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Palaeomagnetic Study of the Tertiary Volcanics of Sardinia

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Abstract. A thorough investigation of the Sardinian Oligo-Miocene calc-alkaline volcanics has been carried out in Anglona, Logurodo, Bosano and Sulcis. Standard palaeomagnetic techniques applied to 790 specimens representing 94 sites of ignimbrites, andesites, and tuffites show that the magnetic and palaeomagnetic properties vary with the petrographic nature of the rocks. Thermomagnetic curves in high field as well as thermal and alternating field demagnetization reveal the importance of secondary magnetization, mainly due to regional hydrothermal alteration. Except for the upper ignimbritic layer the directions of characteristic magnetization considered as original TRM are scattered around the mean direction $D=332°$, $I=52°$ with $k=22$.

Key words: Sardinia – Palaeomagnetism – Oligo – Miocene volcanics.

1. Introduction

The geological structure of Sardinia consists essentially of a Palaeozoic basement cut by a Tertiary graben which is oriented NS in the northern part and NW-SE in the southern. This graben is filled by thick and massive volcanic and volcano-sedimentary series (Fig. 1). The volcanism can be subdivided into two cycles. The first, of calc-alkaline type, began at the limit Oligocene-Miocene and ended in the middle Miocene. The second of alkaline type, succeded the middle Miocene marine transgression.

This large volcanic region has attracted several groups of palaeomagnetists, interested in the movements of Sardinia (de Jong et al., 1969, 1973; Bobier and Coulon, 1970; Coulon et al., 1974; Bobier, 1974; Manzoni, 1974, 1975). The diverse palaeomagnetic investigations have generally given comparable results but the ensuing interpretations are rather divergent.

In the Plio-Quaternary alkaline lavas, all authors agree that the directions of the characteristic magnetization are close to the present N direction. In the calc-alkaline lavas, de Jong et al. (1969, 1973) and Manzoni (1974, 1975) found dominent NW directions of magnetization. They explain the transition from NW directions to N directions by an anticlockwise rotation of Sardinia relative

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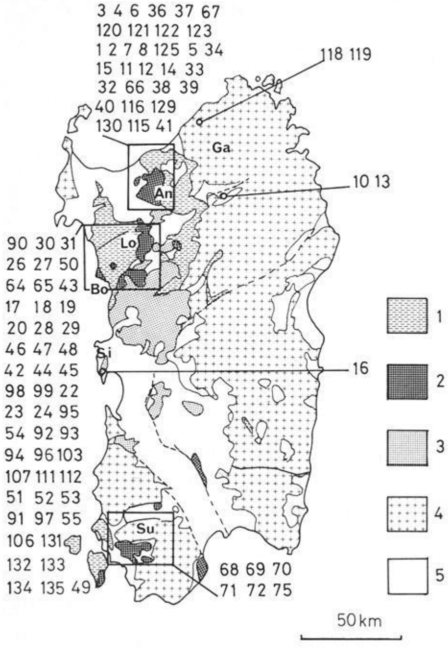


Fig. 1. Geology of Sardinia and location of sampling sites (*numbers*). 1: Tertiary ignimbrites; 2: Tertiary andesites; 3: Plio-quaternary basalts; 4: Palaeozoic basement; 5: sediments; *An*, Anglona; *Ga*, Gallura; *Lo*, Logudoro; *Bo*, Bosano; *Si*, Sinis; *Su*, Sulcis

to Europe. Bobier (Coulon et al., 1974; Bobier, 1974) did not find such NW directions in the lower unit of the calc-alkaline volcanics. Thus he proposed two other solutions. In the first he explains the NW directions by secular variations and anomalous positions of the geomagnetic field during a reversal. The second involves two successive rotations in opposite directions.

To remove this incertainty a thorough investigation of the Sardinian volcanics was required. This study had to deal with the largest stretch of geological time and the widest geographical sampling possible. Preliminary results based on 55 sites were in agreement with the hypothesis of a rotation during the calc-alkaline volcanism (Edel and Lörtscher, 1978). Nevertheless they showed a rather important scatter of the directions. A more detailed investigation, based on a better separation of the different components of the natural remanent magnetization was necessary. In the present paper these results have been refined by measurements of supplementary specimens and enhanced by complete investigations on 39 new sites. To obtain better information on the palaeomagnetic quality of the different rocks, their properties and their behaviour during both alternating field demagnetization and heating up to the Curie temperature, have been measured.

