Lauer 1984; this paper) are so similar that it should be legitimate to combine them, although in doing so some duplication (multiple sampling) is likely. This 'grand mean' for the Lesbos Neogene volcanics, weighted by R (magnitude of the vector sum from each study) is $D=5.9°$, $I=48.9°$, $k=12.8$, $N=71$, $\alpha_{95}=4.9°$.

This direction definitely is discordant. The Besse & Courtillot (1991) compilation 20 Ma reference pole for Eurasia has an average age of 18.8 Ma and thus can be used as a reference, although it may be slightly too old. The expected direction calculated for a point near the centre of Lesbos using this reference pole is $D_x=8.0°$, $I_x=54.4°$. The 95 per cent confidence limit on the mean pole is 3.3°. Following Beck *et al.* (1986), the flattening of inclination is $F=5.5°\pm4.7°$. Rotation is essentially negligible: $R=-2.1°\pm6.8°$. Using this reference pole, Lesbos has not rotated significantly with respect to Eurasian coordinates since the Miocene but may have moved relatively northwards by ~500 km. However, other scenarios need to be explored.

7 RECORDING ERROR CAUSED BY LOCAL EFFECTS

Could the anomalously shallow magnetization observed in the Lesbos volcanics be due to some property of the rocks or their environment? Mechanisms that have been suggested for other areas include deflection of magnetization into the easy magnetization direction of anisotropic rocks (e.g. Hargraves 1959; Fuller 1963; Uyeda *et al.* 1963), and local magnetic anomalies due to the magnetization and form of the terrain (Baag *et al.* 1995). To evaluate these possibilities, we measured magnetic susceptibility and anisotropy of magnetic susceptibility (AMS) on most samples collected, and anisotropy of anhysteretic remanent magnetization (AARM, McCabe *et al.* 1985) on some. Susceptibilities of most samples were measured before demagnetization. Anisotropies of all specimens that physically survived demagnetization or were non-demagnetized spares were measured later with a KLY-3 instrument. We reduced the anisotropy measurements to site means and their confidence intervals using the bootstrap method of Constable & Tauxe (1990).

Susceptibility is moderate, with site-mean susceptibilty ranging from 2.5×10^{-3} to 4.8×10^{-2} SI. Anisotropies (h of Tauxe *et al.*

1990) ranged from 0.2 to 2.8 per cent, with the mean and median under 1 per cent. There appears to be some tendency for rhyolitic flows and tuffs to have lower susceptibilities and higher anisotropies, andesite flows to have higher susceptibilities and lower anisotropies, and dykes to have higher susceptibilities and anisotropies than flows. However, there appears to be no correlation between susceptibility and anisotropy. Fig. 9 shows examples of the anisotropy of individual sites and the

