NIEDERSÄCHSISCHE STAATS- UND
UNIVERSITÄTSBIBLIOTHEK GÖTTINGEN

Werk

Jahr: 1981
Kollektion: fid.geo
Signatur: 8 Z NAT 2148:49
Digitalisiert: Niedersächsische Staats- und Universitätsbibliothek Göttingen
Werk Id: PPN1015067948_0049
PURL: http://resolver.sub.uni-goettingen.de/purl?PPN1015067948_0049

LOG Id: LOG_0013
LOG Titel: Paleomagnetic evidence from Mesozoic carbonate rocks for the rotation of Sardinia
LOG Typ: article

Übergeordnetes Werk

Werk Id: PPN1015067948
PURL: http://resolver.sub.uni-goettingen.de/purl?PPN1015067948
OPAC: http://opac.sub.uni-goettingen.de/DB=1/PPN?PPN=1015067948

Terms and Conditions

The Goettingen State and University Library provides access to digitized documents strictly for noncommercial educational, research and private purposes and makes no warranty with regard to their use for other purposes. Some of our collections are protected by copyright. Publication and/or broadcast in any form (including electronic) requires prior written permission from the Goettingen State- and University Library.
Each copy of any part of this document must contain there Terms and Conditions. With the usage of the library's online system to access or download a digitized document you accept the Terms and Conditions.
Reproductions of material on the web site may not be made for or donated to other repositories, nor may be further reproduced without written permission from the Goettingen State- and University Library.

For reproduction requests and permissions, please contact us. If citing materials, please give proper attribution of the source.

Contact

Niedersächsische Staats- und Universitätsbibliothek Göttingen
Georg-August-Universität Göttingen
Platz der Göttinger Sieben 1
37073 Göttingen
Germany
Email: gdz@sub.uni-goettingen.de

J. Geophys. 49, 11–19 (1981)

Journal of Geophysics

Paleomagnetic Evidence from Mesozoic Carbonate Rocks for the Rotation of Sardinia*

F. Horner and W Lowrie
Institut für Geophysik, ETH-Hönggerberg, CH-8093 Zürich, Switzerland

Abstract. The remanent magnetizations have been analysed in Cretaceous and Jurassic limestones, and Triassic dolomites, from Eastern and Central Sardinia. Ore microscopy and rock magnetic studies, including the acquisition of *isothermal remanent magnetization* (IRM) and the behavior of IRM during high temperature treatment, indicated that magnetite and goethite determine the paleomagnetic properties of these carbonate rocks. At all Cretaceous sites the remanences were either too weak or too unstable to be used for a paleomagnetic study. AF and thermal demagnetization were used to isolate the *characteristic remanent magnetization* (ChRM) in the Jurassic and Triassic samples. Rejection criteria were used to eliminate about one third of these samples because of directional instability, or because only very stable secondary magnetizations associated with goethite were present. For the remaining samples the ChRM direction associated with primary magnetite was extracted with the aid of vector diagrams or vector difference calculations. The ChRM directions are rotated by 70°–90° counterclockwise relative to European directions and by 35°–45° counterclockwise relative to African directions. Part of this results from the 30° microplate rotation of Sardinia in the Miocene. The remainder is due to an earlier phase of microplate rotation which took place in post-Late Jurassic time.

Key words: Rotation of Sardinia – Mesozoic limestones – paleomagnetism – rock magnetism.

Introduction

Sardinia plays a key role in Western Mediterranean tectonic history. Argand (1924) suggested a paleogeographical reconstruction in which the Corso-Sardinian block lies adjacent to Southern France. Several forms of geological evidence support this paleogeography.

Chabrier and Mascle (1975) presented facies evidence and other geological arguments in favour of a similar geological history in Sardinia and Provence. The geographic distribution of the Barremian foraminiferal *Valserina* association supports an Early Cretaceous position for Sardinia close to the south-east coast of France (Cherchi and Schroeder 1973). Micropaleontological research on Cretaceous elements in south-west Sardinia reveal microfaunal assemblages of Iberian provenance (Cherchi and Schroeder 1976).

Geometric fitting of the Corso-Sardinian block to the coast of Provence has been attempted by matching bathymetric contours qualitatively (Alvarez 1972) and with a computer (Westphal et al. 1973). Hercynian structural trends in Corsica, Sardinia and southern France are compatible with this initial paleogeography (Arthaud and Matte 1977).

Paleozoic paleomagnetic directions from Corsica (Nairn and Westphal 1968) and Sardinia (Zijderveld et al. 1970) suggested different amounts of rotation of the two islands relative to the European mainland. Differential rotation allowed also a better match of the Corso-Sardinian block against S. France and could have resulted in the opening of the gulf of Bonifacio (Alvarez 1973). However, Paleozoic tectonic structures show the same alignments on both sides of the straits, suggesting that the Corso-Sardinian block has remained as a unit since the Permian (Arthaud and Matte 1976). The paleomagnetic evidence for the Corsican rotation (Nairn and Westphal 1968) has also been questioned on the grounds that the rocks investigated are heavily altered and no longer possess primary magnetizations (Storetvedt and Petersen 1976).

Abundant paleomagnetic data from Sardinia indicate that the island has undergone at least two phases of counterclockwise rotation since the Late Paleozoic. Many studies of Tertiary volcanics have revealed north-westerly magnetic declinations from which about 30° of rotation relative to Europe may be inferred (see the summaries by Manzoni 1974; Manzoni and Ferriani 1976; Edel and Lörtscher 1977; Edel 1979). An age of 15–17 Myr has been determined radiometrically for this Tertiary rotation (Bellon et al. 1977).

Larger tectonic rotations of Sardinia have been deduced from paleomagnetic investigations in older rocks. Data from Permian ignimbrites from the Gallura region in northern Sardinia (Zijderveld et al. 1970; Westphal et al. 1976; Storetvedt and Markhus 1978) indicate rotation of about 45°–60°, while directions from Permian red sandstones from north-western Sardinia (Zijderveld et al. 1970) are rotated by 90° counter-clockwise relative to stable Europe. From these results it may be inferred that Sardinia underwent an earlier rotation of about 30°–60° relative to Europe between the Permian and Late Tertiary.

Only a meagre amount of rock magnetic data has been published for Sardinian volcanic rocks. In the Permian volcanics more than a single, potentially remanence-carrying magnetic mineral was often present; low temperature oxidation had altered the original magnetic mineralogy (Storedvedt and Markhus 1978).

