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Palaeomagnetism of a Jurassic Ophiolite Series in East Elba (Italy)

H. Soffel

Institut für Allgemeine und Angewandte Geophysik, Universität München, Theresienstraße 41, D-8000 München 2, Federal Republic of Germany

Abstract. Thirty-nine sites from the East Elba (10.3° E, 42.8° N) ophiolite series, of Upper Jurassic age, with gabbro, diabase, pillow lava and radiolarite have been studied with regard to their rock magnetic and palaeomagnetic properties. After tectonic corrections yielding a positive fold test at the 99% level, 25 sites (23 reversed, 2 normal) had the following mean remanence direction: $N=25$, $R=23.7429$, $D=199.3°$, $I=-38.0°$, $k=19.0909$, $\alpha_{95}=6.4°$. There was no significant difference at the 95% level between the mean directions of the radiolarites and the magmatic rocks. Rock magnetic studies as well as a comparison of the observed predominance of reversed polarities with the Post Jurassic polarity time scale suggest a post genetic age of the most stable remanence component (Lower to Middle Cretaceous, around 120 m.y.). This conclusion is supported by the agreement of the observed inclination with inclinations predicted for East Elba from Lower to Middle Cretaceous (120 m.y.) pole positions from Africa and the Umbrian sequence on the Italian mainland. The pole position for the East Elba ophiolites is at 147.3° E, 63.2° N. The pole position for Africa is at 267° E, 48° N for an age of 120 m.y., for the Umbrian sequence it is at 281° E, 35° N, while for Eurasia it is at 153° E, 70° N. The predicted palaeodeclinations for East Elba indicate a Post Middle Cretaceous clockwise rotation of the East Elba ophiolites of 64° with respect to Africa and 82° with respect to Umbria, while the rotational movement with respect to Eurasia is not significant. As the East Elba ophiolites are a small allochthonous unit of rather limited lateral extent, no deductions concerning the rotation of autochthonous Elba or autochthonous Italy can be made. The Koenigsberger ratio of the rocks investigated was in general smaller than unity resulting in a predominance of the induced magnetization. This information, in combination with the post genetic origin of remanence, seems to be of importance for the interpretation of Mesozoic marine magnetic anomalies in the Mediterranean.

Key words: Palaeomagnetium – Ophiolites – Elba.

1. Introduction

Palaeomagnetic measurements indicate that there have been rotational movements in the Mediterranean region since the Upper Cretaceous (Van der Voo and Zijderveld 1969; De Jong et al. 1973; Van den Berg et al. 1975; Soffel 1978). These rotations are related to the collison and subsequent relative displacement of the African and European plates. The angle of counterclockwise rotation varies between 30° and 60°. The data from the Italian peninsula South of the Po Basin have mostly been obtained from allochthonous or parautochthonous pelagic sediments (limestones) from the Apennines. Nevertheless they seem to be indicative of the rotational movement of the Italian peninsula since Upper Mesozoic. Pre-Tertiary magmatic rocks are exposed in the Tuscany region in the form of an Upper Jurassic ophiolite sequence with serpentinites, gabbros, diabases, pillow lavas and radiolarites. A well exposed sequence outcrops in the Eastern part of Elba. An attempt was made to investigate the rock magnetic and palaeomagnetic properties and to compare the results with those obtained from the adjacent plates (Africa, Eurasia, Adria) and to get information about the origin of remanence of rocks formed on the bottom of an ocean.

2. Geology and Sampling

The geology of West Elba is dominated by the large granitic intrusion of Monte Capanne, with an age of 6 m.y. (Ferrara et al. 1961; Borsi et al. 1967). Smaller granitic bodies occur in the Central and Eastern parts of the island, where a larger subsurface granitic intrusion of the same age as the Monte Capanne granite has been confirmed by drilling (Bonadonna, private communication 1978). The geology of East Elba is more complicated. Autochthonous gneisses (complex I, after Trevisan 1953) above the granitic intrusion are overlain by allochthonous series of Upper Carboniferous to Lower Jurassic age showing various degrees of metamorphism (complexes II and III). On top of complex III is the allochthonous ophiolite series of East Elba (complex IV), striking NS and dipping between 30° and 50° west. The legend on the geological map of Elba (Trevisan and Marinelli 1967) indicates that the age of the ophiolite complex is Malm (Upper Jurassic). Middle to Upper Jurassic ages (165 ± 23 m.y.) have been confirmed by radiometric dating of ophiolites from the Northern Apennines, including samples from East Elba (Bigazzi et al. 1972; Bigazzi et al. 1973). The ophiolite complex is overlain by complex V consisting of non-metamorphic Upper Cretaceous to Lower Tertiary flysch sediments.

The ophiolite series is composed (from the bottom to the top) of serpentinite, gabbro, mostly spilitized diabase, pillow lava, chert and radiolarite. The contact of the pillow lavas with the overlying radiolarites is undisturbed in many places, allowing tectonic corrections to be made. However, in some places the tectonic situation was uncertain due to local structures leading to the exclusion of several otherwise suitable palaeomagnetic sampling localities.

The East Elba ophiolites seem to be closely related if not identical to those in Liguria studied by Decandia and Elter (1972).

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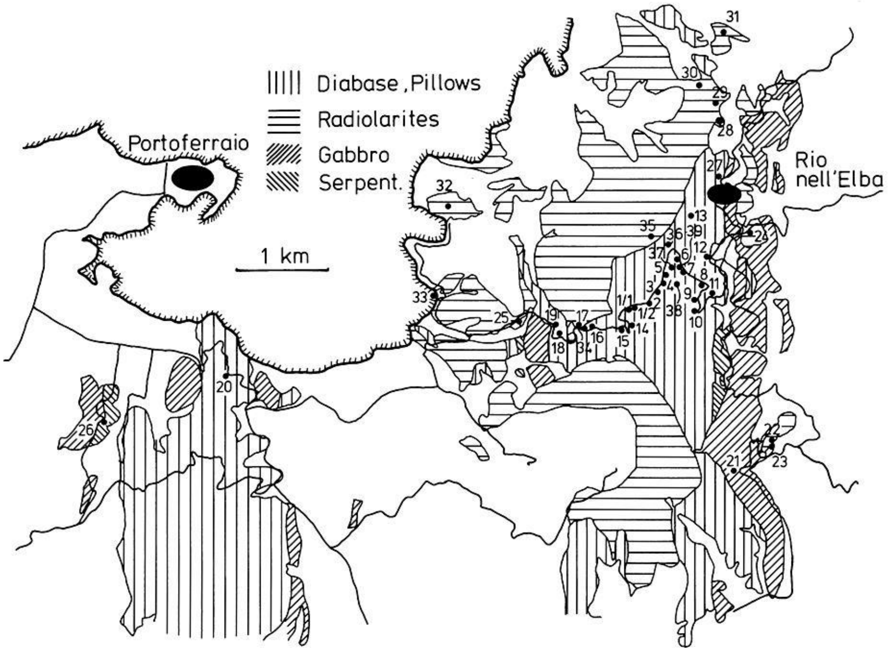

Fig. 1. Sketch map of the geology of NE Elba showing the sampling sites. Numbers refer to those in Table 1

The Ligurian ophiolites at least underwent in situ metamorphism (Cortesogno et al. 1975). Such an in situ metamorphism will also be discussed later in Sect. 4 of this paper. A review on the Ligurian ophiolites has recently been published by Cortesogno et al. (1978). Similar studies on East Elba ophiolites have been made by Horner (1974).