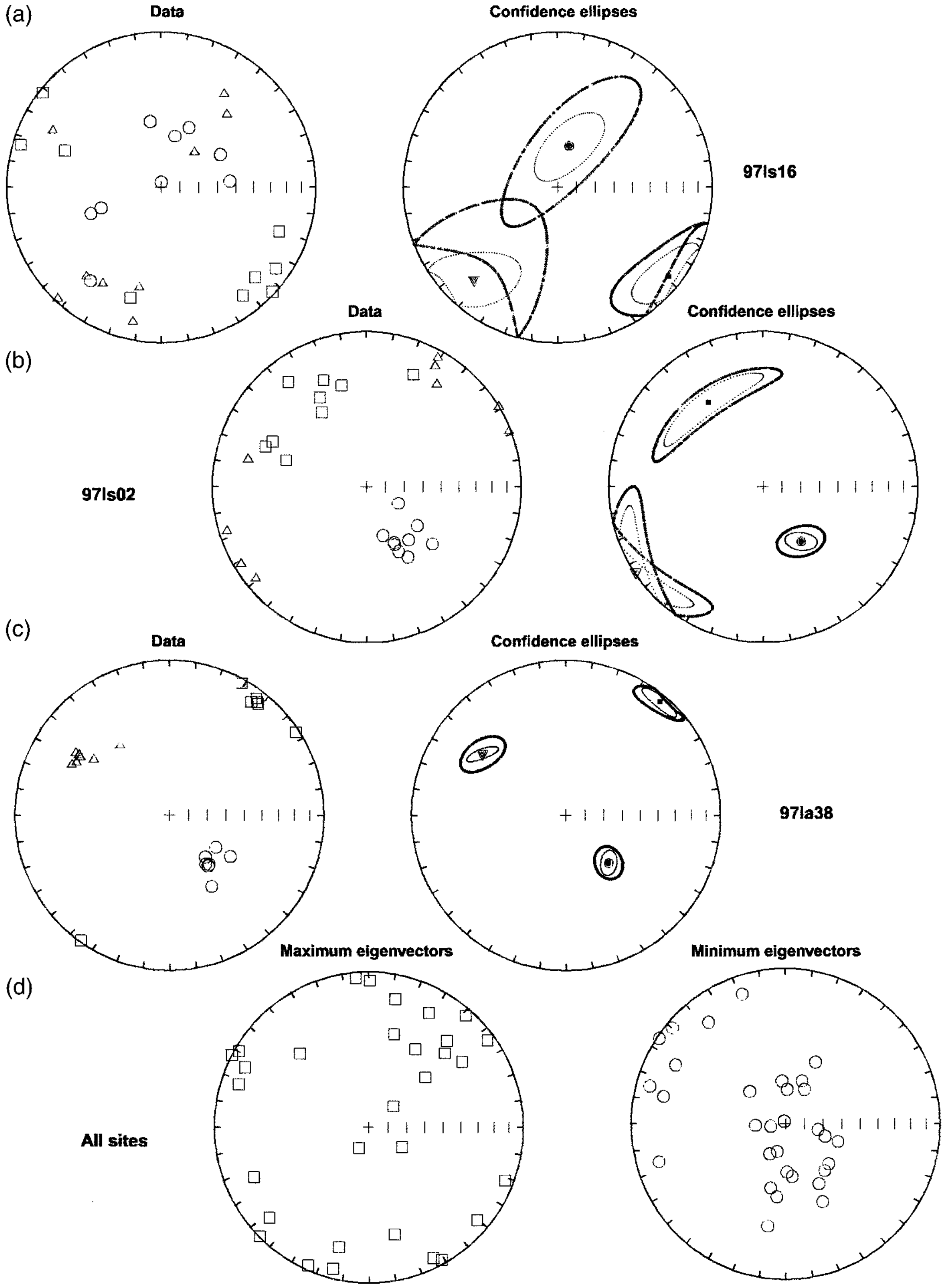

Figure 9. Equal-area plots of AMS data. Points on the lower hemisphere are eigenvectors for maximum (square), intermediate (triangle) and minimum (circle) eigenvalues. Confidence ellipses approximate 95 per cent confidence limits assuming a Kent distribution for bootstrap eigenvectors (inner), and for site parametric bootstrap (outer). (a) Slightly prolate magnetic fabric with considerable scatter from an andesite flow. The flow dips gently NNE; the magnetic foliation dips gently SSW. (b) Rhyolite flow with moderately well-defined oblate magnetic fabric nearly coincident with visual flow fabric. (c) Well-defined triaxial magnetic fabric from another andesite flow. The flow dips gently SE, but magnetic foliation dips more steeply NW. (d) Separate plots for all maximum and minimum eigenvectors. Maxima are fairly scattered but the minima appear to form a larger group with fairly flat foliations and a smaller group with N- to NE- striking steep foliations. Plots after Tauxe (1998).

maximum and minimum susceptibility directions for all sites for which means could be calculated. The steep fabrics (horizontal minimum eigenvectors) are from flows as well as dykes; perhaps the NE–SW orientation of this magnetic foliation and the NE magnetic lineation in other sites reflects a dominant dyke and flow direction.

7.1 Anisotropy

A valid question is whether the AMS measured represents an original fabric that may have influenced directions of magnetization. If demagetization substantially altered magnetic mineralogy or domain state, or if the rocks have an inverse magnetic fabric, our AMS measurements might lead to erroneous conclusions. Thermal demagnetization tended to decrease susceptibilty by up to a factor of 3 for the 15 sites for which that was the primary cleaning method. However, the shapes and orientations of the susceptibility ellipsoids are little different in the few samples for which both thermally and untreated specimens were available. Since it is the shape and orientation that is important in deflection of the remanence (see below) we conclude that the AMS measured after thermal treatment is acceptable.