There is a lack of paleomagnetic information from Sardinia for the period from Permo-Triassic to Tertiary, which is represented only by weakly magnetized sedimentary rocks. It has only recently become feasible to measure these with satisfactory accuracy. In this paper we present the results of a paleomagnetic investi-

---

* Institut für Geophysik contribution No. 307

0340-062X/81/0049/0011/$01.80

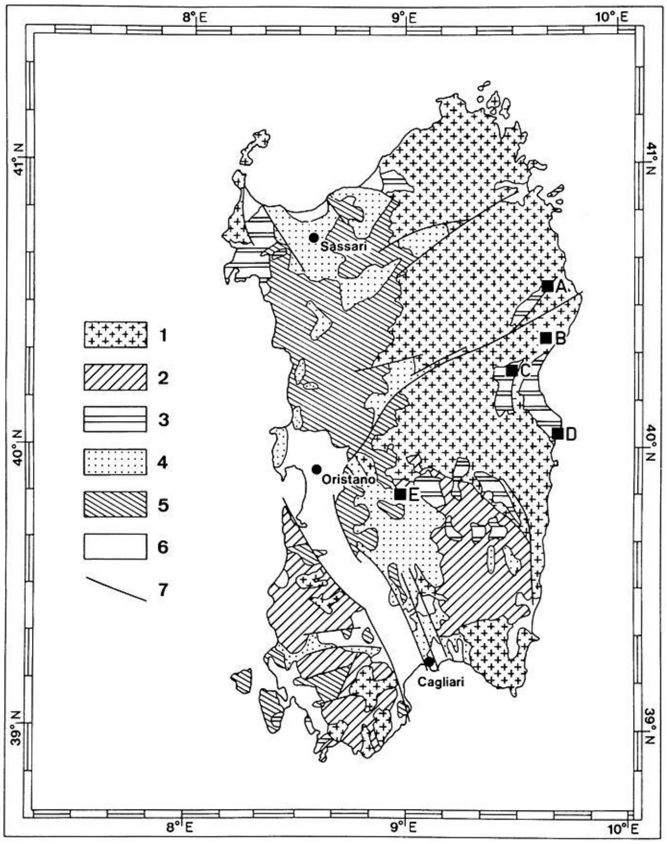

Fig. 1. Simplified geological-structural map of Sardinia (after Cocozza et al. 1974). Key: (1) granitoids, gneisses and micaschists of Variscan age or older, (2) Paleozoic sedimentary rocks, Variscan age or older, (3) post-Variscan Paleozoic rocks and Mesozoic sediments, (4) Tertiary sediments, (5) Tertiary and Quaternary volcanic rocks, (6) Quaternary sediments, (7) faults. Site locations: *A* Jurassic sites FH01, FH02, *B* Cretaceous sites FH04–FH06, *C* Cretaceous site FH03, *D* Jurassic sites FH07–FH09, *E* Triassic sites FH10–FH12

gation on limestones of Triassic, Jurassic and Cretaceous age from central and eastern Sardinia.

Geological Setting and Paleomagnetic Sampling

During the Mesozoic Sardinia was a part of a relatively stable platform which, since the end of the last Hercynian phase of folding, had been disturbed only by movements accompanying isostatic compensation, and otherwise exhibited many characteristics of a cratonic province (Cocozza and Jacobacci 1975). The Mesozoic sedimentary cover was deposited discordantly on the Variscan basement over much of Sardinia (Fig. 1). The sediments are mainly neritic, but pelagic sediments also occur in a few places. The Mesozoic facies pattern in western Sardinia is analogous to that in Provence (Chabrier and Mascle 1975), but somewhat different from that found in eastern Sardinia.

Except for the most westerly part of Sardinia (Nurra region), the Mesozoic cover has not undergone Alpine compressive deformation. It has remained subhorizontal, having been locally affected by post-Mesozoic normal faulting.

Fine-grained Cretaceous limestones were sampled at four sites; 73 cores (110 samples) were obtained. A single site (C, Fig. 1) of Turonian age (I. Dieni, personal communication 1978) was located in the Valle Lanaitto, west of Dorgali (Chabrier 1969), and three sites of Valangian to Albian age (B, Fig. 1) were located in a valley of Monte Tuttavista, called "Badde Funtana Morte", west of Orosei (Dieni and Massari 1966).

Two Jurassic sites (A, Fig. 1) were drilled in gently dipping beds of Callovian age (I. Dieni., personal communication 1978) in the autochthonous part of Monte Albo (Dieni and Massari 1970). Three additional Jurassic sites (D, Fig. 1) were placed in gently dipping beds of the Kimmeridgian, pelagic fine-grained "lithographic limestone" (so named because it was once favoured for preparing printing blocks) near to the village of Baunei (Amadesi et al. 1960). These two groups of sites are separated by NE-SW trending faults bounding the southeastern edge of the Monte Albo block (Fig. 1). Alvarez and Cocozza (1974) reconstructed the tectonic history of this part of Central Eastern Sardinia. Although the major faults were active as vertical faults during the Alpine orogeny, they may have been re-activated with a sinistral strike-slip component during the Neogene. As will later be seen, these faulting episodes did not result in major relative rotation: paleomagnetic directions on both sides of the fault zone are equivalent. A total of 139 Jurassic cores (158 samples) were obtained.

Samples of Triassic Muschelkalk were taken in flat-lying beds at three sites (E, Fig. 1) close to one another in quarries at the base of Monte Maiore in the central part of Sardinia (Damiani and Gandin 1974). These carbonate rocks consist of limey dolomites and contain very few fossils; 54 Triassic cores (83 samples) were taken.

Analysis of Remanent Magnetizations

The remanent magnetizations of the weakly magnetized limestones were measured with a three-axis cryogenic magnetometer. Replicate measurements were made of each remanence, and the accuracy of repeatability was used as a rejection criterion at each stage of demagnetization (Lowrie et al. 1980).

The *natural remanent magnetizations* (NRM) of the Cretaceous samples were exceptionally weak averaging only 2×10^{-8} G (Fig. 2). Many of these samples were too weak to be measured with reliability; at early stages of *alternating field* (AF) and thermal demagnetization the signal soon fell to unmeasurable levels. In those samples which were sufficiently magnetic to be AF or thermally demagnetized no stable vector could be isolated. The remanences of the Cretaceous collection were judged to be too weak or too unstable to be paleomagnetically useful, and all were rejected from further analysis.

Although the Triassic Muschelkalk samples and the Jurassic samples were also very weak, averaging 7×10^{-8} G and 5×10^{-7} G, respectively, the remanences of most samples were adequate to give reliable measurements. They were demagnetized progressively in order to separate individual magnetization components. Wherever possible, twin samples from the same core were subjected to AF or thermal demagnetization respectively. The component analysis was facilitated by the use of vector diagrams and vector difference computations. The categories of demagnetization behaviour observed corresponded to different magnetic mineral compositions of the limestones.