A sketch map of the sampling sites is shown in Fig. 1 (redrawn from Trevisan and Marinelli 1967). Thirty-nine localities with exposures of gabbro, diabase, pillow lava, chert and radiolarite were sampled. For details see Table 1. Most samples were taken with a portable drilling machine; however, from part of the very hard and brittle radiolarites oriented hand samples were taken.

3. Palaeomagnetic and Rock Magnetic Studies

3.1. Natural Remanent Magnetization (NRM)

The site mean directions of NRM are extremely scattered (see Fig. 2 and Table 1). However, there is some indication of a somewhat scattered, great circle distribution between the present geomagnetic field direction in the sampling area (star in Fig. 2) and a reversed direction in the third quadrant at approximately $D = 200°$, $I = -60°$. This direction is close to the mean directions (before tectonic correction) of all sites found after the application of various cleaning techniques (see Fig. 7). The mean intensities of NRM are variable within the different petrographic units, averaging around 50×10^{-6} G. The radiolarites had about the same intensity of NRM as the underlying pillow lavas, which was quite surprising. The Koenigsberger ratios are in general less than unity. Some of the extremely high values of NRM of several diabase cliffs are presumably due to lightning-strikes. For some sites (Nos. 1/1, 1/2, 3, 34, see Table 1) the NRM was so scattered that a mean direction was computed only for a few well grouped samples.

3.2. Demagnetization Experiments and Rock Magnetic Studies

From each sampling site at least one specimen was demagnetized with alternating fields up to 2,000 Oe. Several specimens from each petrographic unit were also thermally demagnetized up to 650° C. Examples of the variation of remanence during alternating field (AF) and thermal demagnetization treatment of radiolarites and magmatic rocks are shown in Fig. 3. As already indicated by the more or less well developed great circle distribution of Fig. 2, the NRM was only in a few cases a single component remanence. In the As-Zijderveld plots of Fig. 3a–d the dots are data points in the horizontal plane while the triangles are those in a vertical North-South directed plane with W being its Northern end.

Figure 3a shows a typical variation of NRM of the pillow lavas (here a specimen from site 1/1) during AF demagnetization up to 2,000 Oe. While the NRM direction remains practically unchanged during demagnetization, the intensity varies considerably. Firstly there is an increase by a factor of about two between NRM and 50 Oe, and a decrease to about two thirds of the initial NRM intensity between 50 and 75 Oe; this is followed by another increase by a factor of three between 75 and 1,500 Oe. Finally there is a drop of about 20% between 1,500 and 2,000 Oe. The intensity after 2,000 Oe is about 50% larger than the NRM. Four approximately antiparallel remanence components seem to be present: (1) an extremely stable reversed component with coercive forces larger than 2,000 Oe; (2) a less stable normal component with a maximum coercive force of 1,500 Oe; (3) a reversed unstable component with a narrow coercivity range between 50 and 75 Oe (this component was often not observed) and (4) a still softer normal component (approximately in the direction of the present geomagnetic field) with a maximum coercive force of 50 Oe.

An example for a thermal demagnetization of a specimen from site 1/2 (pillow lava, close to site 1/1) is presented in Fig. 3b. By stepwise heating and cooling (in zero magnetic field) the NRM intensity increases and reaches a maximum of about twice the NRM intensity after thermal demagnetization at 250°–300° C. At higher temperatures there is a steady decay of remanence without major directional change. From the aspect of the blocking temperatures the following remanence components seem to be present: (1) a reversed component with blocking temperatures higher than 580° C (Curie temperature of magnetite); (2) a likewise reversed component with blocking temperatures mainly between 400° and

Table 1. Palaeomagnetic data

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1/1	Pillow	210/50 W	4	242.2	−36.6	7.8	25.1	500	7	239.5	−45.7	14.1	14.1	181.7	−46.3
1/2	Pillow	210/50 W	6	225.4	−29.5	6.7	22.1	750–1,000	7	224.6	−31.1	10.3	16.5	192.7	−29.7
2	Pillow	210/50 W	7	287.7	40.0	7.8	18.9	No consistent direction							
3	Pillow	Dubious	9	350.9	75.0	27.8	8.9	2,000	10	142.0	−48.4	9.0	14.8		
4	Pillow	210/50 W	13	318.3	69.9	5.9	16.0	No consistent direction							
5	Pillow	210/50 W	8	275.4	−75.6	9.2	16.3	No consistent direction							
6	Pillow	210/35 W	10	321.2	39.8	8.7	15.0	500–1,500	6	220.4	−23.7	8.9	19.2	204.0	−25.1
7	Pillow	210/35 W	9	237.9	53.4	8.8	15.7	500–750	5	210.0	−31.0	29.6	11.5	191.0	−25.0
8	Pillow	210/40 W	7	46.4	29.1	10.4	16.4	No consistent direction							
9	Pillow	210/35 W	10	272.5	−10.9	21.4	9.6	1,000–1,500	8	231.4	−36.9	11.0	14.9	201.9	−41.2
10	Pillow	Dubious	10	260.6	−45.5	6.3	17.6	500–1,000	10	293.5	−67.9	8.8	14.9		
11	Pillow	Dubious	7	351.1	−18.6	5.9	21.8	2,000	7	58.6	−73.1	3.9	26.9		
12	Pillow	210/35 W	10	203.8	−26.3	6.6	17.2	500–750	10	220.3	−42.1	18.1	10.4	189.3	−38.7
13	Pillow	Dubious	11	122.8	59.2	7.9	15.0	500–750	11	359.2	−80.7	18.6	9.8		
14	Pillow	Dubious	13	2.3	69.7	46.0	5.7	1,250	5	139.8	−56.4	18.1	14.7		
15	Pillow	240/55 W	8	274.0	58.3	5.7	20.7	500–2,000	8	262.7	−42.2	10.8	15.1	210.5	−38.3
16	Pillow	240/55 W	10	347.6	5.8	7.5	16.2	500–1,500	8	291.8	−47.5	13.4	13.5	204.4	−59.1
17	Pillow	240/55 W	11	285.4	− 0.4	3.0	24.4	1,500	11	255.9	−40.8	6.3	16.8	210.2	−33.0
18	Pillow	240/55 W	10	36.4	68.7	4.3	21.4	No consistent direction							
19	Gabbro	Dubious	11	109.0	−87.5	4.9	19.1	200–750	9	78.0	−76.4	11.4	13.8		
20	Diabase	Dubious	7	353.7	53.1	13.8	14.2	1,500	5	305.7	−41.3	13.1	17.3		
21	Gabbro	Dubious	10	358.1	51.3	30.5	8.0	No consistent direction							
23	Chert	240/35 W	9	198.4	−57.1	42.8	7.1	300	9	204.3	−48.6	27.5	8.9	185.7	−23.1
25	Diabase	180/50 W	12	33.6	1.1	6.8	15.5	1,500	12	29.3	−12.6	28.3	7.6	29.1	13.0
26	Gabbro	180/50 W	8	8.0	46.4	7.9	17.6	1,500–2,000	8	46.7	−12.7	33.1	8.6	43.0	23.7
27	Diabase	210/40 W	7	335.2	42.2	15.5	13.4	300	4	234.9	−51.8	8.2	24.4	181.4	−50.3
28	Radiol.	210/35 W	10	186.5	−49.5	20.6	9.8	400	10	199.1	−48.0	75.4	5.1	171.1	−32.4
29	Radiol.	250/30 W	11	191.3	−48.3	177.2	3.2	400	11	195.7	−48.8	145.5	3.5	184.6	−22.6
30	Radiol.	280/20 W	15	Scattered				400	15	248.8	−56.0	41.7	5.6	230.7	−42.8
31	Radiol.	280/20 W	10	240.7	−52.9	51.2	6.2	400	10	248.6	−64.3	151.2	3.6	225.4	−50.3
32	Radiol.	10/20 E	5	202.0	−53.4	6.2	25.1	400	4	190.8	−44.4	10.2	21.9	209.2	−40.8
33/1	Pillow	250/30 W	8	192.2	−65.1	8.2	17.3	200	8	260.2	−66.4	4.0	24.8	204.8	−56.0
33/2	Pillow	250/30 W	10	238.2	−47.6	46.1	6.5	1,000	10	238.7	−52.7	85.1	4.8	209.9	−39.0
34	Radiol.	240/55 W	9	236.7	−62.9	39.3	7.4	400	10	231.7	−68.0	62.5	5.6	175.1	−29.2
35	Radiol.	240/50 W	15	232.8	−55.7	20.0	8.1	400	15	214.8	−60.4	36.3	6.0	179.2	−23.4
36	Diabase	240/50 W	11	Scattered				500	11	238.8	−50.2	11.6	12.4	197.0	−28.9
37	Diabase	Dubious	9	Scattered				1,000–1,500	9	201.1	26.0	21.8	10.0		
38	Diabase	240/50 W	8	Scattered				2,000	8	284.1	−30.1	9.2	16.3	240.3	−51.6
39	Diabase	210/50 W	6	Scattered				750–1,000	6	254.2	−42.1	13.1	15.8	191.2	−55.8