Static a.f. demagnetization prior to measurement of anisotropy might alter the anisotropy by aligning domains in the applied field direction (Potter & Stephenson 1990). This is a concern for only nine of the 28 accepted sites cleaned primarily with a.f.—specimens from the other 19 were tumbled during demagnetization. However, none of the specimens from these nine sites had principal axes of susceptibility aligned with the specimens axis (which were parallel to the demagnetizing field) as would be expected if such field-impressed anisotropy dominated. As an additional check, the three sites with the greatest scatter of principal axes in geographical coordinates, which might be attributable to field-impressed anisotropy, were re-demagnetized while tumbled, and their AMS re-measured. There was negligible difference between the AMS measured after static versus tumbling demagnetization. We conclude that field-impressed anisotropy is not a factor in any of the statically demagnetized sites.

We also conclude that inverse fabrics are not present. For the rocks measured, single-domain magnetite is the only likely source of inverse fabrics (Rochette *et al.* 1992). To check for inverse fabrics, the AARM was determined for specimens chosen from a third of the sites to represent the range of rocks sampled, their AMS ellipsoid orientations and their magnetic characteristics. We followed a procedure similar to that of Bogue *et al.* (1995) by imparting and measuring an ARM along each axis of a specimen. For all samples the directions of maximum eigenvectors from AMS and AARM agreed closely and for most there was agreement between the intermediate and minimum eigenvectors as well. We verified these results using a more laborious 15-position method on a few specimens.

To test the likely bias by anistotropy we calculated the direction of the ancient field by multiplying the observed remanence vector by the inverse of the matrix describing the magnetic anisotropy (Bogue *et al.* 1995). We did this using mean directions and mean AMS tensors for 31 sites for which adequate AMS data exist. We did the same after increasing the anisotropy by the squares of the ratios of eigenvalues in order to better reflect its influence at elevated temperature (Cogne 1987; Yan & Hu 1993). Our calculations indicate that the field was at most 0.5° steeper than recorded by the ChRM of Lesbos volcanics. Thus AMS cannot explain the anomalously shallow inclination.

7.2 Magnetic terrain effect

Baag *et al.* (1995) described a phenomenon they called the 'magnetic terrain effect', with Hawaii as its type example. According to them, magnetic fields from strongly magnetized, flat-lying lavas at the surface of the island bias the ambient geomagnetic field towards shallow inclinations. They regarded this effect as a general attribute of lava fields.

If the magnetic terrain effect is real, then it is possible that, as in Hawaii, the Lesbos volcanics obtained a direction of remanent magnetization that was slightly shallower than the field direction. However, the effect would not be as great as on Hawaii because susceptibility and magnetization used for modelling the effect on Hawaii were an order of magnitude larger than those measured on Lesbos. Moreover, even if the magnetic terrain effect contributes to the shallow inclination on Lesbos, it cannot explain the anomalous inclination in the Lesbos rocks, for the following reason.

'Concordance' or 'discordance' of a given palaeomagnetic direction is determined by comparison with a reference direction (the 'expected direction'). The reference direction is obtained from a reference pole, part of the APW path of the continent in question. The reference poles themselves are the result of averaging palaeomagnetic studies from the craton. [In the case of the Besse & Courtillot (1991) curves, reference poles are from several cratons and are assembled using finite rotations derived from seafloor magnetic anomalies.] Most reference poles consist mainly of data derived from sedimentary rocks and/or volcanic rocks. Some sedimentary rocks are known to record an anomalously shallow inclination, and according to Baag *et al.* (1995) the same may be true of some volcanic rocks. It follows that reference poles in general should be displaced from the true (geographical) pole by a few degrees in a direction away from the sampling site. [Observations that could be explained by this process were first reported by Wilson (1970)]. From pole lists presented in Besse & Courtillot (1991) it appears that the reference pole used here to compute the expected direction for Lesbos was derived mainly from volcanic rocks. Thus, if the Lesbos volcanics results are contaminated by the magnetic terrain effect, the reference pole should be similarly contaminated, and the two 'effects' should largely cancel one another out. That is, it is legitimate to expect the Lesbos direction to fall within the cluster of directions for the craton, unless Lesbos has moved with respect to stable Europe. The fact that the European cluster may be 'far-sided' (i.e. gives a mean palaeomagnetic pole that is displaced from the true pole position by a few degrees) is irrelevant.