Samples with Remanences Dominated by Magnetite

In these samples the AF demagnetization behaviour (Fig. 3a) shows a slight initial increase of intensity and a large change in direction in fields up to 100 Oe accompanying removal of a low-coercivity component of normal polarity. The magnetization vector then decays more or less uniformly towards the origin,

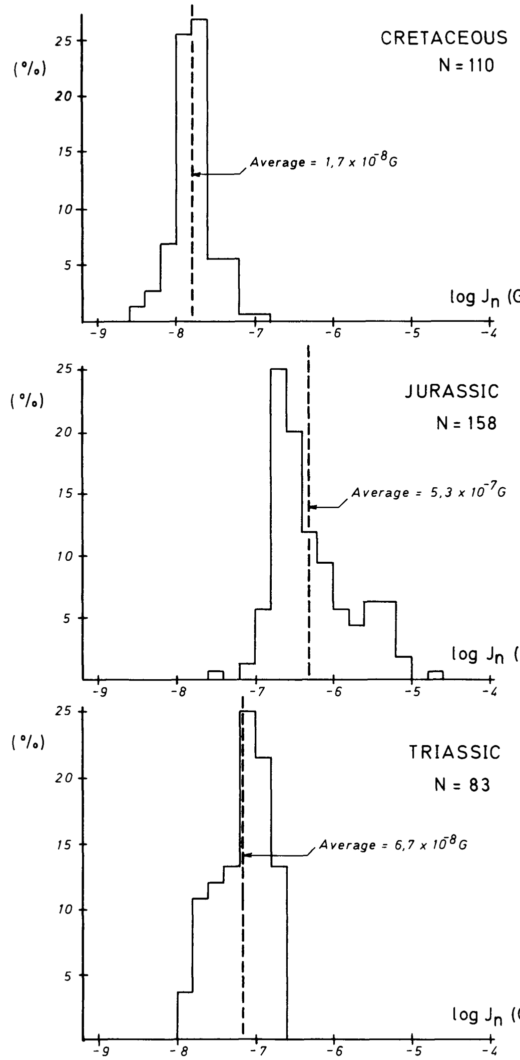

Fig. 2. Histograms of NRM intensities of the Cretaceous, Jurassic and Triassic limestone collections. (*N* number of samples)

which is not quite reached by 500 Oe. A small, high-coercivity component persists in alternating fields up to at least 1 kOe. The remanence component in the region 100–500 Oe is easily determined, and in the example shown has reversed polarity.

Progressive thermal demagnetization of the twin sample from this core showed similar behaviour (Fig. 3b). A component of normal polarity was removed below 200° C, and at higher temperatures a single component of remanence existed. Its direction was identical to that of the component removed by AF demagnetization between 100–500 Oe, and its maximum unblocking temperature was around 550° C.

On the basis of its coercivity and unblocking temperature spectra, we associate this component of remanence with magnetite and identify it as the primary or characteristic remanent magnetization (ChRM) of the sample.

Samples with Remanences Dominated by Goethite

In a large number of samples, the remanent magnetizations were extremely resistant to AF demagnetization. In fields up to 1 kOe no significant change of direction (Fig. 4a) or intensity (Fig. 4b) took place, although both behaved irregularly.

The total coercivity spectrum of the unheated sample was investigated by giving an isothermal remanent magnetization (IRM) in progressively increasing magnetic fields (Fig. 4c). Acquisition of IRM was uniform and continuous throughout the experiment indicating a very broad coercivity spectrum, and saturation IRM was not reached even in a field of 45 kOe produced by a cryogenic magnet.

The strong-field IRM was demagnetized thermally using a high-temperature vector magnetometer which permits quasi-continuous monitoring of all three remanence components (Heiniger and Heller 1976). An immediate, drastic decrease in intensity was observed below 100° C (Fig. 4d); above this temperature only a small erratic component remained.

During thermal demagnetization of the natural remanence of the twin sample from this core the direction changed erratically (Fig. 4e) after removal of a large initial component with very low blocking temperature (Fig. 4f).

The combination of very high coercivity with extremely low unblocking temperature (and Curie point, by inference) in the IRM and NRM indicates that each remanence is controlled by ferromagnetic goethite (Hedley 1971; Heller 1978) whose Curie point is below 110° C. Erratic behaviour of remanence carried by goethite can occur at room temperature (Fig. 4a, b), which corresponds to the blocking temperature of some of the grains.

Polished sections were examined with a reflecting ore-microscope. The observations were difficult because of the sparseness of any opaque minerals. However, goethite was clearly identified by its dull grey reflectance, with yellowish to reddish brown internal reflections, especially under oil-immersion. The goethite occurred both as accretions of minute grains and as a pseudomorph after pyrite, and may be presumed to have formed by alteration of pre-existing pyrite in the latter case. The accretionary form may have a similar origin, or it may be precipitated from iron solutions within the sediment (Berner 1969). In either case the goethite is secondary, and may originate long after deposition. Remanence components carried by goethite post-date the Late Tertiary folding of Jurassic limestones in the Swiss Jura mountains (Van der Voo and Lowrie 1979), and goethite magnetizations of opposing polarities were found in different samples from the same core in the Frankenjura limestones of southern Germany (Heller 1977).

Samples which contained a dominant fraction of goethite as magnetic mineral were therefore rejected from further paleomagnetic analysis, on the grounds that they did not possess a primary remanence component. The remanence directions carried by goethite showed no systematic grouping, before or after tectonic correction.

Summary

In most samples magnetite and goethite were present in comparable proportions. The AF and thermal demagnetization of NRM showed intermediate characteristics between those in Figs. 3 and 4. During IRM acquisition (Fig. 5a) there was an initial sharp increase in magnetization below 1 kOe. The saturation of the magnetite component was followed in higher fields by an increasingly steep acquisition curve which does not saturate in 45 kOe, typical for the goethite component. Continuous thermal demagnetization of the IRM (Fig. 5b) shows an initial sharp drop below 100° C due to the goethite component. This is followed by a more or

