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When did Sardinia rotate? Statistical evaluation of the paleomagnetic data

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Abstract
The existing paleomagnetic results about Sardinia are evaluated in order to verify the timing of its rotation. Previous interpretation of radiometrically dated sites suggests that the island underwent a quick counterclockwise rotation of 30° between 20.5 and 19 Ma ago. In order to verify this hypothesis paleomagnetic data from the Anglona and the Bosano-Logudoro regions were grouped by volcanic series and analyzed by Fisher statistics. Directions obtained from the upper Ignimbrites in the Anglona region (18.5-19.7 Ma) seem to constrain the end of the rotation. However, data from volcanics in the Bosano and Logudoro regions show a progressive shift of the paleomagnetic declinations from a clear north-western population toward more northern directions. Nevertheless even the mean declination calculated for the youngest rocks, such as the terminal Andesites (SA_3; age: 16.6 Ma), yields results implying some rotation. Our results confirm that Sardinia started to rotate in the lower Miocene (around 20-21 Ma), but unequivocal evidences of the end of the rotation are missing.

Key words *Paleomagnetism – Sardinia – rotation – Miocene*

1. Introduction

Many paleomagnetic data on the Tertiary volcanics of Sardinia have been collected in the last 25 years. These data exhibit north-western directions which have been explained by many authors with a counterclockwise rotation of the microplate, relative to Europe (Alvarez, 1972; Bellon *et al.*, 1977; De Jong *et al.*, 1969; De Jong *et al.*, 1973; Edel, 1979; Edel and Lörtsher, 1977; Manzoni, 1974; Manzoni and Ferriani, 1976; Montigny *et al.*, 1981). Even if different interpretations exist (Bobier, 1974; Bobier and Coulon, 1970; Coulon *et al.*, 1974b), the counterclockwise rotation of Sardinia is well supported by geological and geodynamical data on the Mediterranean region (Dewey *et al.*, 1989; Rehault *et al.*, 1984), and also by aeromagnetic data (Galdeano and Ciminale, 1987). Even if a general agreement exists concerning the rotation, its temporal limits have been subject to debate. Several authors have tried to evaluate the age of the rotation and its duration, and different conclusions have been proposed. Many authors placed the event between the upper Oligocene and the lower Miocene (Bobier and Coulon, 1970; De Jong *et al.*, 1973; Manzoni, 1974). On the basis of sedimentological considerations and stratigraphic data, Alvarez (1972) argued that the rotation did not start before Tortonian and lasted through part of Messinian, and therefore suggested a maximum time span for the rotation of 5.5 Ma, between 11.5 and 6 Ma. On the basis of paleomagnetic data, Coulon *et al.* (1974b) suggested that the rotation should have ended in the late Oligocene. According to Bellon *et al.* (1977), the rotation took place during a shorter time span (17-15 Ma) and followed a previous translation occurred between 29 and 17 Ma. Edel (1979) placed the rotation between 17 and 16 Ma. Most of these conclusions have been drawn on the basis of paleomagnetic studies carried out on the sardinian volcanics; the disagreement between different interpretations is due to the inadequacy of the volcanic rocks as a continuous record of the magnetic directions through time.

Montigny *et al.* (1981) made a major contribution to answer this question by combining K/Ar dating and paleomagnetic directions. From the comparison between declinations and absolute ages, these authors concluded that Sardinia underwent a very quick rotation that began 20.5 Ma ago and ended at 19 Ma, within a time span of only 1.5 Ma, which implies that the island moved at roughly 16 cm/yr. Such a high drifting rate has never been reported in the Mediterranean region and should be further constrained by geodynamical data on plate motion rates in this area. Moreover, the conclusion of Montigny *et al.* (1981) seems to conflict with the new reconstruction of the Neogene Central Mediterranean kinematics (Patacca *et al.*, 1993), that links directly the Corsica-Sardinia microplate drift to the emplacement of some Apennines units, metamorphosed in post-Langhian times. On this evidence a rotation ended 19 Ma appears incompatible with the recognized younger timing of the Apenninic kinematics. For these reasons, the age of the rotation is not well defined and still represents object of discussion.

The aim of the present work is to verify the contention of Montigny *et al.* (1981) concerning the duration of Sardinia's drift. Since the number of the paleomagnetic declinations with known absolute age is small compared to the total number of available paleomagnetic data, we took into consideration most of the published data on the Tertiary rocks of Sardinia. In particular we focused our attention on the Bosano-Logudoro and Anglona regions where the volcanism took place over a longer time period, and where most of the paleomagnetic data come from. By taking into consideration greater amount of sites, it is possible to average the effects of secular variations of the geomagnetic field as well as the anomalous data.

2. Tertiary Sardinian volcanism

The Tertiary Sardinian volcanism, calc-alkaline in type, started in the late Oligocene and lasted until the middle Miocene (Beccaluva *et al.*, 1985; Edel, 1979; Savelli *et al.*, 1979). The activity took place along major N-S graben structures, which affected the Paleozoic basement of the western part of the island (fig. 1). The first episodes, characterized by andesitic products, involved the Cixerri graben (29-27 Ma; Cocozza and Massoli Novelli, 1967). The activity moved then progressively northwards (21-20 Ma), where it produced highly explosive ignimbritic deposits, alternated with andesitic lavas. The last episode (14-13 Ma), consisting of minor andesitic lavas, outcrop in the north (Logudoro) and again in Cixerri (Coulon *et al.*, 1974a; Savelli *et al.*, 1979). Because of this discontinuous migration of the volcanism, it is not possible to find a region on the island, where the entire volcanic history is represented. The area where the most complete record of the Tertiary volcanism has been found embraces the Bosano and Logudoro regions. In these regions, Coulon *et al.* (1974a) defined several volcanic «series», on the basis of their «andesitic» or «ignimbritic» character. The volcanic sequence, as these authors defined it, is shown in table I, along with the available radiometric ages. This sequence, however, cannot be applied to the volcanic rocks in Anglona (Northern Sardinia). Here the cycle starts with an undifferentiated «Andesitic Series» (α, on the geologic map «Castelsardo»), which seems to correlate to the «Upper Andesitic Series» in Bosano and Logudoro (Edel, 1979). The Andesites are followed by a mixture of tuffitic and sedimentary layers (M_1t), with intercalated Ignimbrites ($M_1\tau$). The sequence is topped by an «Upper Ignimbritic Series», comparable to the one in Bosano and Logudoro.