8 THE REFERENCE POLE

Perhaps the reason why the Lesbos inclination appears to be too shallow is simply that the reference pole used is slightly mislocated. The Besse & Courtillot (1991) reference curve was created by combining data from four continents (Eurasia, North America, Africa, India), using standard finite rotations to reverse dispersion caused by plate motion. Thus any error in the finite rotations will carry over into the APW path. An obvious step, then, is to compare the Lesbos direction with reference poles derived solely from Europe.

The reference pole of Irving & Irving (1982) was derived entirely from European data, and it gives a similar result: $F=4.8^\circ \pm 4.6^\circ$, where F is the flattening of inclination and the confidence limits are at 95 per cent. Other reference poles give similar results. For instance, the Vogelsberg volcanics of Germany have radiometric ages of 15.5–18 Ma (Sherwood 1990), which make them almost exactly coeval with the Lesbos volcanics. A slight recalculation (to combine duplicate directions and eliminate sites with poor precision) yields a palaeomagnetic pole for the Vogelsberg volcanics at 85.9°N, 258.6°E, with $N=30$ and $A_{95}=7.1^\circ$. The Vogelsberg data sets are circular ($E_d=1.35$; $E_p=1.79$), and normal and reverse subsets are antipodal. Using this pole yields a flattening of $7.1^\circ \pm 6.8^\circ$. Results of seven studies from volcanic rocks (13–20 Ma) from central Europe summarized by Sherwood (1990) give a mean pole at 80.0°N, 137.1°E, $A_{95}=5.2^\circ$. Referred to this pole, the inclination of the Lesbos volcanics is shallow by $5.6^\circ \pm 5.7^\circ$. Finally, a new study of the Velay Oriental, French Massif Central (Riisager *et al.* 2000) yields a flattening of $4.9^\circ \pm 8.0^\circ$, although at 9–13.5 Ma the rocks involved are slightly too young.

An apparent exception to the rule is the 10–30 Ma pole of Besse & Courtillot (1991), based entirely on European data, which gives a flattening of inclination of $F=1.0^\circ \pm 8.2^\circ$. However, if the Besse and Courtillot reference pole is recalculated by substituting new data for the Vogelsberg volcanics, adding new data from the Massic Central, and excluding results from the Riess, Germany, impact crater (which probably was magnetized in a time too short to average the geomagnetic secular variation), the resulting pole of 81.9°N, 161.9°E ($A_{95}=8.1^\circ$) yields a flattening at Lesbos of $3.7^\circ \pm 7.9^\circ$.

As a final test of the reference pole we rotated the 20 Ma North American pole of Harrison & Lindh (1982) into European coordinates, using the Chron 5 finite rotation pole of Srivastava & Tapscott (1986). This gives a reference point at 86.0°N, 140.2°E, and an expected direction at the centre of Lesbos of $D_x=4.6^\circ$, $I_x=57.0^\circ$. Inclination flattening using this pole is $8.1^\circ \pm 4.8^\circ$, where the error limits probably are too small because error on the rotation pole is not included.

We conclude that the Lesbos inclination is indeed too shallow, by about 5°. If the cause of this anomalous shallowing of inclination is tectonic, it follows that Lesbos has moved about 550 km northwards with respect to stable Europe.

9 CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK

Inclinations found in Tertiary igneous rocks throughout the eastern Mediterranean region are systematically too shallow, when referred to a reference pole for stable Europe. (The same is true for African reference poles: Beck & Schermer 1994.) In this study we set out to test whether something in previous palaeomagnetic methodology might be responsible for this anomaly. The answer is certainly 'no', at least with regard to the Lesbos volcanics: earlier results are entirely correct. It also appears that the reference path is not to blame, because all available alternatives yield essentially the same result.