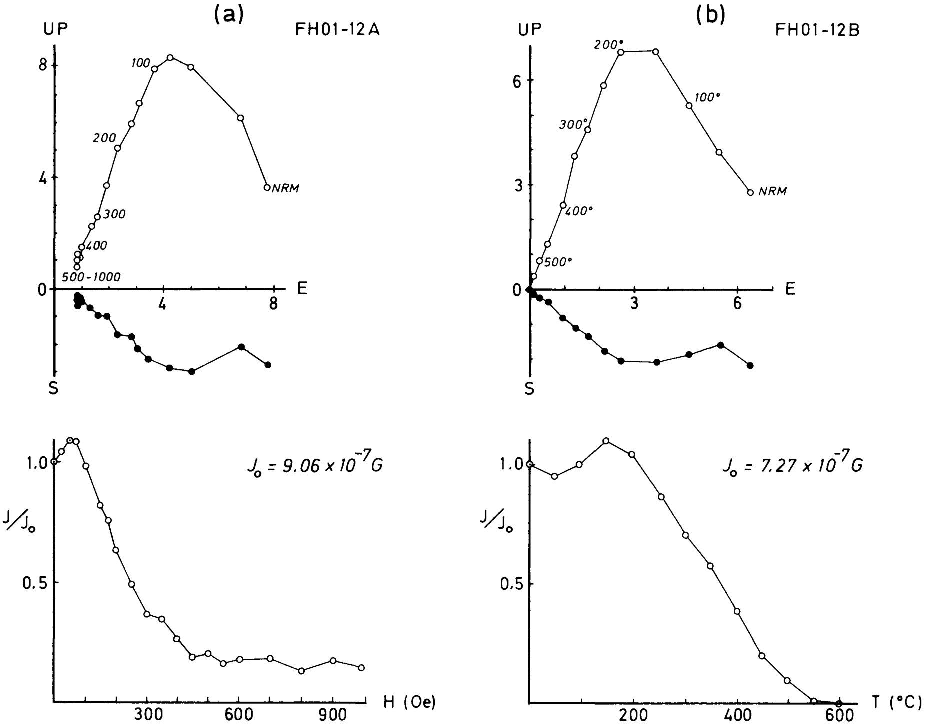

Fig. 3a and b. Comparison of (**a**) AF demagnetization and (**b**) thermal demagnetization of twin samples from the same (reversely magnetized) core FH01–12. *Open* and *solid dots* indicate components in the vertical EW and horizontal planes, respectively. *Numbers* on each diagram refer to the peak AF demagnetizing field in oersteds, or temperature in °C.

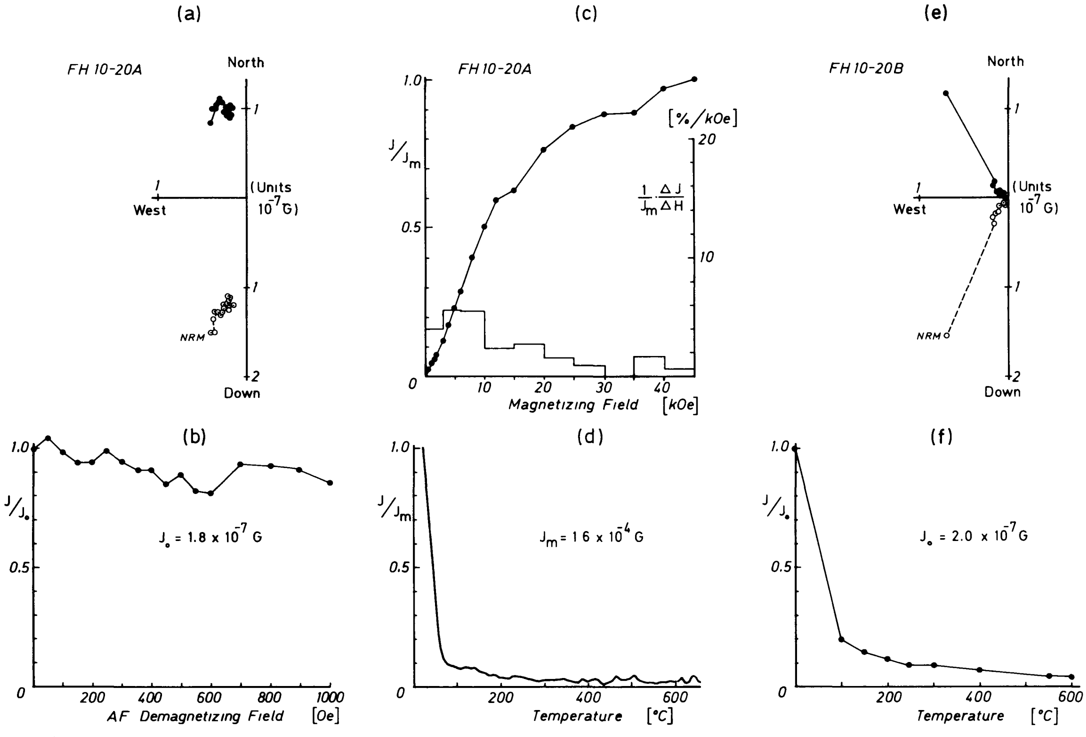

Fig. 4a–f. Magnetic characteristics of samples whose magnetization is dominanted by goethite. (**a**) The vector diagram shows stable directions, and (**b**) the intensity changes little during AF demagnetization. (**c**) Acquisition of IRM does not reach saturation even in 45 kOe, but (**d**) this IRM is almost entirely destroyed by heating to 100° C. Thermal demagnetization of the twin sample demonstrates the thermal instability of (**e**) direction and (**f**) intensity of the NRM associated with goethite

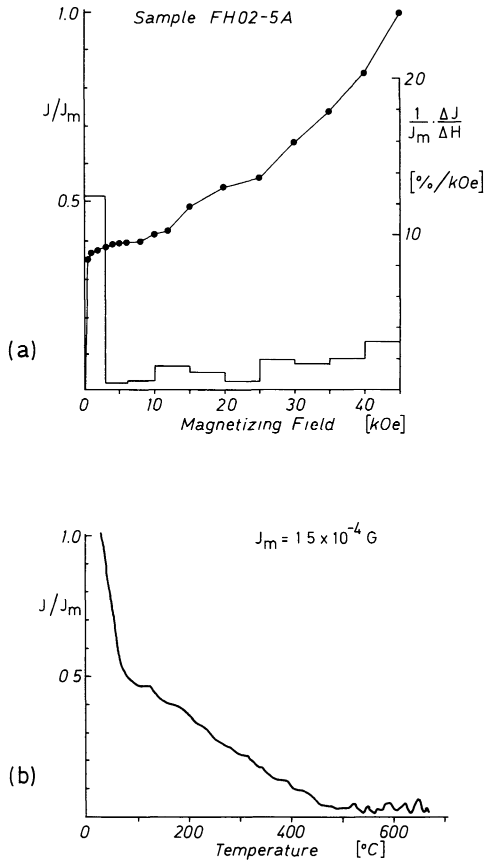

Fig. 5 a and b. Magnetic characteristics of a sample whose magnetization contains comparable magnetite and goethite components. **a** Saturation IRM is not reached in 45 kOe but the histogram of coercivities reveals a strong fraction below 3 kOe. **b** On heating the IRM the goethite component disappears by about 100° C and the magnetite component unblocks uniformly until 500° C

less regular unblocking of the magnetite component until 500° C, above which the signal is mostly instrumental noise.

Demagnetization treatment was therefore specifically oriented towards extracting the direction of the magnetite component, by AF demagnetization in the range 100–500 Oe or by thermal demagnetization between 100° C and 500° C. A satisfactory general treatment consisted of thermal demagnetization to 150° C (to eliminate the goethite component) followed by AF demagnetization to define the direction of the magnetite component.

Characteristic Remanent Magnetizations

Each sample was AF or thermally demagnetized in several steps. The ChRM was derived with the aid of vector diagrams and vector difference computations. Data were rejected (a) if the magnetization was too weak to measure accurately, (b) if the remanence was too unstable to be of use, (c) if the only remanence component resided in goethite, and (d) if the intermediate (magnetite) component was too small or too weakly defined to be determined with acceptable precision. All Cretaceous samples, 34 Jurassic and 27 Triassic samples were rejected on the first two grounds, a further 30 Jurassic samples were rejected for the last two reasons.