1 Site number (see Fig. 1); 2: rock type; 3: strike/dip; 4–8: NRM data. 4: Number of samples used for calculation of the site mean direction; 5: declination in °E; 6: inclination; 7: precision parameter *k*; 8: α_{95}, semiangle of 95% cone of confidence; 9: peak alternating field; 10–14: RM data after partial demagnetization. 10: Number of samples; 11 declination in °E; 12: inclination; 13: precision parameter *k*; 14: α_{95} semiangle of 95% cone of confidence; 15 and 16: declination and inclination respectively, after tectonic correction

580° C; (3) a normal (approximately parallel to the present geomagnetic field) component with maximum blocking temperatures below 300° C.

Figures 4a and b show polished sections of a pillow lava from sites 12 and 1/2. The characteristic ore composition of this rock type is: (1) highly oxidized titanomagnetites (see Fig. 4a) with an oxidation class VI, after Ade-Hall et al. (1968) and (2) an occasionally large abundance of hematite needles (see Fig. 4b) in the silicates. The oxidized titanomagnetites consist of a cubic magnetic mineral (magnetite) and exsolution lamellae of an anisotropic phase (ilmenite). There is also some evidence for a low temperature oxidation in the form of secondary hematite along the margins and cracks. The hematite needles are about 10 μm long and 1 μm wide. Sometimes they are clustered together forming a sort of network in the reddish silicates.

Saturation magnetization versus temperature curves (J_s/T) are presented in Fig. 5. Figure 5a shows the heating and cooling curve of a pillow lava from site 4. Typical for this rock type is an initial increase of the saturation magnetization (measured at 5,000 Oe in air) between room temperature and about 160° C, then a decay with a slight kink in the gradient of the curve at about 450° C. The main Curie temperature of the heating curve is at 590° C. Some amount of saturation magnetization is still present and remains unchanged (no hyperbolic decay!) up to temperatures above 600° C (highest temperature possible for the apparatus). Similar J_s/T curves with a kink at temperatures below 200° C have been found by Ade-Hall et al. (1971) on highly altered basalts from Iceland. The cooling curve shows a Curie temperature at 580° C, which is 10° lower than that of the heating curve. This effect is not due to a temperature hysteresis of the instrument because it does not appear when pure magnetite is measured. It has often been observed by the author on exsolved titanomagne-

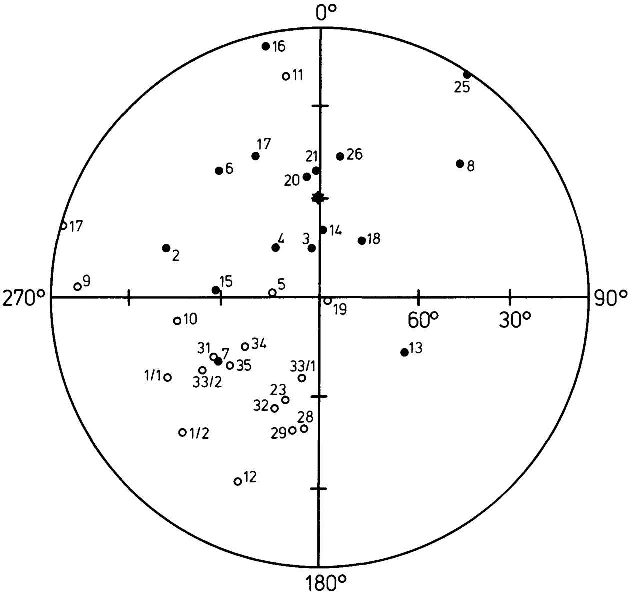

Fig. 2. Site mean directions of NRM in equal area projection. *Closed and open symbols*. positive and negative inclination respectively. *Star:* present geomagnetic field direction in the sampling area. *Numbers* refer to site numbers (Fig. 1, Table 1)

tites and is believed to be caused by diffusion of titanium from the titanium rich phase forming the exsolution lamellae (ilmenite?) back into the magnetite of the groundmass. None of the kinks at 160° and 450° C are seen on the cooling curve, which lies about 25% below the heating curve.

A further set of experiments is shown in Fig. 6, where the isothermal remanence (IRM) is plotted versus the exciting field in Oe. The data (normalized for the highest IRM intensity obtained) of pillow lavas and diabases are plotted in Fig. 6a and will be discussed below.