2. Geological Setting and Sampling

In Logurodo and Bosano, Coulon et al. (1974), Coulon (1977) distinguish several series in the calc-alkaline volcanics

– a lower andesitic series, SA1 (or α_1 on the geologic maps 'Alghero' and 'Bonorva'

– a lower ignimbrites series SI1 (τ_1, t_1)

– an upper andesitic series SA2 (α_2)

– the dacites of Cossoïne and M. Frusciu (τ_3)

– the rhyolite of M. Traessu (τ_3)

– an upper ignimbritic series SI2 (τ_2, t_2)

All these units have been sampled for palaeomagnetic studies. Nevertheless it is often not possible to know in which series one is, and the geologic maps include several errors.

In Anglona the geologic map 'Castelsardo' shows three main series

– an andesitic series (α) that Coulon compares to SA2 (personal communication)

– a volcano-sedimentary series (M_1t) consisting of a succession of tuffitic and sedimentary layers and of intercalations of ignimbrites ($M_1\tau$)

– an upper ignimbritic series (τ_2) which is the same in Logudoro and Bosano.

Our sampling concerns α, M_1t and $M_1\tau$.

In Sulcis (SW of Sardinia) the geologic map 'Iglesias' mentions undifferentiated andesites (α) and liparites (τ). Both have been sampled.

In Gallura and near Oschiri the samples of sites 118, 119, 10, 13 have been taken in ignimbrites overlying the granitic basement.

Our study is based on measurements on 790 specimens representing 549 samples and 94 sites. Figure 1 shows the distribution of the sites as follows: 32 sites in Anglona, 51 in Bosano and Logudoro, 6 in Sulcis, 2 in Gallura, 2 near Oschiri and 1 in Sinis. Sites 49 and 16 belong to the Plio-quaternary alkaline volcanics.

The samples of sites 1 to 33 have been broken off in hand samples, oriented with an horizontal plaster cap (geog. N, mag. N) and cut into 43 mm cubes. The samples of the succeeding sites have been drilled and cut into 25 mm cores. Each sample is composed of 2 to 5 specimens.

3. Magnetic Properties of the Calc-Alkaline Volcanics

To study the magnetic properties of the different rocks which compose the calc-alkaline series, we have measured different parameters such as the 'natural remanent magnetization' (NRM), the rate of viscosity (Iv) and the susceptibility (K). The equipment used for measurements consists of a Spinner magnetometer P.A.R. SMI and a Digico magnetometer. Susceptibility is measured in a field of 0.7 mT and 10 kHz with a susceptibility bridge. We consider the results now and discuss them later.

Figure 2 shows the behaviour of the NRM (J), the susceptibility (K) and the Koenigsberger factor (Q) for the three main volcanic rocks, ignimbrites, andesites and tuffites. Each sample is represented by a point. J is weakest for the tuffites. For the lower values, a trend at Q=constant can be observed.

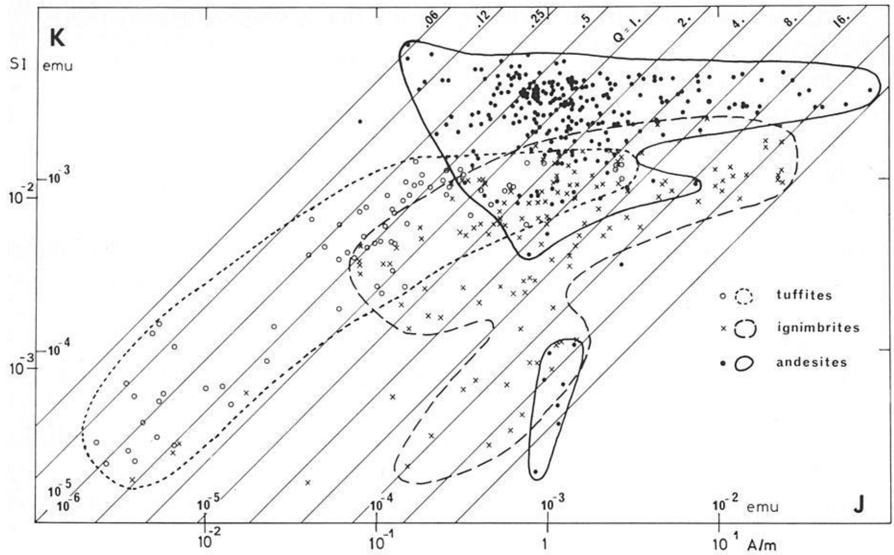


Fig. 2. Intensity of NRM (J), susceptibility (K) and Koenigsberger factor (Q)