In general the differently demagnetized (one AF, the other thermal) twin samples from the same core gave similar ChRM directions, which were therefore averaged. The ChRM sample directions for each of the 5 Jurassic and 3 Triassic sites are shown in Fig. 6 and 7 respectively. All Triassic samples were normally polarised, and the directions were closely grouped. A few reversely polarised samples were measured at one of the Jurassic sites (compare Fig. 3); the Jurassic directions were somewhat more dispersed than the Triassic directions.

At site FH08 the ChRM directions are smeared out, and some appear to lie near a great circle connecting the normal and reversed polarity groups. This is an indication that the ChRM directions

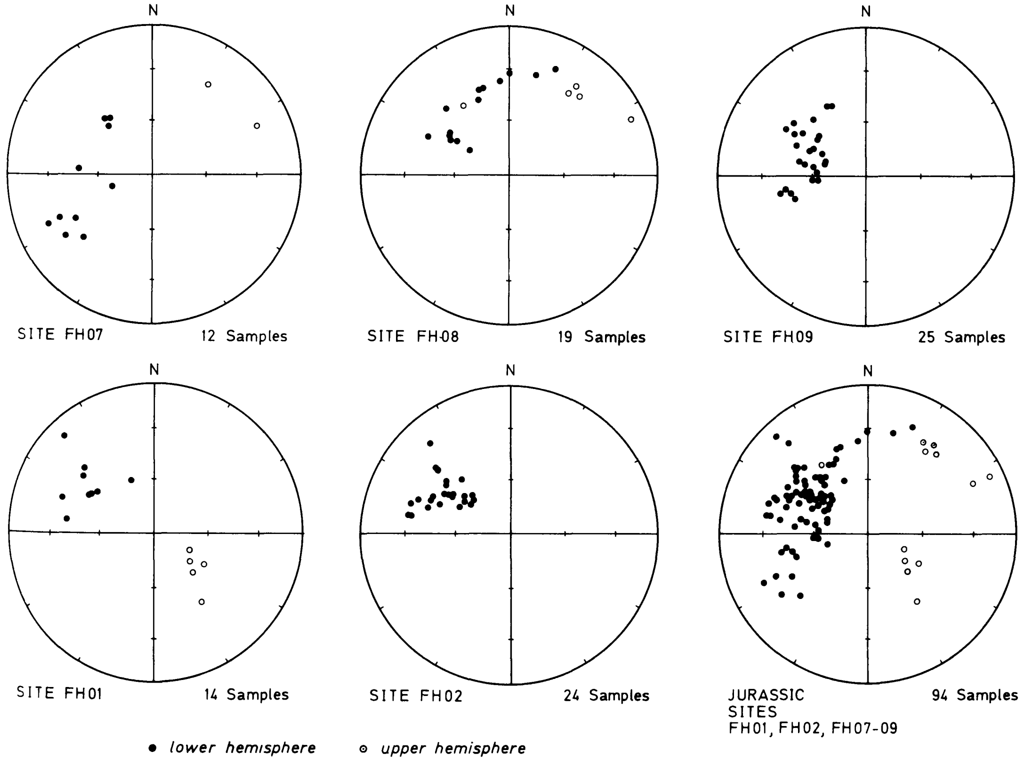

Fig. 6. Stereograms of ChRM directions at the 5 Jurassic sites, individually and collectively

Table 1. Fisher statistical analysis of sample directions

Sampling description			Mean Directions									
			Before bedding corrections					After bedding corrections				
Age	Site	*N(n)*	*R*	*D*	*I*	α	*K*	*R*	*D*	*I*	α	*K*
Jurassic	FH01	13(14)	12.49	304	31	8.7	23.59	12.42	307	47	9.3	20.66
	FH02	14(24)	13.49	288	40	8.0	25.47	13.64	303	46	6.8	35.68
	FH07	10(12)	8.72	251	28	19.6	7.03	8.71	260	49	19.7	6.95
	FH08	8(9)	7.74	308	63	10.8	27.35	7.74	318	47	10.8	27.30
	FH09	18(25)	17.32	282	36	7.1	24.98	17.38	290	55	6.7	27.59
All cores		63	57.06	285	39	5.8	10.44	58.66	296	51	4.9	14.29
								Jurassic Pole Position 292E 40N			5.8	10.63
Triassic	FH10	17(31)	16.75	296	33	4.5	62.82	16.74	294	43	4.6	60.69
	FH11	13(19)	12.73	290	43	6.3	44.78	12.72	295	41	6.4	42.61
	FH12	4(6)	3.96	286	42	10.7	74.39	3.96	290	41	10.8	74.03
All cores		34	33.26	293	38	3.7	44.63	33.41	294	42	3.3	55.91
								Triassic Pole Position: 285E 33N			3.1	62.26

N(n) = number of cores (samples), *D*/*I* = declination/inclination of mean direction, α = 95% confidence circle radius, *K* = precision parameter (Fisher 1953)

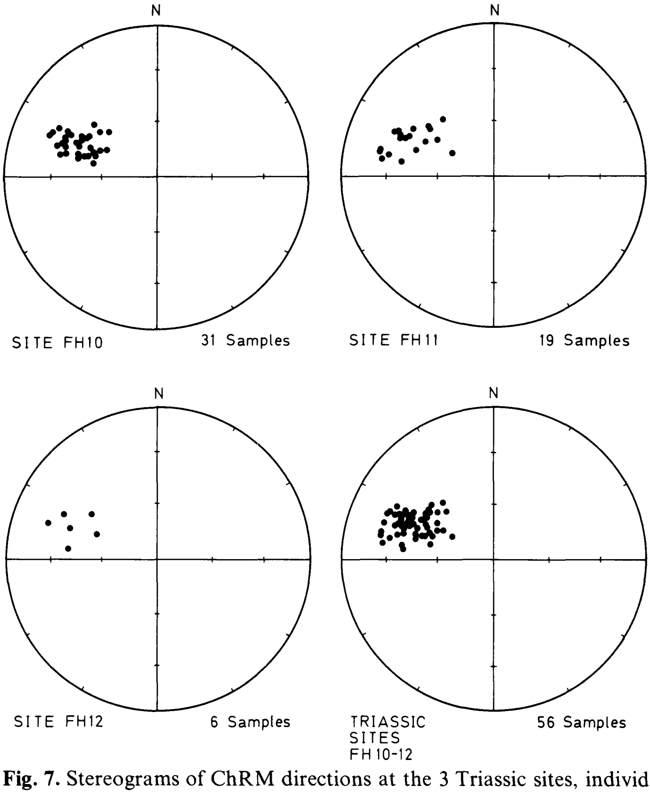

Fig. 7. Stereograms of ChRM directions at the 3 Triassic sites, individually and collectively

of these samples are not the primary directions. However, inspection of the AF demagnetization vector diagrams of these samples revealed well-defined trajectories to the origin. We have no satisfactory explanation for these deviant directions. The suspect samples came from a common region of a small roadside quarry in which the limestone was rather karstic in varying degrees. These ChRM directions were excluded from further paleomagnetic analysis.