For the southern regions, geological maps indicate two undifferentiated series (α and τ), whose stratigraphic position is unknown with respect to the northern region.

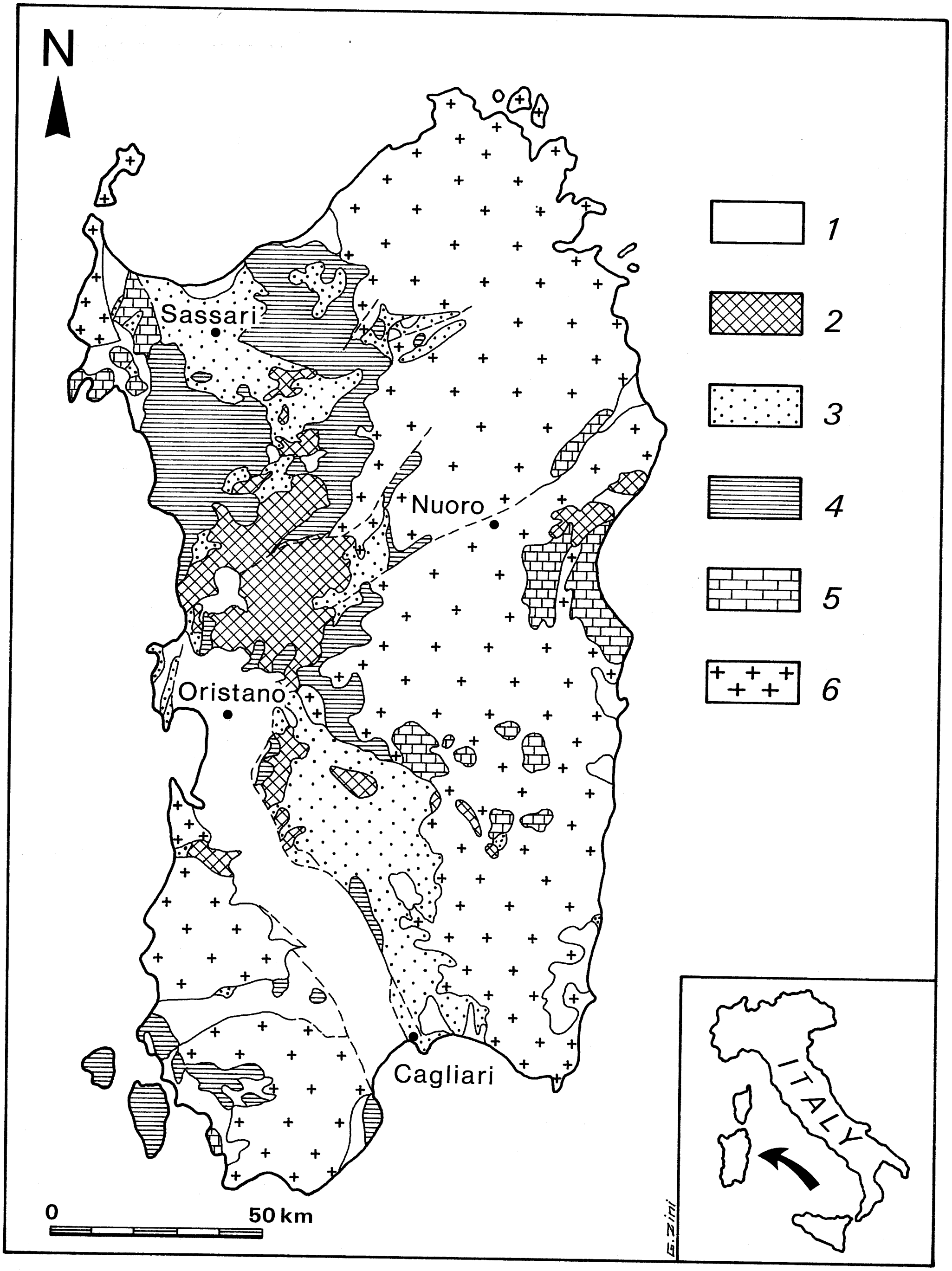

Fig. 1. Geologic sketch-map of Sardinia (re-drawn after Edel, 1980). 1: Plio-Quaternary. 2: Plio-Quaternary volcanism. 3: Miocene. 4: Oligo-Miocene volcanism. 5: Mesozoic. 6: Paleozoic basement.

Table I. Volcanic sequence in Bosano and Logudoro. Symbols after the geological map «Bonorva» n. 193 (1:100 000) and Coulon *et al.* (1974b). References are referred to absolute dating: a) Savelli *et al.* (1979); b) Coulon *et al.* (1974b); c) Edel (1980).