The observation of the demagnetization experiments (AF and thermal), the polished section studies, the J_s/T curves and IRM/H data are interpreted as follows. The main carrier of saturation magnetization of the magmatic rocks are titanomagnetites which have been almost entirely altered to magnetite plus another titanium rich phase (possibly ilmenite) by high temperature oxidation. This high temperature oxidation also affected the silicates (red colour). From the polished section studies it remains uncertain whether the exsolution of the titanomagnetites and the formation of hematite needles occurred simultaneously. Nevertheless the hematite does not contribute much to the saturation magnetization. Needle shaped hematite is not present in the diabases underlying the pillow lavas. Hematite (if present) is always found here along cracks and margins as a product of low temperature oxidation. The irreversible kink at around 160° C (see Fig. 5a) seems to be due to remnants of the primary titanium rich titanomagnetite (about TM 65, according to Bleil 1973). By heating above 600° C this phase is destroyed and probably also converted into magnetite plus ilmenite. The J_s/T curve shows a negative magnetostatic coupling between the (probably primary) TM 65 and the magnetite. The irreversible kink at 400°–450° C (which is much more pronounced in the diabases than in the pillow lavas) indicates the collapse of a minor amount of metastable titanomaghemite phases.

The dominance of magnetite in the diabases and in part also in the pillow lavas is also demonstrated in the IRM/H plots of Fig. 6a. Samples from sites 38 and 39 are diabases with altered (exsolved and/or low temperature oxidized) titanomagnetites without visible hematite needles and only minor amounts of secondary hematite along cracks and margins. They saturate as expected at fields below 3,000 Oe. Most of the pillow lavas containing hematite needles have IRM/H-curves similar to those of samples from sites 27 and 33.2 in Fig. 6a. After an initial saturation at a few thousand Oe (indicative of magnetite) the final saturation is obtained between 8,000 and 10,000 Oe (indicative of hematite). The sample from site 37 obviously has only a little magnetite besides hematite. The NRM at this site was extremely scattered and a stable endpoint could not be obtained with AF demagnetization (see Table 1).

From the above discussion it can be concluded that the magmatic rocks have essentially three major remanence components: (1) a normal component (with approximately the present geomagnetic field direction) with blocking temperatures below 300° C and maximum coercive forces below 1,500 Oe. There is evidence from the J_s/T curves, IRM/H data and polished section studies that this remanence resides in the magnetite. It is interpreted as a viscous component acquired in the local geomagnetic field. (2) A reversed component with maximum blocking temperature of 580° and a maximum coercive force of 1,500 Oe, eventually a little higher. The experiments indicate that this component is also located in the magnetite. It carries information about a reversed geomagnetic field at the time when most of this mineral was formed by an oxidation process. Section 4 of this paper discusses whether this oxidation process was syngenetic or a later event. (3) The third and likewise reversed component is not so clearly evident from the AF demagnetization experiments. It resides in a phase with coercive forces well above 2,000 Oe and blocking temperatures of at least 650° C. The experiments (J_s/T, IRM/H) point to hematite as the carrier of this remanence component. This component is strongest in the pillow lavas containing the hematite needles and less pronounced (or even absent) in the diabases, where the rarely occurring hematite is a product of low temperature oxidation. The coincidence of the remanence directions of the two reversed components indicate that formation of the hematite needles and the high temperature oxidation of the titanomagnetites occured at the same time.

The analysis of the rock magnetic and palaeomagnetic properties of the radiolarites is no less complicated. Figure 3c shows the results of the AF demagnetization of a typical specimen (site 30). All radiolarites (except many specimens from site 30 which had large superimposed viscous components) already had a quite well grouped reversed NRM direction (see Table 1). With a small directional change, the test specimen (Fig. 3c) shows a large drop of intensity between NRM and 200 Oe. At higher demagnetizing fields the intensity is only slightly reduced and the direction remains constant. Three main remanence components are present (1) a normal component (roughly parallel to the present geomagnetic field) with a maximum coercive force of about 200 Oe. (2) A reversed component with a maximum coercive force of about 500 Oe and (3) another reversed component of the same direction with coercive forces larger than 2,000 Oe. A sharp drop of NRM intensity could also be observed during thermal demagnetization (Fig. 3d, also a specimen from site 30). The strong component, which is removed between room temperature and 150° C, differs considerably in direction from the remaining component. For most sites this soft component was weak and roughly aligned along the present geomagnetic field, but for site 30 alone it was strong and almost randomly scattered. After 150° C the remanence decays steadily without systematic changes in direction towards zero. (The kinks in the plot may be due to secondary components originating