The statistical analysis (Fisher 1953) of the core directions is given for each site and age in Table 1. Tectonic corrections within each site did not have much effect on the directional dispersion because within-site bedding attitudes did not vary much. Between-site corrections slightly improved the directional scatter of each age group.

Discussion

Although Permian and Carboniferous paleomagnetic pole positions are well defined for Europe, only a single African pole of acceptable quality exists for each of these geological epochs. The Mesozoic portions of African and European *apparent polar paths* (APW) are weakly defined. To overcome these difficulties Van der Voo and French (1974) reconstructed the ancient positions of the Atlantic-bordering continents and combined for each epoch paleomagnetic data which they considered to be of acceptable quality. Subsequently, Irbing et al. (1976a–b, c) compiled summaries of all paleomagnetic data up to 1975, including the latest Russian results. Irving (1977) adopted more liberal acceptability criteria for these data than Van der Voo and French had applied. He combined the data in fairly broad moving windows (20–40 Myr interval width) and produced smoothed APW paths for Eurasia, North America and Gondwana (in which the continental reconstruction of Smith and Hallam 1970, was assumed). These paths are in fact swathes of variable width (Fig. 8) corresponding to the different radii of 95% confidence along the trajectory.

A pseudo-African APW path (VandenBerg 1979) can be constructed by rotating the North American APW path about the appropriate rotation poles for the opening of the north Atlantic ocean (Sclater et al. 1977). This path (Fig. 8) lies quite far from the Gondwana APW path of Irving (1977). In order to bring North America and Africa into their positions for the Bullard et al. (1965) reconstruction a large dextral transcurrent displacement of about 3,500 km, ending by the Late Triassic, must be invoked (Irving 1977). The discrepancy between Laurasian and Gondwanan paleomagnetic data was noticed earlier by Van der

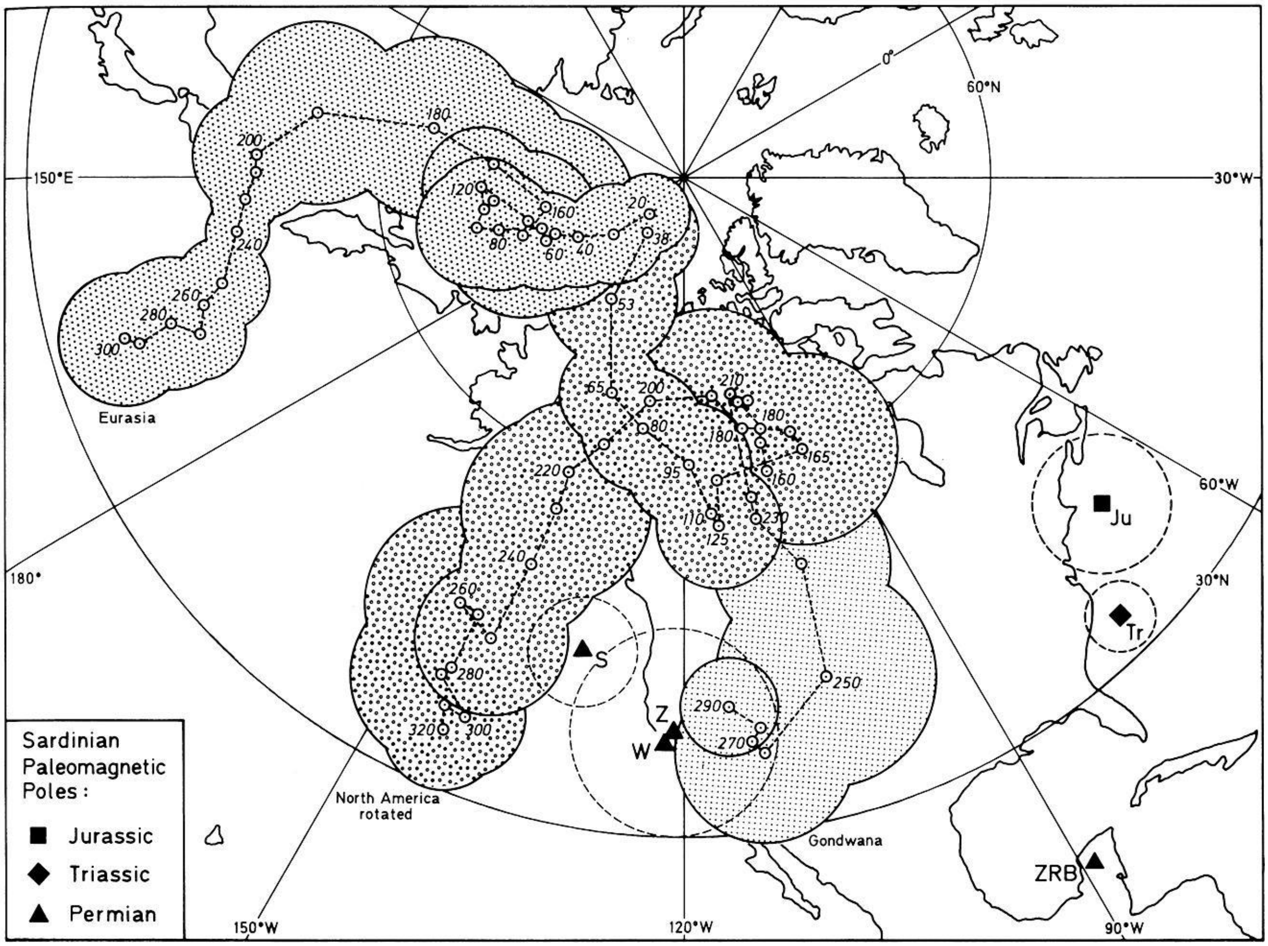

Fig. 8. Jurassic and Triassic paleomagnetic pole positions (with 95% confidence circles) from this study of limestones and Permian poles from studies of ignimbrites. *S* Storetvedt and Markhus (1978), *W* Westphal et al. (1976), *Z* Zijderveld et al. (1970). *ZRB* is the Permian pole from redbeds (Zijderveld et al., 1970). For comparison are shown (with their 95% confidence widths) the APW paths for Eurasia and Gondwana (Irving 1977) and the North American path rotated around the poles of opening of the Atlantic derived by Sclater et al. (1977)

Table 2. Comparison of palaeomagnetic directions measured in Sardinia (40.3° N, 9.7° E) in Mesozoic limestones with those expected from the Eurasian and African (Gondwanan) APW paths of Irving (1977)

	Middle and Late Jurassic		Triassic	
	D	*I*	*D*	*I*
Observed mean direction	296	51	294	42
Expected directions				
African	330	42	338	47
European	7	46	25	12
Inferred CCW rotation				
Sardinia relative to				
Africa	34°		44°	
Europe	73°		91°	

Voo and French (1974) who also proposed a dextral shear between the supercontinents, of smaller magnitude than that proposed by Irving (1977).