Series	Symbol	Age (Ma)
Terminal Andesites	SA_3 (α_3)	14-13 (a,b); 16.6 (c)
Upper Ignimbrites	SI_2 (τ_2)	15-17 (a); 16.3 (b); 18.6-19.2 (c)
Rhyolites of M. Traessu Dacite of Cossoine and M. Frusciu	τ_3	17.5-16.8 (a,b); 19.6 (c)
Upper Andesites	SA_2 (α_2)	12.2-13.7 (b); 15-20 (a); 18-18.9 (c)
Lower Ignimbrites	SI_1 (τ_1)	17.5 (b); 18-19.5 (a); 20.6-22.6 (c)
Lower Andesites	SA_1 (α_1)	21.3-23.8 (a,b); 22-25 (c)

3. Paleomagnetic data of radiometrically dated sites

Montigny *et al.* (1981) carried out K-Ar radiometric dating of sites with known paleomagnetic directions. Their results (table II) were summarized in a plot (declination vs absolute age), that is reproduced here in fig. 2. The figure appears somewhat different from the original plot, since we included all the published data, also those the authors considered unreliable and omitted from their plot. According to Montigny *et al.* (1981) this plot suggests that Sardinia reached its present position after a quick, counterclockwise rotation, occurred between 20.5 and 19 Ma. This conclusion is based on the idea that when the microplate rotation started, the magnetic directions began to move from north-westerly declinations close to 330° (150° for reversed polarity), and shifted gradually toward northerly values (360°, 180°). It is therefore assumed that a sample with a declination value of around 330° was formed before the rotation started and samples with northern directions are supposed to be younger than the end of the rotation, whereas rocks with declinations between 330° and 360° were emplaced during the rotation.

The data older than 20 Ma actually cluster around a 330° declination value; Montigny *et al.* (1981) calculated a mean value of D=329°, I=51°, $\alpha95=2°$ for 102 sites yielding directions in the interval 310°<D<350, 30<I<70. The expected direction for Sardinia is D=359°, I=58° implying a 30° of CCW rotation for the island with respect to the pole. For rocks younger than 20 Ma there is a shift toward northern values (fig. 2); however along with the first occurrence of northerly directions, several sites still show rotated declinations. In some cases this can be explained by errors in the dating of some sites, while other sites have been rejected due to dubious magnetization (sites 1, 2, 8), as argued by Montigny and his colleagues. For some sites only whole rock dating is available (sites 29, 72, 39, 41, 38, 119, 118), which is considered to be less reliable than dating carried out on separate crystals (Montigny *et al.*, 1981). In other cases stratigraphic considerations may contradict the radiometric age: in the Bosano-Logudoro area, samples belonging to the volcanic series SA_1 (sites 22, 23, 24) appear to be younger than samples collected from more recent series, such as SI_1, SA_2 and even SI_2, whereas samples from the SA_2 series (sites 30, 26, 27) show younger ages than the samples from the SI_2 series (sites 148, 97, 133). These inconsistencies may partially be explained considering that these samples do not derive from the same outcrop and that the long-lasting volcanic activity caused partial overlapping between different series. However, these contradictions suggest a particular care in evaluating radiometric data on these rocks.

Table II. Paleomagnetic directions and absolute ages of Sardinian volcanics. Reference: A = Montigny *et al.* (1981); B = Edel (1979). C = mean value obtained by converging circles; F = Fisher statistic (Fisher, 1953); α_{95} = Fisher statistic parameter (Fisher, 1953); N = number of studied samples (good estimation of the scatter and precision parameters is possible for N > 6; Tarling, 1983); ?: questionable data according to Edel (1979); ??: questionable data according to Montigny *et al.* (1981).

Site	Locality	Rock type	Ref.	Dec	Inc	α_{95}	N	Age (Ma)
38	Anglona	SA_2	B	358	48	4	8	17.2?
27	Bosano-Log.	SA_2	B	C 182	−47	5	5	
				F 172	−32	11	4	18.3
69	Sulcis	SA_1	B	179	−47	4	9	18.6
143	Anglona	SI_2	A	357	47	3	6	18.8
146	Anglona	SI_2	A	7	58	4	10	18.9
97	Bosano-Log.	SI_1	B	359	52	3	7	19.1
147	Anglona	SA_2	A	9	44	6	6	30.4
26	Bosano-Log.	SA_2	B	174	−41	3	3	17.6
145	Anglona	SI_2	A	354	42	2	7	18.8
22	Bosano-Log.	SA_1	B	160	−43	2	5	16.4?
132	Bosano-Log.	SA_3	B	160	−56	3	6	16.6
39	Anglona	SA_2	B	157	−36	4	7	18.9
148	Bosano-Log.	SI_2	B	341	53	2	4	19.2
134	Bosano-Log.	SI_2	B	342	55	1	4	19.3
116	Anglona	SA_2	B	343	53	3	6	20.2
46	Bosano-Log.	SA_1	B	163	−33	4	9	24.3
119	Gallura	SI_2	B	146	−44	4	6	17.2
23	Bosano-Log.	SA_1	B	145	−59	5	4	17.6?? (18.6)
103	Bosano-Log.	SI_2	B	333	43	2	7	20.6
98	Bosano-Log.	SA_1	B	C 147	−57	5	7	
				F 145	−43	4	3	21.4
72	Sulcis	SA_1	B	333	31	4	10	21.5
11	Anglona	SA_2	B	330	53	9	4	22.9
12	Anglona	SA_2	B	332	49	6	5	22.9
29	Bosano-Log.	SA_1	B	141	−68	7	6	23.8
3	Anglona	M_1t	B	328	58	3	8	69.8
118	Gallura	SI_2	B	144	−44	2	6	16.6
24	Bosano-Log.	SA_1	B	142	−45	6	5	18.2?? (20.6)
133	Bosano-Log.	SI_2	B	328	48	1	4	18.6
41	Anglona	SA_2	B	C 155	−53	5	4	
				F 118	−21	17	6	18.8
30	Bosano-Log.	SA_2	B	139	−40	6	9	18.9
2	Anglona	$M_1\tau$	B	287?	54	2	7	20.3
1	Anglona	$M_1\tau$	B	286?	53	6	5	20.6
8	Anglona	$M_1\tau$	B	281?	60	3	6	21.3
111	Bosano-Log.	SI_1	B	141	−61	3	6	22.6
112	Bosano-Log.	SI_1	B	132	−52	5	5	22.6
75	Sulcis	SA_1	B	130	−59	5	7	23.0
5	Anglona	SA_2	B	356??	−17	5	8	21.1
131	Bosano-Log.	SA_1	B	160	−35		4	24.3
71	Sulcis	SA_1	B	75?	−55	4	6	31.3
106	Bosano-Log.	porf.	B	147	−38	10	10	33.0
55	Bosano-Log.	porf.	B	140	−60	7	8	47.4?