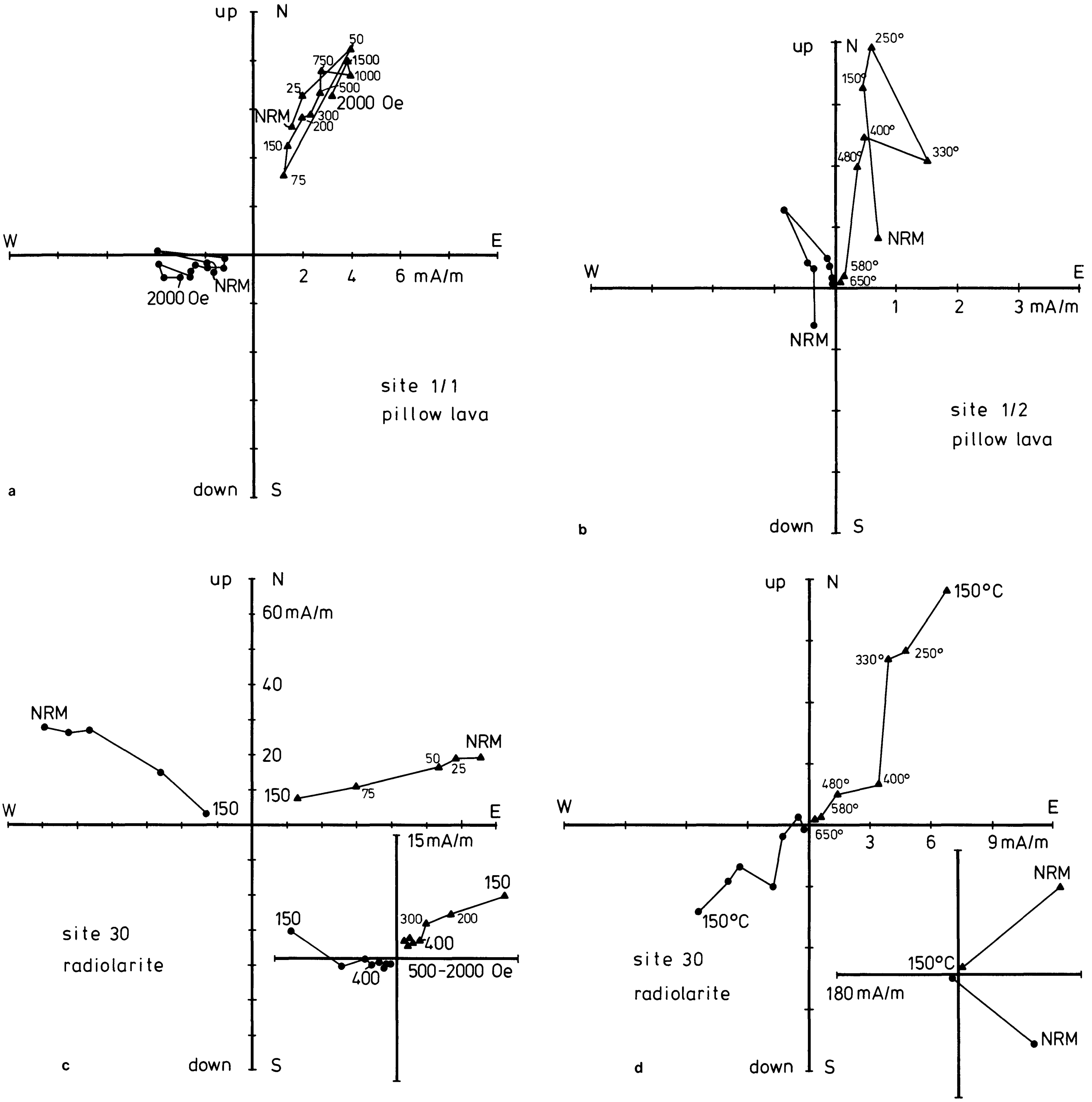

Fig. 3a–d. As-Zijderveld diagrams showing the variation of the remanence vector during progressive AF and thermal demagnetization. *Dots*. data points in the horizontal plane. *Triangles*. data points in a vertical North-South directed plane with W being its Northern end. **a** AF demagnetization of a pillow lava specimen from site 1/1. **b** Thermal demagnetization of a pillow lava specimen from site 1/2. **c** AF demagnetization of a radiolarite specimen from site 30. **d** Thermal demagnetization of a radiolarite specimen from site 30

from imperfections of the thermal demagnetizing equipment and uncontrolled field variations in the laboratory). At 580° C (Curie temperature of magnetite) there is still some remanence left which is further reduced at 650° C. Two remanence components seem to be present: (1) a soft component either parallel to the present geomagnetic field or randomly scattered with blocking temperatures below 150° C. (2) A reversed component with blocking temperatures higher than 650° C.

Figure 4c shows a polished section of a radiolarite from site 30 containing fragments of exsolved titanomagnetite grains, isolated hematite needles as well as fragments of silicates with hematite needles inside. The ores are similar to those found in the underlying pillow lavas and diabases. It can therefore be concluded that the remanence of the radiolarites is located mainly in detritus of the magmatic rocks underneath.

Figure 5b represents the heating and cooling J_s/T curve of

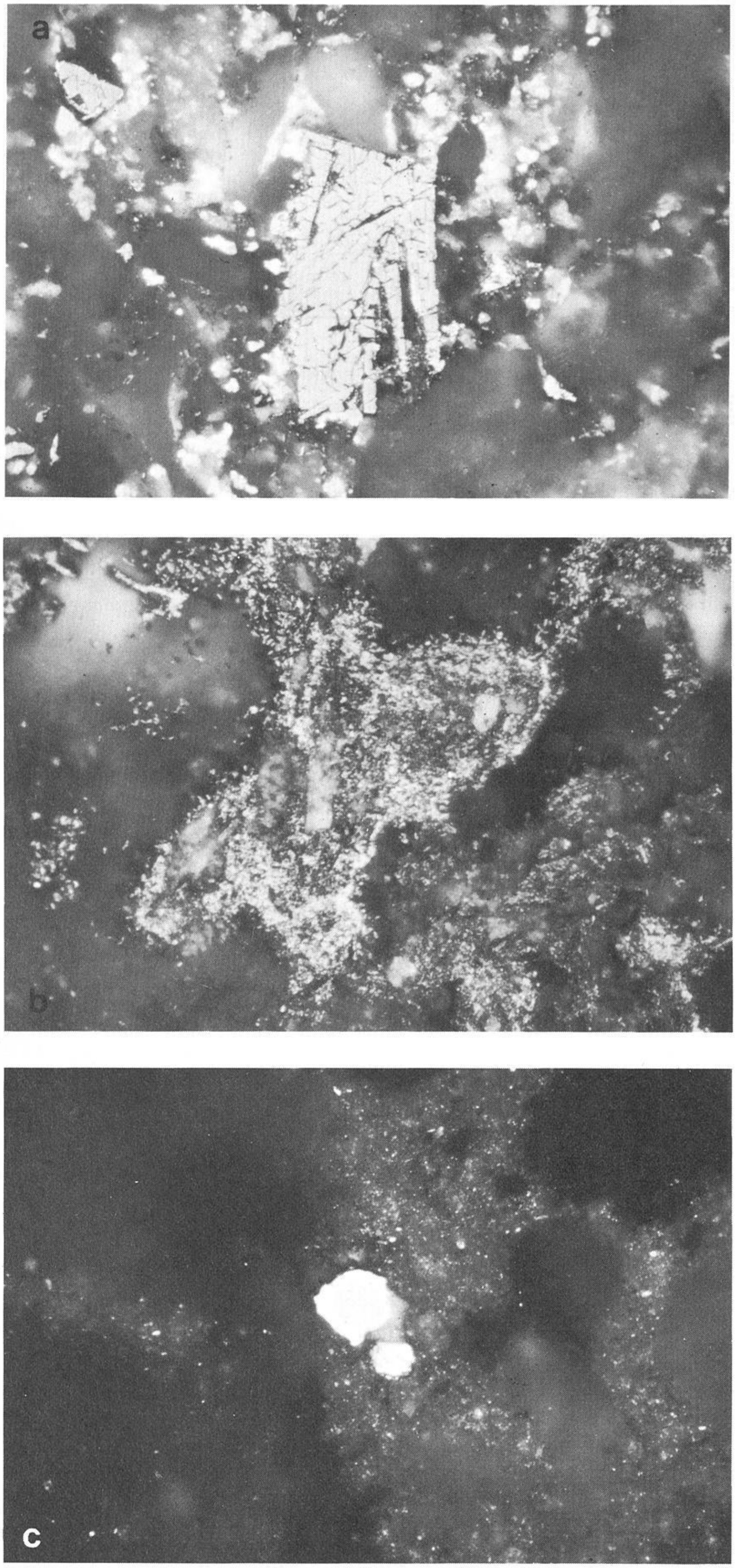

Fig. 4a–c. Polished sections. The long side of the figures corresponds to 270 µm.
a Pillow lava from site 12. Highly oxidized titanomagnetite grain with exsolved magnetite and ilmenite
b Pillow lava from site 1/2. Hematite needles in the silicates
c Radiolarite from site 30. Detrital magnetite grain and hematite needles