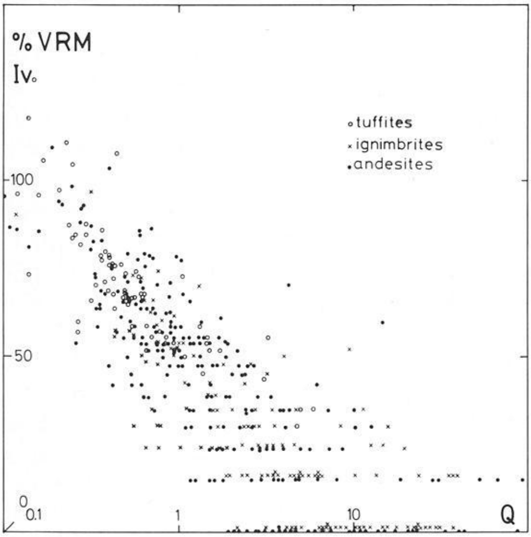


Fig. 3. Viscosity (Iv) and Koenigsberger factor (Q)

This is also visible for the samples at the same site. The behaviour of the andesites is quite different. J varies between 10^{-1} and 10^{-2} A/m but K remains rather constant. This observation can also be made at numerous sites. The greatest density of population corresponds to $J=1$ A/m, $K=3{,}7\ 10^{-2}$, and consequently $Q=0{,}74$. For the ignimbrites the distribution is intermediate. The remanence is comparable with that of the andesites but the susceptibility is generally weaker. At any one site the trend looks sometimes like that of the tuffites but more often it is also intermediate.

The samples were stored for 3 weeks in a normal laboratory field. After measurement of the NRM, they were inverted and left for about 3 weeks in a reverse laboratory field. The quantity of viscosity if given by:

$$Iv = 100 \times \frac{|\mathbf{M}_1 - \mathbf{M}_2|}{|\mathbf{M}_1 + \mathbf{M}_2|} \%$$

with: $\mathbf{M}_1$ = NRM vector in the normal field position
$\mathbf{M}_2$ = NRM vector in the inverted field position

Figure 3 shows the distribution of the samples in a logarithmic diagram of Iv against Q. The points seem to be scattered about a straight line. Thus, Iv is a function of the type $Iv = \mathrm{a}/Q^{\log \mathrm{a}}$. The quantity of viscosity decreas Q increases. For $Q > 0.2$, the scatter is least for the tuffites and greatest for the ignimbrites. The scatter increases as Q increases.

4. Magnetic Properties After Alternating Field and Thermal Demagnetizing

Thermomagnetic Curves

Our aim is to assess the magnetization acquired during the cooling of the lavas. Theoretically the coercivity is greater for that magnetization than for secondary magnetization acquired later. Usually, the blocking temperature is also higher for that primary magnetization. Therefore we have tried to eliminate the secondary magnetizations by applying an alternating magnetic field and by heating the samples up to the Curie temperature. Our equipment allows us to reach alternating fields of up to 150 mT. All specimens have been demagnetized. At least one specimen per site has been heated up to 550°–600° C. The alternating field demagnetization for all other specimens has been done at 5 to 15 different field intensities.

Figure 4a shows some examples of the behaviour of the intensity after alternating field demagnetization. Figure 4b gives the variations of the intensity of the remanent magnetization and of the susceptibility after heating at different temperatures and after cooling in null field. Thermomagnetic curves obtained with a horizontal Curie balance (Artzt, 1972) in a high field (0.5 T) complete the study of the magnetization with temperature (Fig. 5).

Typical curves for ignimbrites are given by samples 54211 and 54212 (54:number of the site, 2:number of the sample, 11 and 12:number of the specimens). They shows a strong coercitivity and a blocking temperature higher than 600° C. An intermediate inflection appears on some intensity curves and on some susceptibility curves (53112, 7312). Thermomagnetic curves in high field show often a similar behaviour (Lörtscher, 1976).