As reference APW path for Africa in this study we take the portion of the rotated North American APW path from the present to 160 Myr B.P. and the Gondwana APW path for ages older than 160 Myr. The Jurassic and Triassic pole positions for Sardinian limestones lie far from the Eurasian and 'African' APW paths (Fig. 8). By implication the island has undergone counterclockwise rotations relative to both Europe and Africa.

The Jurassic and Triassic directions expected in Sardinia from the appropriate segments of the Eurasian and 'African' APW paths were computed, and compared to the observed paleomagnetic directions in Sardinia for the purpose of determining the amounts of rotation involved (Table 2).

The total counterclockwise rotation of Sardinia relative to Europe has been estimated at 45° (Storetvedt and Markhus 1978) to 60° (Westphal et al. 1976; Zijderveld et al. 1970) from Permian porphyries, and up to 90° in Permian redbeds (Zijderveld et al. 1970). In a current study of Permo-Triassic rocks very large directional rotations of 50°–100° have been observed (J.-B. Edel personal communication 1979).

The 70°–90° counterclockwise rotation inferred from Sardinian Mesozoic limestones is in accord with the larger amounts of rotation in older rocks. It is greater than previous estimates (60°) based upon paleomagnetic data and on matching the Corso-Sardinian and Provencal coastlines.

The declinations of the mean Jurassic and Triassic directions measured in Sardinian Mesozoic limestones are practically identical. The total difference in direction of 9° is mainly due to the difference in inclinations. In this respect the Sardinian directions resemble African directions which have been rotated by 34°–44° counterclockwise (Table 2). The similarity of Sardinian Permian directions to African Permian directions was pointed out by Zijderveld et al. (1970).

Recently VandenBerg (1979) has associated Sardinia with Adria, a promontory of the African plate (Channell and Horvath 1976; Channell et al. 1979). VandenBerg proposed that Adria (with Sardinia) was decoupled from the African plate and underwent a 25°–30° counterclockwise rotation relative to Africa in the Late Tertiary. This rotation would be equivalent to the well-documented 30° rotation about 15–17 Myr B.P (Bellon et al. 1977). The earlier rotational history of Sardinia would represent the rotation of the African plate relative to the European plate.

Although our paleomagnetic observations follow the general sense of VandenBerg's interpretation, the total amount of observed rotation is appreciably greater than that required by his model. About 10°–15° of counterclockwise rotation of Sardinia relative to Africa is unaccounted for.

Sardinian paleomagnetic data support a paleohistory in which Sardinia rotated relative to both Africa and Europe, presumably as an independent microplate. The new Mesozoic data imply that the earlier rotational phase occurred since the Late Jurassic.

Conclusions

Paleomagnetic data from Mesozoic limestones in Sardinia were of variable quality. All Cretaceous samples were rejected because of instability or weakness of the remanent magnetization. The magnetizations of Jurassic and Triassic samples were carried by primary magnetite and secondary goethite. The direction of a stable ChRM component carried by magnetite was extracted in as many samples as possible.

The new Mesozoic data, interpreted in conjunction with Tertiary and Paleozoic data, support the concept that Sardinia has undergone two phases of counterclockwise rotation relative to both Europe and Africa. The more recent rotation as an independent microplate occurred in the Early Miocene. The earlier rotation was also at least partly a microplate rotation relative to both neighbouring plates. It occurred in the Paleogene or Cretaceous, since our Late Jurassic data also show its effects. In could not be timed more exactly in the present study because of the unsuitability of our Cretaceous samples for paleomagnetic analysis

Acknowledgements. During this project invaluable advice and suggestions were received from Drs. F. Heller and J.E.T Channell, who also critically reviewed the manuscript. The location and description of suitable sites for this study was facilitated in the field by the generous cooperation of A. Gandin, I. Dieni, and F. Massari. We are grateful to J.-B. Edel for a preprint of his study of Permo-Triassic rocks in Sardinia, to the Research Laboratory of Brown Boveri Company (Dällikon, Switzerland) for allowing us to use their cryogenic magnet and to M.S. Lowrie for kindly typing the manuscript.

References

Alvarez, W.. Rotation of the Corsica-Sardinia microplate. Nature Phys. Sci. **235**, 103–105, 1972

Alvarez, W.: The application of plate tectonics to the Mediterranean region. In: Implications of continental drift to the earth sciences, Vol. 2, pp. 893–908. London: Academic Press 1973

Alvarez, W., Cocozza, T . The tectonics of central eastern Sardinia and the possible continuation of the alpine chain to the south of Corsica. In: Paleogeografia del Terziario sardo nell'ambito del Mediterraneo occidentale. Suppl. ai Rend. Fac. Sci. Univ. Cagliari **43**, 5–34, 1974

Amadesi, E., Cantelli, C., Carloni, G., Rabbi, E.: Ricerche geologiche sui terreni sedimentari del foglio 208-Dorgali. G. Geol. **28**, 58–87, 1960

Argand, E.: La tectonique de l'Asie. 13th International Geological Congress (Brussels) pp. 171–372, 1924

Arthaud , F., Matte, P.: Arguments géologiques en faveur de l'absence de mouvements relatifs de la Corse par rapport à la Sardaigne depuis l'orogenèse hercynienne. C. R. Acad. Sci. Paris **283**, 1011–1014, 1976

Arthaud, F., Matte, P.: Détermination de la position initiale de la Corse et de la Sardaigne à la fin de l'orogenèse hercynienne grâce aux marqueurs géologiques anté-mésozoïques. Bull. Soc. Geol. Fr. **19**, 833–840, 1977

Bellon, H., Coulon, C., Edel, J.B.. Le déplacement de la Sardaigne. Synthèse des données géochronologiques, magmatiques et paléomagnétiques. Bull. Soc. Géol. Fr. **19**, 825–832, 1977

Berner, R.A.: Goethite stability and the origin of red-beds. Geochim. Cosmochim. Acta **33**, 267–273, 1969

Bullard, E.C., Everett, J.E., Smith, G.A.: The fit of the continents around the Atlantic. In: A symposium on Continental Drift. Philos. Trans. R. Soc. London Ser. A.: **258**, 41–51, 1965

Chabrier, G.: Sur la stratigraphie et la structure des monts d'Oliena (Sardaigne orientale). C. R. Somm. Seances Soc. Géol. Fr. **6**, 218–220, 1969

Chabrier, G., Mascle, G.: Comparaison des évolutions géologiques de la Provence et de la Sardaigne (à partir d'exemples de la région Toulonnaise et de la Nurra Sarde). Rev. Geogr. Phys. Geol. Dyn. **17**, 121–136, 1975