We return to a tectonic explanation. We do not know enough about the geology of the mountain ranges bordering the Aegean to the north to speculate fruitfully on whether they can accommodate ~500 km of northward encroachment on stable Europe. But the palaeomagnetic evidence suggests precisely that. Perhaps a re-evaluation of the geological evidence is in order.

Further palaeomagnetic tests would be useful. It would be especially helpful to re-visit the Miocene lavas of the Central European volcanic province to refine the Late Cenozoic European reference pole, although the recent work of Sherwood (1990) is convincing. It also would be useful to obtain detailed palaeomagnetic data for older volcanics elsewhere in the Aegean, and at the same time re-examine the relevant point on the European APW path. We have obtained preliminary data for Oligocene rocks from the islands of Lemnos and Samothraki (Kondopoulou, in preparation), and these appear to have an anomalously shallow inclination. The same is true for Oligocene volcanics in Thrace (M. Beck & E. Schermer, unpublished data). The curious pattern of shallow inclinations in Aegean rocks remains unexplained.

ACKNOWLEDGMENTS

Travel was paid by NATO grant CRG-960536. We thank Sarah Nosler, Sarah Amidon and Liam House-Doyle for help in the laboratory. Programs by L. Tauxe were useful in analysing the AMS data. Reviews by L. Brown and M. Wesphal are appreciated. Drafting by Kevin Short.

REFERENCES

Angelier, J., Lyberis, N., Le Pichon, X. & Huchon, P., 1982. The tectonic development of the Hellenic arc and the sea of Crete: a synthesis, *Tectonophysics,* **86,** 159–196.

Atzemoglou, A., Kondopoulou, D., Papamarinopoulos, S. & Dimitriadis, S., 1994. Palaeomagnetic evidence for block rotations in the western Greek Rhodope, *Geophys. J. Int.,* **118,** 221–230.

Baag, C., Helsley, C., Shi-Zhe, X. & Liernert, B., 1995. Deflection of paleomagnetic directions due to magnetization of the underlying terrain, *J. geophys. Res.,* **100,** 10 013–10 027.

Beck, M., 1997. On the probability of selecting a sample with inclination less than the true mean from a circular distribution: paleomagnetic and tectonic implications, *Tectonophysics,* **269,** 317–321.

Beck, M., 1999. On the shape of paleomagnetic data sets, *J. geophys. Res.,* **104,** 25 427–25 441.

Beck, M. & Schermer, E., 1994. Aegean paleomagnetic inclination anomalies. Is there a tectonic explanation? *Tectonophysics,* **231,** 281–292.

Beck, M., Burmester, R., Craig, D., Gromme, C. & Wells, R., 1986. Paleomagnetism of Middle Tertiary volcanic rocks from the Western Cascade Series, northern California, *J. geophys. Res.,* **91,** 8219–8239.

Besse, J. & Courtillot, V., 1991. Revised and synthetic apparent polar wander paths of the African, Eurasian, North American and Indian plates, and true polar wander since 200 Ma, *J. geophys Res.,* **96,** 4029–4050.

Bogue, S., Gromme, C. & Hillhouse, J., 1995. Paleomagnetism, magnetic anisotropy, and mid-Cretaceous paleolatitude of the Duke Island (Alaska) ultramafic complex, *Tectonics,* **14,** 1113–1152.

Cogne, J., 1987. TRM deviations in anisotropic assemblages of multidomain magnetite, *Geophys. J. R. astr. Soc.,* **91,** 1013–1023.

Constable, C. & Tauxe, L., 1990. The bootstrap for magnetic susceptibility tensors, *J. geophys. Res.,* **95,** 8383–8395.

Dankers, P. & Zijderveld, J., 1981. Alternating field demagnetization and the problem of gyromagnetic remanence, *Earth planet. Sci. Lett.,* **53,** 89–92.

Fisher, R., 1953. Dispersion on a sphere, *Proc. R. Soc. Lond., A,* **217,** 295–305.

Fuller, M., 1963. Magnetic anisotropy and paleomagnetism, *J. geophys. Res.,* **68,** 293–309.