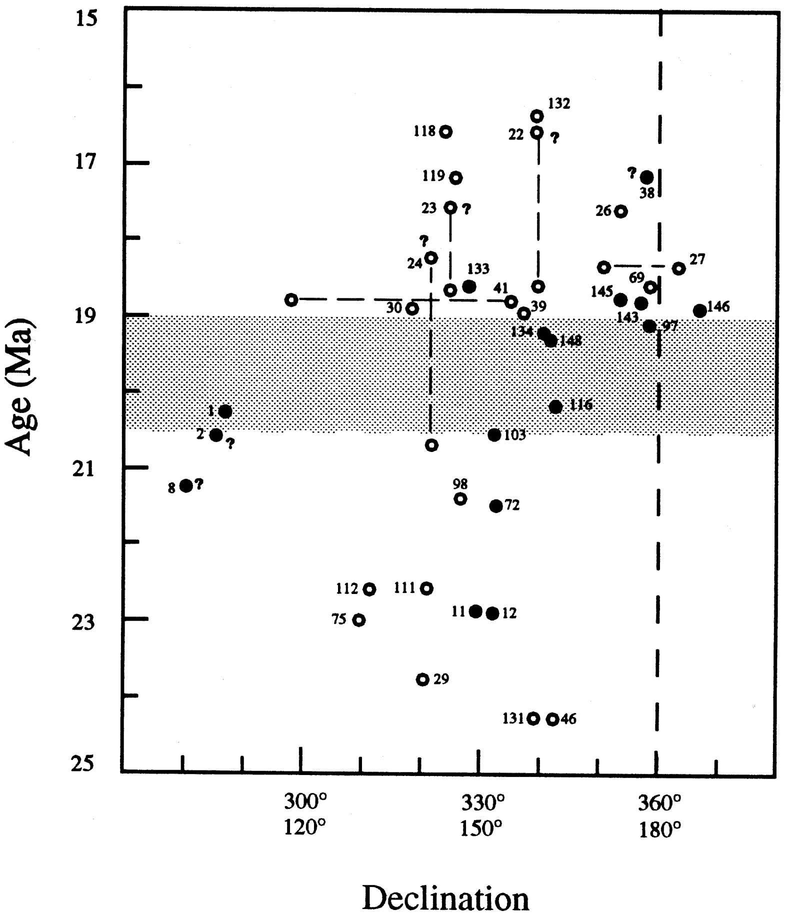

Fig. 2. Magnetic declination versus radiometric age (data from Montigny *et al.*, 1981). Full symbols: normal polarity; open symbols: reverse polarity; question marks: doubtful data (see table II).

If the data distribution suggests that the shift in the magnetic declination may have started between 21 and 20 Ma ago, data younger than 19 appear to be scattered and it is not possible to find a clear age after which all the declinations cluster around a certainly unrotated value. Moreover, uncertainty associated with radiometric dating is often of the order of 1 Ma, and therefore the definition of short time intervals, such as that proposed for the rotation by Montigny *et al.* (1981), should not be based on these absolute ages. It should also be noted that the very first declinations clustering around the northern direction in the fig. 2 (sites 143, 145 and 146 from the Anglona region, and site 97 from the Logudoro region) are upper Ignimbrites characterized by normal polarity. It is noteworthy that rotated data younger than 19 Ma exhibit a reversed polarity (fig. 2). Remagnetization processes may contribute to the measured declinations of these sites, also considering that complex magnetizations have often been found among rock samples from the Anglona region. Even accepting these first northern declinations as true values, it should be considered that only few reliable data (about 10 values cover the time span between 19 and 15 Ma) are utilized to assess the end of the rotation. Considering the statistical nature of these data, the possible presence of errors in both the paleomagnetic measurements and the radiometric dating, and considering that paleo-secular variation in the Earth magnetic field may have affected part of these findings, we do not consider the results plotted in fig. 2 as an unquestionable basis to constrain the end of the rotation.

3.1 *Paleomagnetic direction of regional data*

The above considerations take into account the amount of rotation of each single site, separately. This approach is not beyond critical evaluation because the data derive from volcanic rocks which, from a paleomagnetic point of view, have some limits: first, volcanic rocks cool rapidly, and therefore their magnetization represents only a spot of the geomagnetic field which is not averaged for secular variation; second, in volcanic series it is generally difficult to recognize any tilt, so it is difficult to apply a tectonic correction to the data. For these reasons, paleomagnetic measurements carried out on volcanic rocks can only have a statistical meaning, and their significance depends on the number of studied sites. Since the number of the paleomagnetic sites with known absolute age is small when compared to the available paleomagnetic data, we analyzed by the Fisher statistics (Fisher, 1953) all the paleomagnetic data from the most studied regions: Bosano-Logudoro and Anglona. In the absence of absolute dating, the temporal drift of the paleomagnetic direction can only be evaluated by comparing declination values of rocks sampled at different stratigraphic levels. Even if attempts have been made to correlate the volcanic units from different regions, it is a delicate task to establish the relative ages of magnetic directions belonging to different geographic areas. The volcanic activity was discontinuous and it is difficult to define chrono-stratigraphic correlations based on lithological evidences. Even when it is possible to find petrographic links and stratigraphic analogies between the volcanic units, the resulting correlation does not necessarily mean that the sequences are strictly coeval. Since volcanic series in Bosano-Logudoro outcrop over a wide area and they often overlap in time (table I), for each series we calculated paleomagnetic mean directions grouping sites according to their geographical locations. We analyzed all the existing data but few showing very anomalous directions, uncompatible with a dipolar magnetic field (for example: south directions with positive inclinations), were discarded. Also we did not take into consideration some sites studied by early authors (*i.e.* Bobier and Coulon, 1970) because the stratigraphic attribution to the volcanic units was problematic in the field as recognized by the same authors.