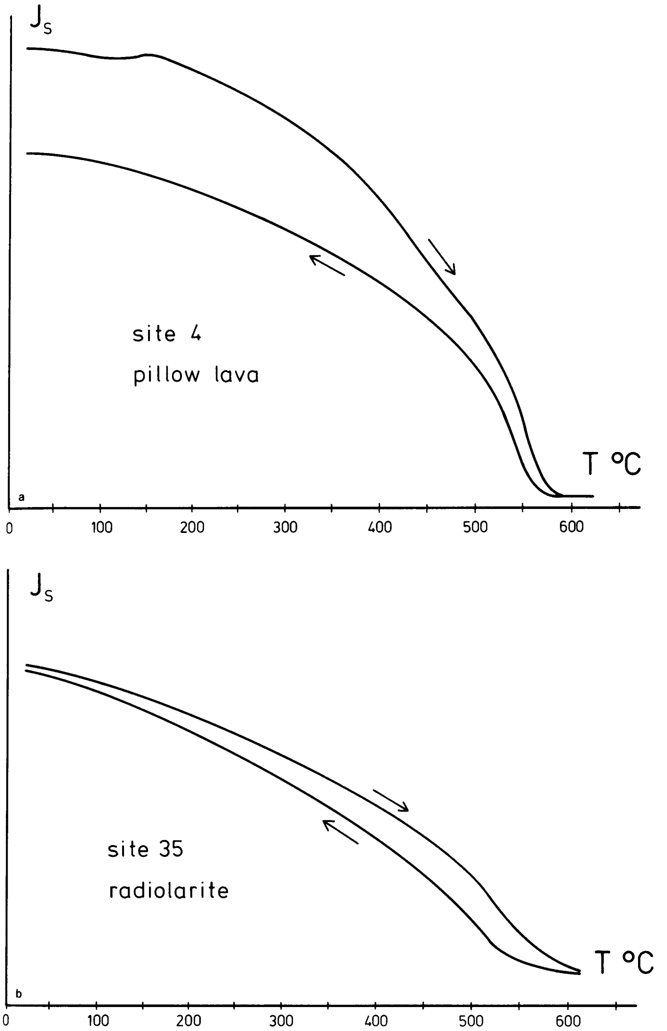

Fig. 5a and b. Saturation magnetization (in arbitrary units) versus temperature. **a** Powder of a pillow lava from site 4. **b** Separated magnetic material from a radiolarite specimen of site 35

a magnetic concentrate of radiolarites from site 35. The major phase has a Curie temperature of 550° C (close to magnetite). Above 600° C some hematite component may be responsible for the remaining intensity of J_s. The IRM/H plots (Fig. 6b) of radiolarites from several sites are more or less identical. Saturation is achieved in fields between 10,000 and 13,000 Oe. Magnetite, though the dominant phase in the J_s/T curves, does not contribute much to the IRM. This may, to a large extent, be due to the imperfect separation of the entire ore content by the hand magnet technique. The saturation field (10,000–13,000 Oe) points to coarse grained hematite as the main carrier of IRM. Goethite seems to be absent. Otherwise a saturation of IRM could not have been obtained below 15,000 Oe.

The experiments indicate that magnetite and hematite, probably both derived as detritus from the underlying magmatic rocks are the carrier of the remanence in the radiolarites. Geothite as a secondary mineral seems to be absent. Both magnetite and hematite carry a stable reversed remanence direction. This is demonstrated by the thermal demagnetization experiments. The question of the origin of the quite homogeneous reversed magnetization of the radiolarites (no normal polarities have been found so far in the whole sequence) are discussed in Sect. 4.

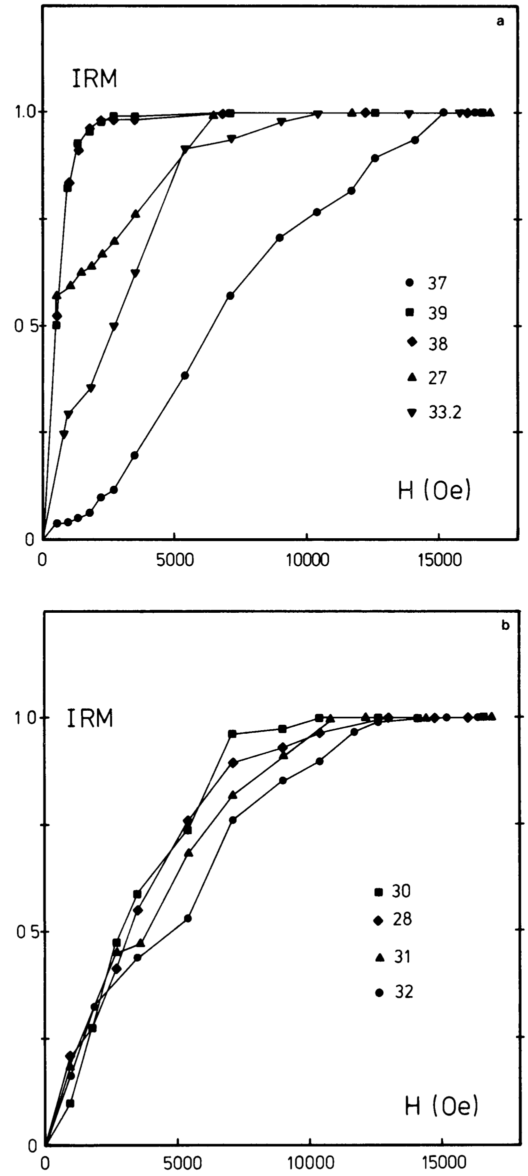

Fig. 6a and b. Isothermal remanence (IRM) as a function of the generating field H, normalized to the maximum value of IRM. Numbers refer to site numbers. For details see text. **a** Specimens of magmatic rocks. **b** Radiolarite specimens

3.3. Palaeomagnetic Results

For some sites, a consistent mean direction could not be found for a statistically sufficient number of individual samples or specimens. Except for these cases the isolated most stable directions before tectonic correction are listed in Table 1 and plotted in Fig. 7. For nine sites (3, 9, 11, 14, 20, 23, 27, 29, 33/1) the scatter of NRM was smaller than that of the isolated most stable remanence component (see precision parameter in Table 1). In most cases (sites 3, 9, 11, 14, 20, 27) this was due to the presence of a large secondary component by which all vectors grouped along the present geomagnetic field in the sampling area irrespective of the scatter of a small stable (reversed) component. After the removal of the softer (normal) component the intensity of the stable reversed component was often smaller than 10^{-6} G

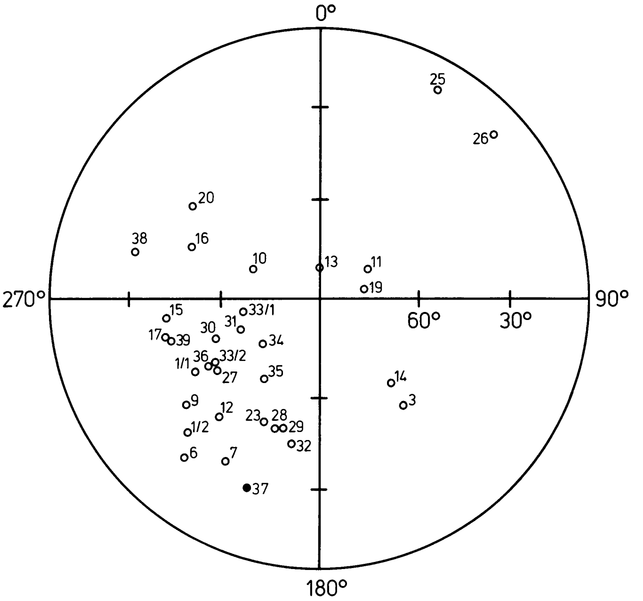

Fig. 7. Site mean directions after AF demagnetization without tectonic corrections. For symbols see legend of Fig. 2