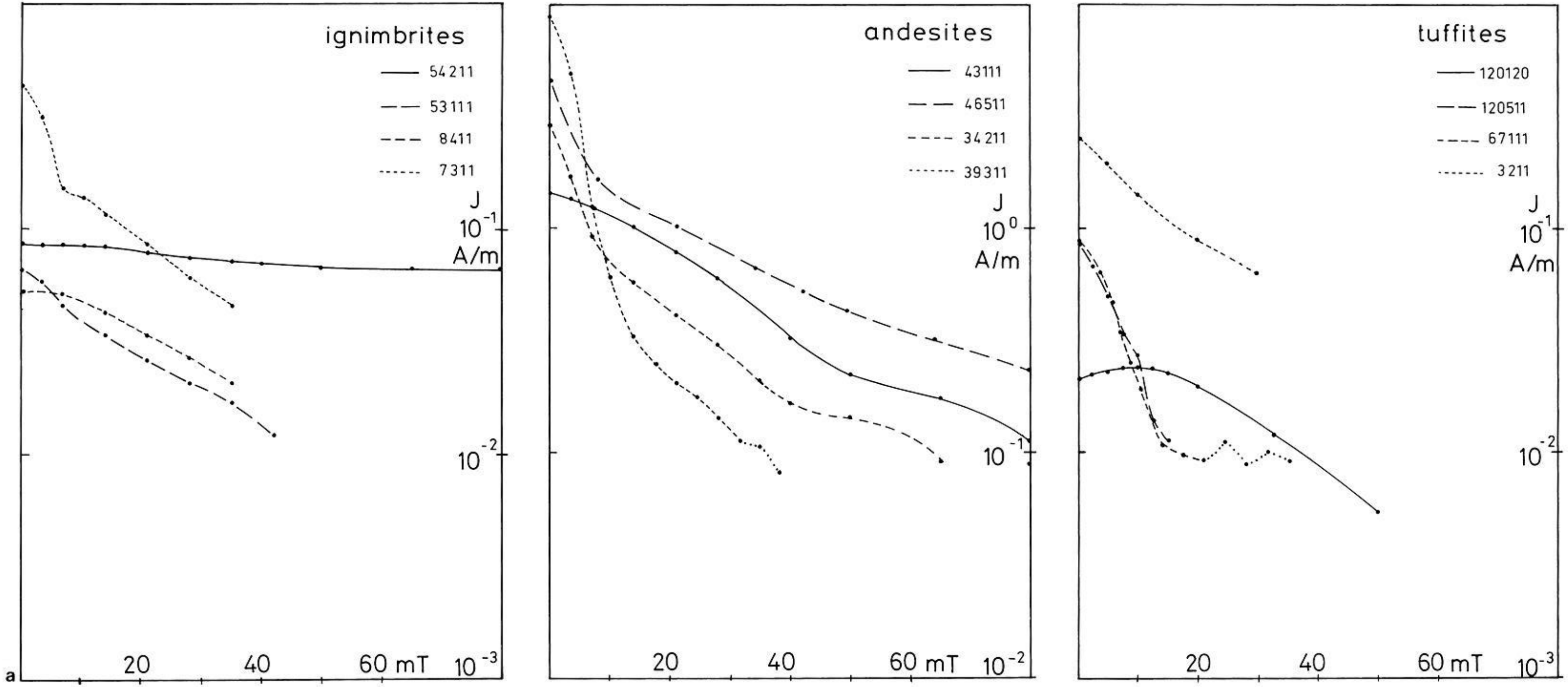
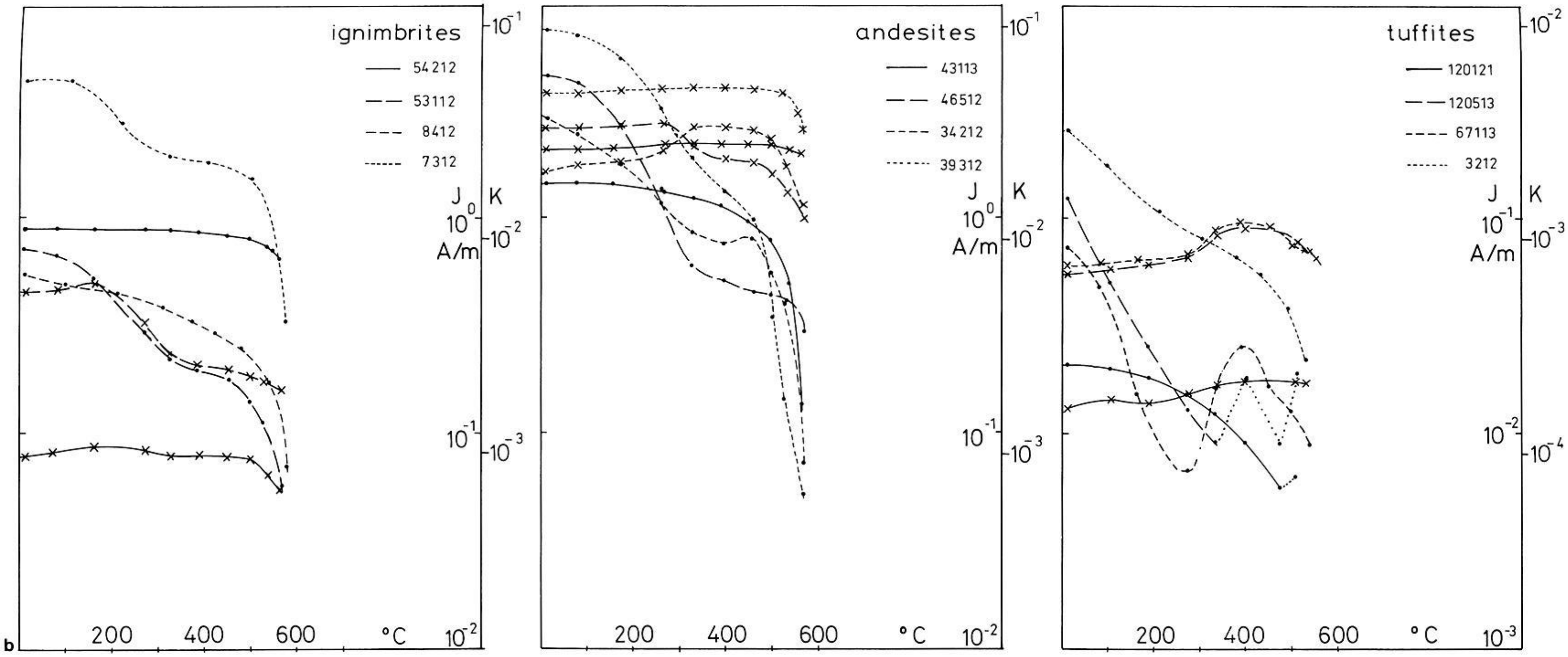