a) *Bosano-Logudoro*

These regions represent the classical sequence of the Tertiary volcanism of Sardinia. Here the volcanic activity lasted for the longest time and here most of the volcanic series defined by Coulon *et al.* (1974) outcrop in stratigraphic sequence. Since the end of the 1960s they have been the subject of paleomagnetic investigations, with more than 100 sites studied by several authors (fig. 3) (Bobier and Coulon, 1970; Coulon *et al.*, 1974b; De Jong *et al.*, 1969; Edel, 1979).

The seven volcanic series were divided in twelve areas: 3 areas for SA_1 (A, B, C); 2 for SI_1 (D, E); 3 for SA_2 (F, G, H); 2 for SI_2 (I, L); 1 for the Dacite of M. Frusciu and Cossoine (M), and 1 for SA_3 and the Rhyolite of M. Traessu (N). The latter grouping is justified by stratigraphic considerations, but may be questionable because of ages discrepancy exhibited by the rocks from M. Traessu. Coulon *et al.* (1974) detected a whole-rock radiometric age of 16.8 Ma for these rhyolites. A similar age (17.2 Ma) was found by Edel (1980) on plagioclases, but the most reliable biotites exhibited an older age of 19.3 Ma. The results from the lower Andesites (SA_1) at Capo Marargiu studied by Coulon *et al.* (1974b) have been considered before the tectonic correction applied by the author because the data do not improve after this correction,