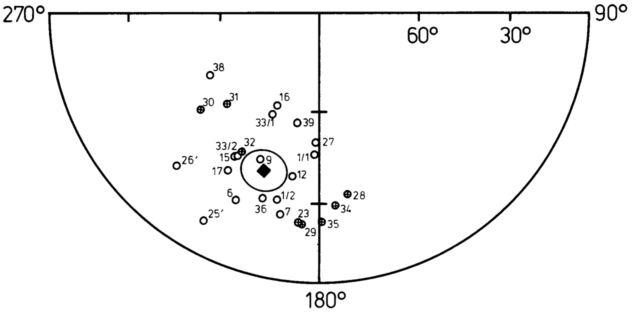

Fig. 8. Site mean directions after AF demagnetization with tectonic corrections. The directions of sites 25 and 26 have been reversed, all sites with dubious tectonic position have been omitted. *Square:* mean of all 25 directions together with cone of confidence. For symbols see legend of Fig. 2. Radiolarite sites are marked by a central cross

so that the noise level of the spinner magnetometer (Digico) was approached.

The mean remanence direction of the 25 palaeomagnetically suitable sites before tectonic correction is: $N=25$; $R=22.4117$; $D=232.2°$; $I=-45.4°$; $k=9.2724$; $\alpha_{95}=9.2°$ Application of structural corrections, omitting all sites with uncertain tectonic position (see Table 1), reduced the scatter of the stable directions considerably (Fig. 8). The mean direction of all 25 sites after tectonic correction is: $N=25$; $R=23.7429$; $D=199.3°$; $I=-38.0°$; $k=19.0909$; $\alpha_{95}=6.4°$. The ratio of the precision parameters after and before tectonic correction is 19.0909:9.2724, or 2.0589. The critical limit for $N=25$ to provide a positive fold test (McElhinny 1964) is 1.62 for the 95% level and 2.0 for the 99% level. So the fold test is positive even on the 99% level. It should be emphasized here that among the 17 suitable sites for magmatic rocks only two have normal polarity. All 8 radiolite sites have reversed polarity. There is no significant difference between the mean remanence direction of the radiolarites ($N=8$; $R=7.5270$; $D=192.5°$; $I=-34.8°$; $k=14.8$; $\alpha_{95}=12.9°$) and the underlying magmatic rocks ($N=17$; $R=16.2819$; $D=202.6°$; $I=-39.3°$; $k=22.3$; $\alpha_{95}=7.2°$). The critical value for both groups is 1.27, while a value of 2.5 would be required for a statistically significant difference of the remanence directions at the 95% level after Watson (1956). The coincidence of the remanence of the radiolarites and the magmatic rocks will be discussed again in Sect. 4.

With mean geographical latitude and longitude $\lambda=10.3°$ E, $\varphi=42.8°$ N, the pole position for the tectonically corrected remanence direction of all 25 sites ($D=199.3°$, $I=-38.0°$) is at $\lambda'=147.3°$ E, $\varphi'=63.2°$ N. It is plotted in Figure 9 together with a part of the Eurasian and African apparent polar wander paths after Irving (1977). Figure 9 also includes Cretaceous pole positions from the Italian peninsula (after Channell and Tarling 1975; Lowrie and Alvarez 1975) as well as Cretaceous pole positions from Northern Africa (after Hussain et al. 1980). Details will be discussed in Sect. 4.

4. Discussion and Conclusions

One major problem of this investigation is the age of the isolated most stable remanence component, for which the following characteristics have been found: large coercive forces (median destructive fields of 1,000 Oe and more); no significant difference in the mean remanence directions of the radiolarites and the pillow lavas lying immediately beneath, all being reversely magnetized; the occurrence of only two sites of normal polarity, both orginating in the lower parts of the ophiolite complex; positive fold test at the 99% level; lastly, a Fisherian distribution of directions with a normal degree of scattering ($k=19.3$).

Several possible age intervals for the acquisition of the stable remanence component can be discussed. (i) A Pliocene age, with remanence due to a magnetic overpring following the reheating by the 6 m.y. old granite intrusion beneath East Elba (during the reversed Gilbert polarity epoch 5.3–3.4 m.y.). This age of remanence is not likely, because only the lowermost complex I in East Elba (for definition see Sect. 2) has been seriously affected, and complexes II and III to a lesser degree. In the ophiolite complex IV only moderately increased temperatures (less than 300° C) are considered possible for the lowermost parts (serpentinites) according to Berner (1980, private communication). The radiolarites have probably not been reheated at all. It is therefore unlikely that a total magnetic overprint of the magmatic rocks and the overlying radiolarites took place in Uppermost Miocene/Lower Pliocene. The inclination which has been measured for the ophiolite complex (−38.0°) is also too low for a Tertiary age of remanence. An inclination of about 60° would be expected. (ii) The high temperature oxidation leading to an exsolution of the primary titanomagnetites and the formation of the hematite needles in the silicates (see Sect. 3.2) is, in general, indicative of a syngenetic age for remanence (in this case a Middle-Upper Jurassic age). Bigazzi et al. (1973) determined a radiometric age of 163 ± 23 m.y. for the ophiolites of Tuscany, including also samples from East Elba. During that time the geomagnetic field had constant normal polarity over a long interval, lasting from about 170 m.y. to 150 m.y. This is illustrated in Fig. 10. Following the compilation of McElhinny (1978) the polarity ratios, with a sliding window of 5 m.y., have been determined between 170 m.y. and 50 m.y. . From the predominance of the observed polarities of the East Elba ophiolites (see Sect. 3.3 and Table 1) it must be concluded that this remanence is not strictly syngenetic but younger, although the exsolution of the titanomagnetites in the pillow lavas may have occurred syngenetically. (iii) The coincidence of polarity and remanence direction of the pillow lavas

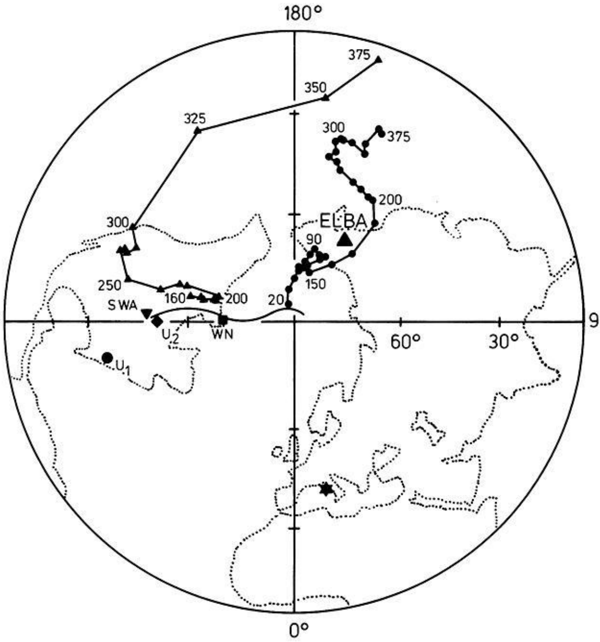

Fig. 9. Pole positions. Apparent polar wander paths of Eurasia *(small dots)* and Gondwanaland *(small triangles)* after Irving (1977). Large upward pointing triangle: pole position of the East Elba ophiolite sequence. WN: pole position of the 70 m.y. to 100 m.y. old rocks from Wadi Natash, Egypt (Hussain et al. 1980). SWA: Southwest African pole position of 110 m.y. to 128 m.y. old magmatic rocks after Gidskehaut et al. (1975). U_1: Umbrian sequence (Aptian age) after Channell and Tarling (1975). U_2: Umbrian sequence (Upper Cretaceous) after Lowrie and Alvarez (1975). The sinuous line is an apparent polar wander path for Afria between Middle Cretaceous and Lower Tertiary compiled by Hussain et al. (1980). *Star:* sampling locality