Channell, J.E.T., D'Argenio, B., Horvath, F.: Adria, the African promontory in Mesozoic Mediterranean palaeogeography. Earth Sci. Rev. **15**, 213–292, 1979

Channell, J.E.T., Horvath, F.: The African/Adriatic promontory as a palaeogeographical premise for Alpine orogeny and plate movements in the Carpatho-Balkan region. Tectonophysics **35**, 71–101, 1976

Cherchi, A., Schroeder, R.· Sur la biogéographie de l'association *Valserina* du Barrémien et la rotation de la Sardaigne. C. R. Acad. Sci. Paris **277**, 829–832, 1973

Cherchi, A., Schroeder, R.· Présence de galets du Vraconien supérieur-Cénomanien basal de provenance ibérique dans le Paléogène continental du Sud-Ouest de la Sardaigne. Bull. Soc. Geol. Fr. **18**, 1217–1219, 1976

Cocozza, T., Jacobacci, A.: Geological outline of Sardinia. In: Geology of Italy, C. Squyres, ed.· pp. 49–81. Tripoli: Earth Sci. Soc. Lybian Arab Republic 1975

Cocozza, T., Jacobacci, A., Nardi, R., Salvadori, I.: Schema stratigrafico-strutturale del Massiccio Sardo-Corso e minerogenesi della Sardegna. Mem. Soc. Geol. Ital. **13**, 85–186, 1974

Damiani, A.V., Gandin, A.: Geologia e ambiente di sedimentazione della successione triassica di Monte Maiore (Sardegna centrale). Note II. Boll. Soc. Geol. Ital. [Suppl.] **92**, 41–83, 1974

Dieni, I., Massari, F.: I foraminiferi del Valanginiano superiore di Orosei (Sardegna). Paleontol. Ital. **61**, 75–186, 1966

Dieni, I., Massari, F.: Tettogenesi gravitativa di età oligocenica nella Sardegna centro-orientale. Boll. Soc. Geol. Ital. **89**, 57–64, 1970

Edel, J.-B.: Palaeomagnetic study of the Tertiary volcanics of Sardinia. J. Geophys. **45**, 259–280, 1979

Edel, J.-B., Lörtscher, A.: Paléomagnétisme du volcanisme tertiaire de Sardaigne. Nouveaux résultats et synthèse. Bull. Soc. Geol. Fr. **19**, 815–824, 1977

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

Hedley, I.: The weak ferromagnetism of goethite (α-FeOOH). J. Geophys. **37**, 409–420, 1971

Heiniger, C., Heller, F.: A high temperature vector magnetometer. Geophys. J. R. Astron. Soc. **44**, 281–288, 1976

Heller, F.: Palaeomagnetism of Upper Jurassic limestones from Southern Germany. J. Geophys. **42**, 475–488, 1977

Heller, F.: Rock magnetic studies of Upper Jurassic limestones from Southern Germany. J. Geophys. **44**, 525–543, 1978

Irving, E.: Drift of the major continental blocks since the Devonian. Nature **270**, 304–309, 1977

Irving, E., Tanczyk, E., Hastie, J.: Catalogue of paleomagnetic directions and poles. Third issue. Paleozoic results 1949–1975. Energy, Mines and Resources, Canada, Geomagnetic Series, Nr. **5**, Ottawa, 1976a

Irving, E., Tanczyk, E., Hastie, J.: Catalogue of paleomagnetic directions and poles. Fourth issue. Mesozoic results 1954–1975 and results from seamounts. Energy, Mines and Resources, Canada, Geomagnetic Series No. **6**, Ottawa, 1976b

Irving, E., Tanczyk, E., Hastie, J.: Catalogue of paleomagnetic directions and poles. Fifth issue. Cenozoic results 1927–1975. Energy, Mines and Resources, Canada, Geomagnetic Series Nr. **10**, Ottawa, 1976c

Lowrie, W., Channell, J.E.T., Heller, F.: On the credibility of remanent magnetization measurements. Geophys. J. R. Astron. Soc. **60**, 493–496, 1980

Manzoni, M.: Un interpretazione dei dati paleomagnetici del Terziario dell Sardegna ed alcuni nuovi resultati. In: Paleogeografia del Terziario sardo nell'ambito del Mediterraneo occidentale. Suppl. ai Rendiconti del Seminario della Facultà di Scienze dell'Università di Cagliari, 283–295, 1974

Manzoni, M., Ferriani, A.: Trattamento statistico e validita dei dati paleomagnetici delle vulcaniti Terziarie della Sardegna. Boll. Soc. Geol. Ital. **95**, 1263–1281, 1976

Nairn, A.E.M., Westphal, M.: Possible implications of the palaeomagnetic study of late Palaeozoic igneous rocks of northwestern Corsica. Palaeogeogr. Palaeoclimatol. Palaeoecol. **5**, 179–204, 1968

Sclater, J.G., Hellinger, S., Tapscott, C.. The paleobathymetry of the Atlantic ocean from the Jurassic to the present. J. Geol. **85**, 509–552, 1977

Smith, A.G., Hallam, A.: The fit of the southern continents. Nature **225**, 139–144, 1970

Storetvedt, K.M., Markhus, L.A.: Multivectorial magnetization in late Palaeozoic volcanics from North Sardinia; partial remagnetization and rotation. Geophys. J. R. Astron. Soc. **53**, 245–258, 1978

Storetvedt, K.M., Petersen, N.: Postulated rotation of Corsica not confirmed by new palaeomagnetic data. J. Geophys. **42**, 59–71, 1976

VandenBerg, J.: Paleomagnetism and the changing configuration of the Western Mediterranean area in the Mesozoic and Early Cenozoic eras. Geol. Ultriectina **20**, 178 pp., 1979

Van der Voo, R., French, R.B.: Apparent polar wandering for the Atlantic-bordering continents: Late Carboniferous to Eocene. Earth Sci. Rev. **10**, 99–119, 1974

Van der Voo, R., Lowrie, W.: A preliminary magnetic study of Jurassic limestones from the Swiss Jura mountains and adjacent areas (abstract). EoS, Trans. AGU **60**, 569, 1979

Westphal, M., Bardon, C., Bossert, A., Hamzeh, R.: A computer fit of Corsica and Sardinia against southern France. Earth Planet. Sci. Lett. **18**, 137–140, 1973

Westphal, M., Orsini, J., Vallutini, P.. Le microcontinent corso-sarde, sa position initiale: données paléomagnétiques et raccords géologiques. Tectonophysics **30**, 141–157, 1976

Zijderveld, J.D.A., De Jong, K.A., Van der Voo, R.. Rotation of Sardinia: Paleomagnetic evidence from Permian rocks. Nature **226**, 933–934, 1970

Received May 2, 1980; Revised Version July 21, 1980
Accepted August 7, 1980