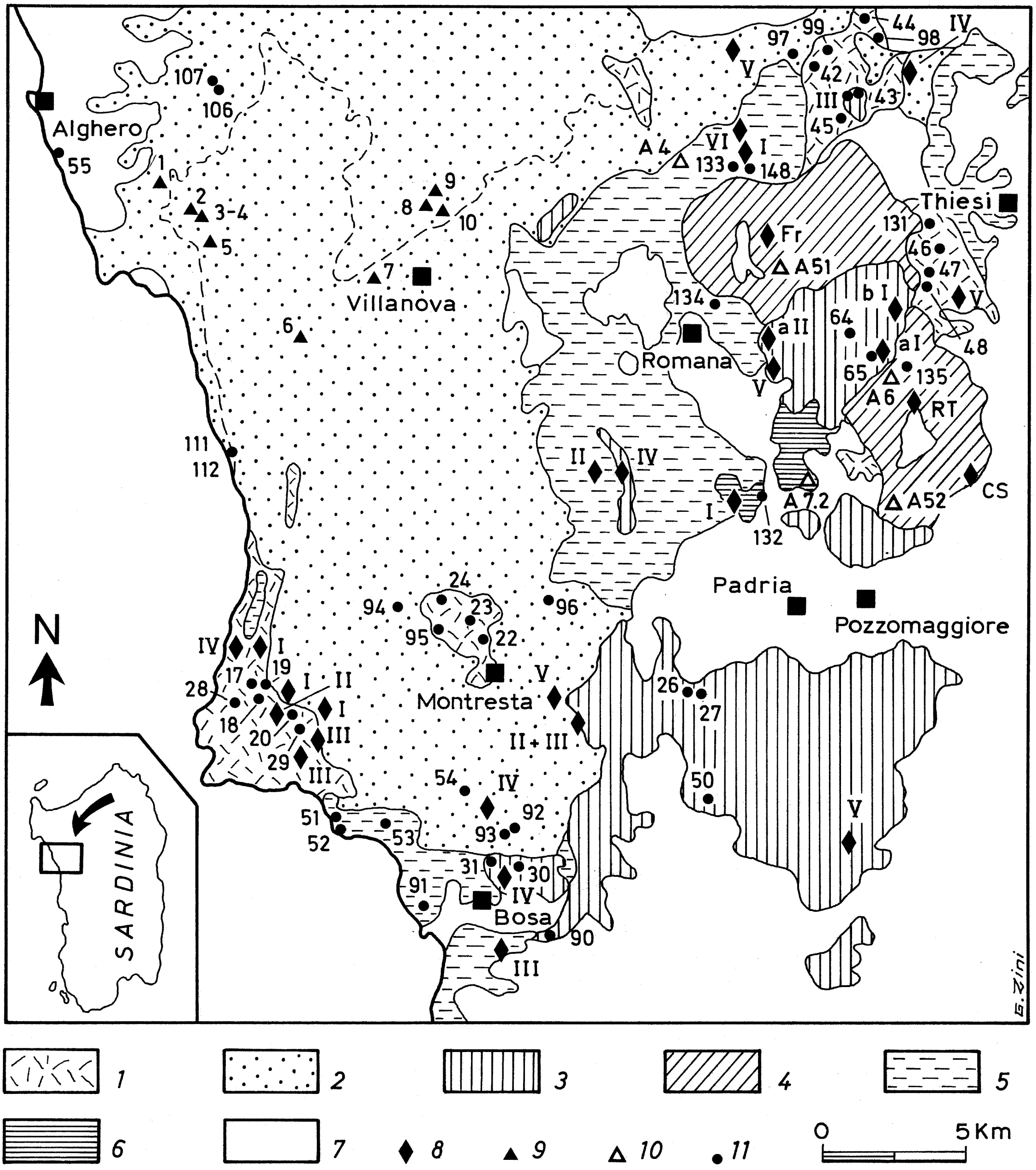

Fig. 3. Geological sketch-map of the Bosano and Logudoro region (re-drawn after Edel, 1980). 1: Lower Andesitic series (SA_1). 2: Lower Ignimbritic series (SI_1). 3: Upper Andesitic series (SA_2). 4: Rhyolites and Dacites (M. Frusciu and Cossoine). 5: Upper Ignimbritic series (SI_2). 6: Terminal Andesites (SA_3). 7: Plio-Quaternary. 8: Paleomagnetic sites studied by Coulon *et al.* (1974b). 9: Paleomagnetic sites studied by De Jong *et al.* (1969). 10: Paleomagnetic sites studied by Bobier and Coulon (1970). 11: Paleomagnetic sites studied by Edel (1979).

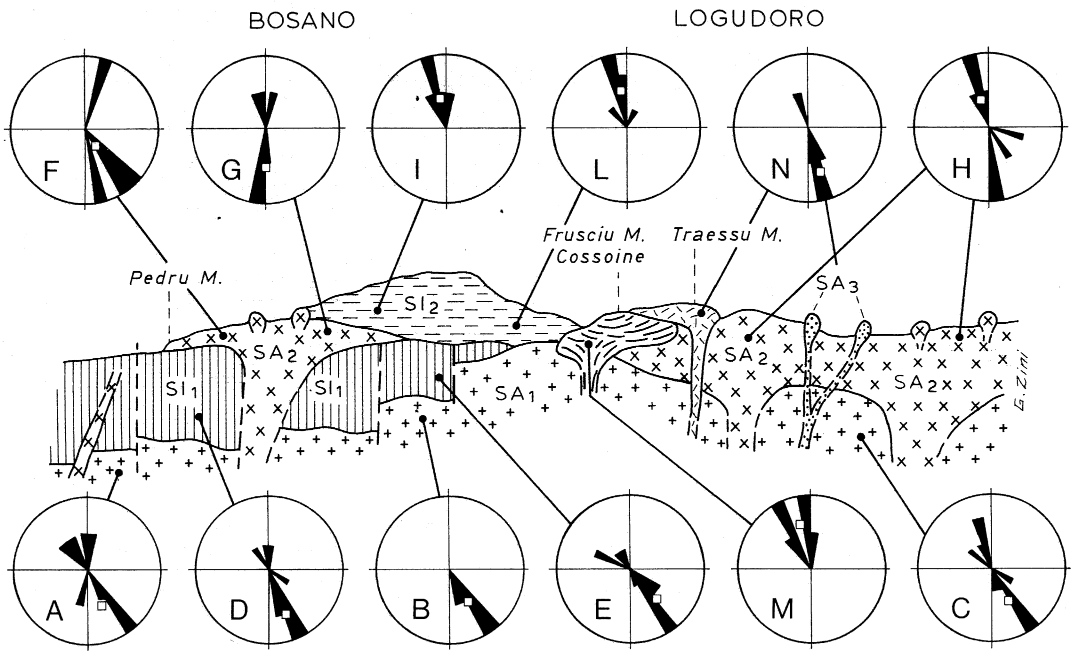

Fig. 4. Theoretical stratigraphic relationships of the volcanic series in the Bosano-Logudoro regions (re-drawn after Coulon *et al.*, 1974b). In the rose diagram are plotted the paleomagnetic declinations (open square for mean value) of the studied sites grouped according to a geographical location. Letters (A-N) refer to the groups as reported in table III.

and the amount of tilting is not well constrained.

The results are reported in table IIIa and plotted in fig. 4. The oldest volcanic series such as the lower Andesites and Ignimbrites (SA_1 and SI_1) are characterized by clear north-western (south-eastern) declinations, testifying to their pre-rotation emplacement. Younger series as the upper Andesites and Ignimbrites (SA_2 and SI_2) yield slightly more northerly directions, but even the youngest series as the terminal Andesites (SA_3), the Rhyolites of M. Traessu ($\tau3$), or the Dacites of Cossoine and M. Frusciu ($\tau3$) show mean declination values still compatible with rotation. The only exception is represented by the upper Andesites from the Padria region (fig. 4, group G) which show a mean direction clearly aligned with the north. The clear N-S antiparallel direction exhibited by the rocks from this area excludes effects related to secular variation. A local incorrect tilting may account for this direction justifying our geographical subdivision of the data.

The statistical parameters do not demonstrate a great grouping of the data especially for the younger series because the number of the studied sites is quite low. For this reason any quantitative relationship between the emplacement of these units and the amount of rotation can be hardly constrained. However it should be noted that in most of the cases the northern directions appear only in rocks with a normal polarity, which could indicate possible remagnetization. The weathering of these rocks is sometimes quite severe, as recognized also by Edel (1980) who suggested that these processes affected the magnetization of the

Table III. Continued.