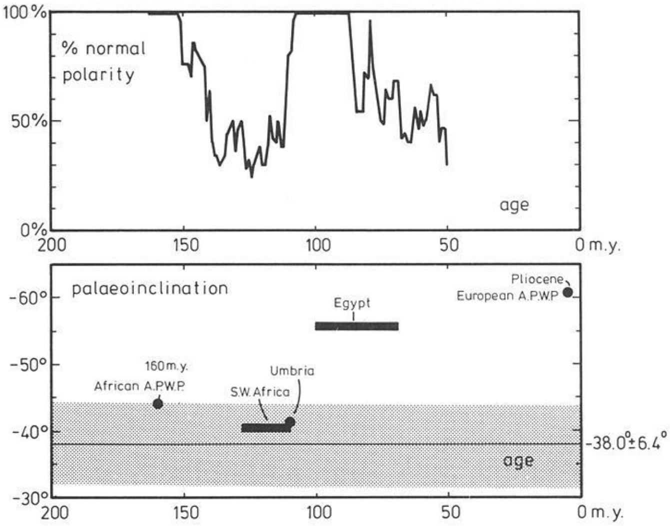

Fig. 10. Polarity ratio between 170 m.y. and 50 m.y. with a 5 m.y. window based on a compilation of polarity time scales by McElhinny (1978). The measured palaeoinclination of the East Elba ophiolite sequence ($-38.0° \pm 6.4°$) is indicated by a *horizontal line* and a *shaded area*. The palaeoinclination values which can be predicted for East Elba from other pole positions are also plotted. For details see text. The observed polarity ratio and the coincidence of the palaeoinclinations point to 120 m.y. as most probably age of remanence of the East Elby ophiolites

and the overlying radiolarites suggests a postgenetic origin of remanence during time intervals of predominantly reversed polarity. Several intervals can be considered in the Upper Mesozoic as well as during the Tertiary, with long periods of predominantly reversed polarity. Using McElhinny's (1978) compilation (see Fig. 10), there is an interval between 140 m.y. and 110 m.y. (Lower to Middle Cretaceous) with many polarity changes but a dominance of reversed polarities. The time interval 110 m.y.–85 m.y. can be excluded as a possible age for remanence, because this is the Cretaceous quiet zone of exclusively, or at least predominant, normal polarity. Since Uppermost Cretaceous there has been a tendency for a roughly even balance between normal and reversed polarity, none of them lasting longer than about 3 m.y. . So, any time interval with a reversed polarity long enough to allow a total magnetic overprint should be regarded as a possible age for the stable remanence of the East Elba ophiolites.

Channell et al. (1979) advocate that the foreland of Adria has moved in coordination with Africa since the Early Mesozoic. From the Gondwanaland (African) apparent polar wander path (Irving 1977) a pole position of 256° E, 60° N can be expected for an age of 160 m.y. . For the present geographic coordinates of East Elba (10.3° E, 42.8° N) a (reversed) remanence direction of $D = 149.4°$, $I = -44.2°$ can be predicted. The inclination value is plotted in Fig. 10. The difference between the predicted inclination and that actually measured ($-38.0°$) is 6.2° and not significant ($\alpha_{95} = 6.4°$) at the 95% level. However, it is unlikely that the age of remanence is younger than 80 m.y. . Otherwise an inclination of at least 55.6° should be observed (see Fig. 10). This value has been computed from the pole position (269° E, 70° N) of the volcanics and sandstones of Wadi Natash (Egypt) with an age of 70 m.y.–100 m.y. (Hussain et al. 1980). The best agreement with the observed inclination is obtained using the pole position at 267° E, 48° N determined by Gidskehaug et al. (1975) from age dated lavas (110 m.y.–128 m.y.) from SW Africa. The predicted (reversed) remanence direction for East Elba is: $D = 134.9°$, $I = -40.4°$. A similar value for the inclination is obtained by using a Lower to Middle Cretaceous pole position determined by Channell and Tarling (1975) from 6 sites of Aptian age from the Umbrian sequence in the Apennines (all normal polarity). This pole is at 281.4° E, 35.2° N and yields a predicted remanence direction for East Elba of $D = 116.7°$, $I = -41.4°$. This data point is also plotted in Fig. 10 (setting it at an age of 120 m.y.).

From the comparison of the inclination data and the predominance of the reversed polarity it is concluded that the ophiolite complex in East Elba has been remagnetized during the Lower Cretaceous at around 120 m.y. in a period of predominantly reversed polarity of the geomagnetic field.

For this time interval, a pole position at 267° E, 48° N has been determined for Africa by Gidskehaug et al. (1975). The corresponding Eurasian pole position for 120 m.y. is at 153° E, 70° N according to Irving (1977). The predicted remanence directions for East Elba are: $D = 134.9°$, $I = -40.4°$ from the African, $D = 193.3°$, $I = -44.3°$ from the Eurasian and $D = 116.7°$, $I = -41.4°$ from the Aptian pole position of the Umbrian sequence. The palaeodeclination data suggest a Post Lower Cretaceous clockwise rotation of the East Elba ophiolites with respect to the African plate of about $199° - 135° = 64°$. The likewise clockwise rotation with respect to Italy is $199° - 117° = 82°$, while the rotational movement with respect to Eurasia is not significant ($199° - 193° = 6°$, which is the radius of the 95% circle of confidence).

It should be emphasized here that the ophiolite complex in East Elba is an allochthonous unit of rather restricted lateral extent which rests on a pre-Triassic basement. The time of emplacement is not exactly known. It may be related to the closing of a Mesozoic ocean since Late Cretaceous. Part of the observed rotational movements with respect to Africa and the Umbrian sequence may have occurred during this emplacement. In the Pliocene the whole ophiolite complex was uplifted and tilted towards the Northwest by the granite intrusion. Additional (but smaller) rotational movements may have been caused by this event as well. So, no deductions concerning the rotation of autochthonous Elba or autochthonous Italy can be made from the East Elba ophiolite data.

Another aspect of this paper is the evidence for a post genetic origin for the remanence of ocean floor basaltic magma and radiolarites. The Koenigsberger ratio of the investigated rocks was in general smaller than unity which means a predominance of induced magnetization. The effect of a magnetic overpring on ocean floor basalts should therefore be considered seriously in the interpretation of the magnetic quiet zones of the marine magnetic anomalies.

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