Fytikas, M., Innocenti, F., Manetti, P., Mazzuoli, R., Peccerillo, A. & Villari, L., 1984. Tertiary and Quaternary evolution of volcanism in the Aegean region, *Geol. Soc. Lond. Spec. Publ.,* **17,** 687–699.

Fytikas, M., Lombardi, S., Papachristou, M., Pavlides, S., Zouros, N. & Soulakellis, N., 1999. Investigation of the 1987 Lesbos (NE Aegean) earthquake fault pattern based on soil-gas geochemical data, *Tectonophysics,* **308,** 249–261.

Hargraves, R., 1959. Magnetic anisotropy and remanent magnetization in hemo-ilmenite from ore deposits at Allard Lake, Quebec, *J. geophys Res.,* **64,** 1565–1578.

Harrison, C. & Lindh, T., 1982. A polar wandering curve for North America during the Mesozoic and Cenozoic, *J. geophys. Res.,* **87,** 1903–1920.

Irving, E. & Irving, G., 1982. Apparent polar wander paths, Carboniferous through Cenozoic, and the assembly of Gondwana, *Geophys. Surv.,* **5,** 141–188.

Kirschvink, J., 1980. The least-squares line and plane and the analysis of paleomagnetic data, *Geophys. J. R. astr. Soc.,* **62,** 699–718.

Kissel, C., Laj, C., Poisson, A., Savascin, Y., Simeakis, K. & Mercier, J., 1986a. Paleomagnetic evidence for Neogene rotational deformation in the Aegean domain, *Tectonics,* **5,** 783–795.

Kissel, C., Laj, C. & Mazaud, A., 1986b. First paleomagnetic results for Neogene formations in Evia, Skyros, and the Volos region and the deformation of central Aegea, *Geophys. Res. Lett.,* **13,** 1446–1449.

Kissel, C., Kondopoulou, D., Laj, C. & Papadopoulos, P., 1986c. New paleomagnetic data from Oligocene formations on Northern Aegea, *Geophys. Res. Lett.,* **13,** 1039–1042.

Kissel, C., Laj, C., Sengor, A. & Poisson, A., 1987. Paleomagnetic evidence for rotation in opposite senses of adjacent blocks in north-eastern Aegea and western Anatolia, *Geophys. Res. Lett.,* **14,** 907–910.

Kondopoulou, D., 1986. Tertiary rotational deformation in the Greek Serbomacedonian Massif, *Bulg. geophys. J.,* **12,** 71–80.

Kondopoulou, D., 1993. Paleomagnetism of Greece and geodynamic implications: A review of data from Paleozoic, Mesozoic and Cenozoic formations, in *Proc. 2nd Cong. Hellenic Geophys. Un.,* pp. 550–578, ed. Papazachos, B., Zita Publications, Florina.

Kondopoulou, D. & Lauer, J., 1984. Paleomagnetic data for Tertiary units of the North Aegean zone, in *The Geological Evolution of the Eastern Mediterranean,* pp. 681–686, eds Dixon, J. & Robertson, A., Blackwell, Oxford.

Kondopoulou, D. & Westphal, M., 1986. The paleomagnetism of the Tertiary intrusions of Chalkidiki (northern Greece), *J. Geophys.,* **59,** 62–66.

Kondopoulou, D., Leci, V. & Symeakis, C., 1993. Paleomagnetic study of the Tertiary volcanics in Chios Island (Greece), in *Proc. 2nd Cong. Hellenic Geophys. Un.,* pp. 676–688, ed. Papazachos, B., Zita Publications, Florina.

McCabe, C., Jackson, M. & Ellwood, B., 1985. Magnetic anisotropy in the Trenton limestone: results of a new technique, anisotropy of anhysteritic susceptibility, *Geophys. Res. Lett.,* **12,** 333–336.

McFadden, P. & Lowes, F., 1981. The discrimination of mean directions drawn from Fisher distributions, *Geophys. J. R. astr. Soc.,* **67,** 19–33.

Merrill, R. & McElhinny, M., 1983. *The Earth's Magnetic Field,* Academic Press, London.

Merrill, R., McElhinny, M. & McFadden, P., 1998. *The Magnetic Field of the Earth,* Academic Press, London.