ANGLONA (b)

Site	n/N	D	I	α_{95}	Ref. (note)
Series α					
14	8/9	134	−7	4	B (s)
32	7/7	307	67	5	B
33	8/8	322	11	3	B
39	12/1	160	−35	8	B (c)
40	9/15	321	55	8	B
41	4/6	155	−53	5	B (c)
66	9/9	123	−17	2	B
115	7/8	8	47	3	B
116	6/7	343	53	3	B
129	12/1	316	67	5	B
130	7/9	8	50	10	B
11	4/9	330	53	14	B
12	5/10	332	49	6	B
15	5/5	349	27		B (*)
38	6/6	358	48	4	B
1		326	12		D
2		318	12		D
3		326	5		D
4		326	14		D
5		130	−65		D
6		110	−62		D
7		119	−49		D
147		9	44	6	C
M	23/23	329.4	41.2	10.3	K=10
Series M_1t					
67	11/1	143	−56	10	B (c)
3	8/11	328	58	3	B
36	5/5	358	48	4	B
120	3/15	130	−64	5	B (c)
124	8/9	131	−70	8	B (c)
126	5/5	5	56	4	B (s)
127	9/9	159	−60	7	B (c)
128	9/11	148	−61	5	B
4	6/7	359	57	4	B
6	6/6	358	54	10	B
121	9/9	331	64	4	B
122	6/9	335	60	7	B (s)
123	3/5	352	62	7	B (s)
8		334	64		D
9		322	74		D
M	15/15	339.1	61.6	5.1	K=575

Site	n/N	D	I	α_{95}	Ref. (note)
Series $M_1\tau$					
2	7/7	287	54	2	B
7	4/4	281	57	13	B
8	6/6	281	60	3	B
1	5/6	286	53	6	B
125	9/10	166	−31	2	B
10		324	72		D
11		328	69		D
12		287	62		D
13		301	56		D
14		272	52		D
15		296	56		D
16		306	56		D
M	12/12	299.3	58.6	8.9	K=25
Series SI_2					
143		357	47	3	C
145		354	42	2	C
146		7	58	4	C
17		360	51		D
18		359	46		D
19		6	52		D
20		6	46		D
21		8	62		D
32		358	55	12	G
33		1	48	14	G
34		2	45	16	G
M	11/11	1.3	50.3	3.8	K=144

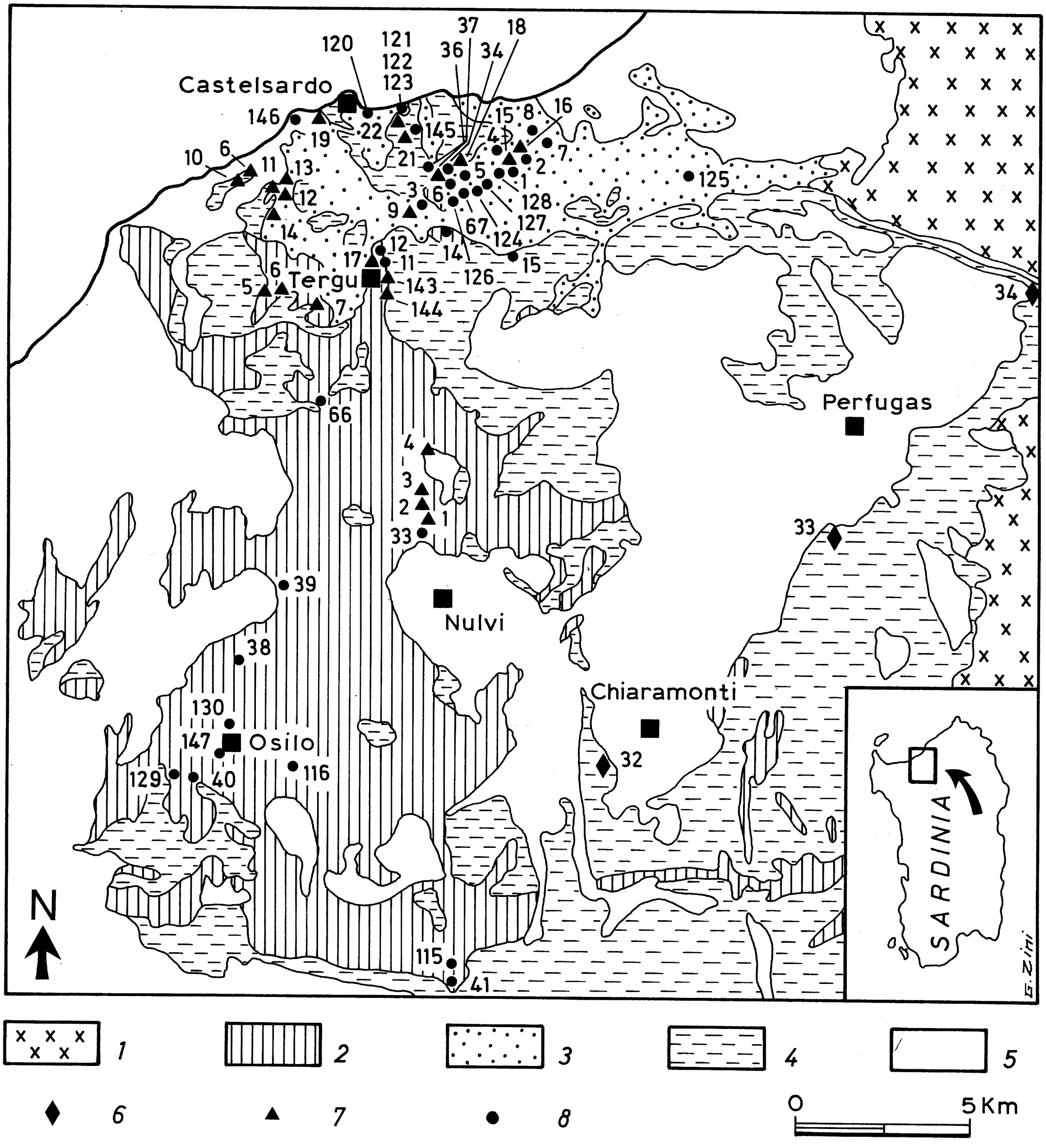

Fig. 5. Geological sketch-map of the Anglona region (re-drawn after Edel, 1980). 1: Paleozoic basement. 2: Andesitic Series (α). 3: Tuff and sedimentary layers (M_1t) with intercalated ignimbrites ($M_1\tau$). 4: Upper ignimbritic series (SI_2). 5: Tertiary and Quaternary sediments. 6: Paleomagnetic sites studied by Manzoni (1974). 7: Paleomagnetic sites studied by De Jong *et al.* (1973). 8: Paleomagnetic sites studied by Edel (1979) and Montigny *et al.* (1981).

lower Andesites at Capo Marargiu, where some sites exhibited northern direction (fig. 4, group A).

b) *Anglona*

As described in section 2, only four units have been recognized in the Anglona region (fig. 5). The simple stratigraphic relationships between the units are summarized in fig. 6, where the paleomagnetic data are also plotted on rose diagrams. The results relevant to these volcanic units are reported in table IIIb. The Andesites (α) show clearly north-western declinations, implying that they were emplaced before the rotation. The overlying tuffs and sedimentary layers (M_1t) appear characterized by both the northern-western and northern values, suggesting that the rotation took place during their deposition. Nevertheless some inconsistencies within the sequence make this interpretation dubious. Rotated and unrotated directions are separated and only rotated directions can be found with reversed polarity (fig. 6). Paleomagnetic data from this unit were carried out by (Edel, 1979, 1980) in the classic section of Punta Molino, near Castelsardo. This section has been recently re-studied by Vigliotti and Langenheim (1992) who found a complex paleomagnetic record in most of the outcropping rocks, probably resulting from widespread remagnetization processes. Intervals with a well defined magnetic vector exhibited only rotated directions. The western mean direction of the intercalated Ignimbrites ($M_1\tau$) could be related to a secular variation of the geomagnetic field. The mean direction of upper Ignimbrites (SI_2), which

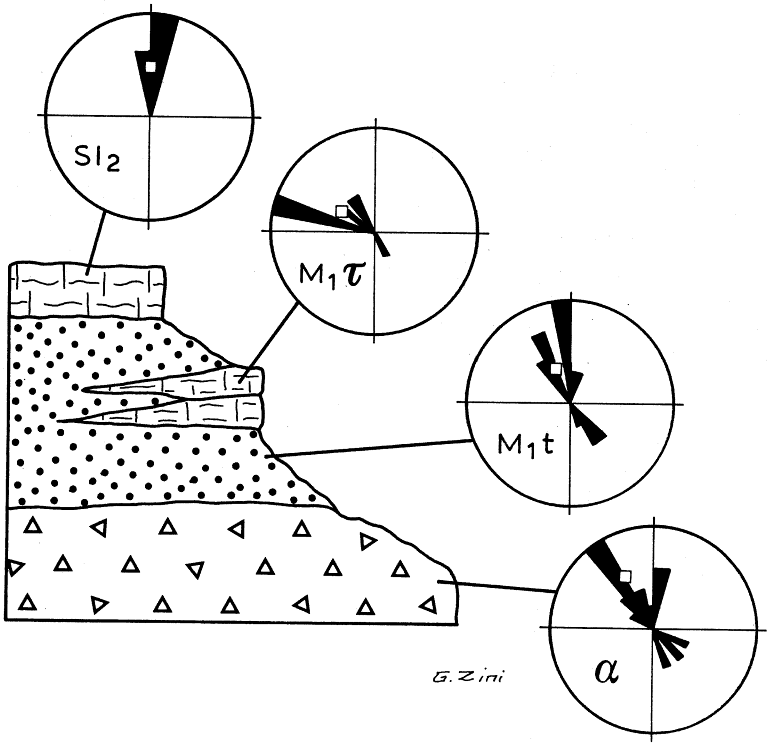

Fig. 6. Theoretical stratigraphic relationships of the volcanic series in the Anglona region (re-drawn after Edel, 1980). Rose-diagrams show the paleomagnetic directions (open square for mean value) reported in table IIIb.

have been radiometrically dated about 19 Ma (Montigny *et al.*, 1981), are clearly unrotated and this result is the only one supporting the hypothesis of Montigny *et al.* (1981).

4. Conclusions

The existing paleomagnetic data from Sardinian Tertiary volcanics well support a beginning of the rotation between 21 and 20 Ma as suggested by Montigny *et al.* (1981). It is noteworthy that this time coincides with the maximum volcanic activity on the island (Beccaluva *et al.*, 1985). More questionable appears the entire length of the rotation. The existing paleomagnetic data do not constrain the time for the end of the rotation. Two reasons account for this: first, the primary interest of most of the authors was to verify the rotation and not the timing; second, the volcanic activity decreased toward the end of the Burdigalian and therefore volcanics of the appropriate age (and paleomagnetic data) are missing. Directions found in the upper Ignimbrites from the Anglona region (radiometric age: 18.5-19.7 Ma; Montigny *et al.*, 1981) support a post-rotation emplacement, however the secular variation of the geomagnetic field may have an important role on this direction. Data from the Bosano-Logudoro regions show some amount of the rotation even in rocks as young as 16.5 Ma. Middle-upper Burdigalian sediments from the St. Florent basin in Northern Corsica exhibited a direction (D=164.6; I=45.9) compatible with an amount of rotation (Vigliotti and Kent, 1990). If the two islands moved as a whole, these results imply that the rotation lasted for a longer time than the previously suggested 1.5 Ma. A longer and younger rotation is also in agreement with the timing of the geodynamic evolution of the adjacent areas (Tyrrhenian basin, Apennines). Moreover it matches well with the duration of the volcanism in the island.

New paleomagnetic data on both volcanics and sedimentary rocks from Sardinia (Vigliotti and Langenheim, 1992) suggest that the rotation was still to be completed in Langhian times implying that it lasted not less than 5 Ma.

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