Onstott, T., 1980. Application of the Bingham distribution function in paleomagnetic studies, *J. geophys. Res.,* **85,** 1500–1510.

Pavlides, S., Kondopoulou, D., Kilias, A. & Westphal, M., 1988. Complex rotational deformations in the Serbo Macedonian massif (N. Greece): structural and paleomagnetic evidence, *Tectonophysics,* **145,** 329–335.

Pe-Piper, G. & Piper, D., 1993. Revised stratigraphy of the Miocene rocks of Lesbos, Greece, *N. Jb. Geol. Palaont. Mh.,* **1993,** 97–110.

Potter, D. & Stephenson, A., 1990. Field-impressed anisotropies of magnetic susceptibility and remanence in minerals, *J. geophys. Res.,* **95,** 15 573–15 588.

Riissager, J., Perrin, M., Riisager, P. & Ruffet, G., 2000. Paleomagnetism, paleointensity and geochronology of Miocene basalts and baked sediments from Velay Oriental, French Massic Central, *J. geophys. Res.,* **105,** 883–896.

Rochette, P., Jackson, M. & Aubourg, C., 1992. Rock magnetism and the interpretation of anisotropy of magnetic susceptibility, *Rev. Geophys.,* **30,** 209–226.

Sherwood, G., 1990. A paleomagnetic and rock magnetic study of Tertiary volcanics from the Vogelsberg (Germany), *Phys. Earth planet. Inter.,* **62,** 32–45.

Spais, C., 1987. Palaeomagnetic and Magnetic Fabric investigations of Tertiary rocks from the Alexandroupolis area, N.E. Greece, *PhD thesis,* University of Southampton, Southampton.

Srivastava, S. & Tapscott, C., 1986. Plate kinematics of the North Atlantic, in *The Western North Atlantic Region,* pp. 379–404, eds Vogt, P. & Tucholke, B., Geological Society of America, Boulder.

Tauxe, L., 1998. *Paleomagnetic Principles and Practice,* Kluwer Academic Publishers, Dordrecht.

Tauxe, L., Constable, C., Stokking, L. & Badgely, C., 1990. Use of anisotropy to determine the origin of characteristic remanence in the Siwalik red beds of northern Pakistan, *J. geophys. Res.,* **95,** 4391–4404.

Uyeda, S., Fuller, M., Belshe, J. & Girdler, R., 1963. Anisotropy of magnetic susceptibility of rocks and minerals, *J. geophys. Res.,* **68,** 279–291.

Van der Voo, R., 1993. *Palaeomagnetism of the Atlantic, Tethys, and Iapetus Oceans,* Cambridge University Press, Cambridge.

Westphal, M., 1993. Did a large departure from the geocentric axial dipole hypothesis occur during the Eocene? Evidence from the magnetic polar wander path of Eurasia, *Earth planet. Sci. Lett.,* **117,** 15–38.

Westphal, M. & Kondopoulou, D., 1993. Paleomagnetism of Miocene volcanics from Lemnos island: implications for block rotations in the vicinity of the north Aegean trough, *Ann. Tect.,* **7,** 142–149.

Westphal, M., Bazhenov, M., Lauer, J., Pechersky, M. & Sibuet, J., 1986. Paleomagnetic implications of the evolution of the Tethys belt from the Atlantic ocean to the Pamirs since the Triassic, *Tectonophysics,* **123,** 37–82.

Westphal, M., Kondopoulou, D., Edel, J. & Pavlides, S., 1991. Paleomagnetism of the late Tertiary and Plio-Pleistocene formations from N. Greece, *Bull. geol. Soc. Greece,* **25,** 239–250.

Wilson, R., 1970. Permanent aspects of the Earth's non-dipole magnetic field over Upper Tertiary time, *Geophys. J. R. astr. Soc.,* **19,** 417–438.

Yan, G. & Hu, S., 1993. The correction of TRM deviation induced by AMS and its application, *J. Geomag. Geoelectr.,* **45,** 495–502.

Zouros, N. & Fytikas, M., 1997. Post-Congress field trip to Lesbos Island, *29th Gen. Ass. IASPEI,* pp. 5–39, eds Zouros, N. & Fytikas, M., IASPEI, Thessaloniki.