Fig. 4a and b. Typical results of: **a** alternating field demagnetization; **b** thermal demagnetization. (.) remanence intensity J, (x) susceptibility K as a function of temperature


b
ignimbrites
54212
53112
8412
7312
J
K
10^{0}
A/m
10^{-1}
10^{-2}
10^{-1}
10^{-2}
10^{-3}
200
400
600
°C
andesites
43113
46512
34212
39312
J
K
10^{0}
A/m
10^{-1}
10^{-2}
10^{-1}
10^{-2}
10^{-3}
200
400
600
°C
tuffites
120121
120513
67113
3212
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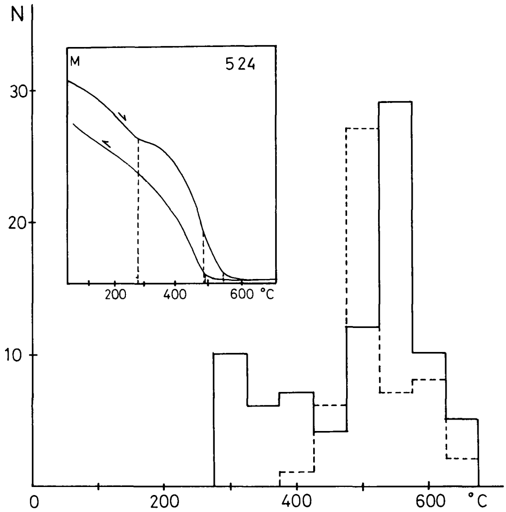

Fig. 5. Curie temperature distribution; *Full line,* heating; *dashed line,* cooling

The andesites show more variable coercivities. Demagnetization was obtained for samples 43111 and 43113 without any problem. The coercivity is strong and the temperature curve is a typical curve for a magnetite poor in titanium. But more often this is not the case. The NRM is mainly due to a secondary magnetization which disappears sometimes rather quickly at 10–20 mT (39311). The intermediate temperature of 300° C appears on many curves: at that temperature the susceptibility can either decrease or increase (46512, 34212).

The tuffites have two types of behaviour. In one, the coercivity is rather strong and after heating the intensity decreases slowly (120120, 120121). In the other, the NRM is essentially due to a magnetization with a weak coercivity. The intensity decreases quickly up to 300° C, then either increases again, or begins to oscillate. At 300° C the susceptibility increases slightly.

5. Components of the Normal Remanent Magnetization

When the coercivity spectra of the different magnetizations which compose the NRM are distinct, it is possible by a judicious demagnetization to separate the directions of the magnetizations. Our demagnetization procedures have yielded several patterns shown as cases (a) and (b) in Fig. 6.

In case (a) which corresponds to the majority of the ignimbrites, the NRM is composed of only a secondary magnetization, which is mainly a very weak viscous magnetization, and a primary magnetization which can be considered to be the characteristic magnetization. That primary vector can either be easily demagnetized (a1) or not (a2) and then directions begin to oscillate. These oscillations are a function of the rock and of the demagnetizing equipment.

In case (b) which is very often that for the andesites and the tuffites, we have obtained three components: the viscous magnetization which rapidly disap-

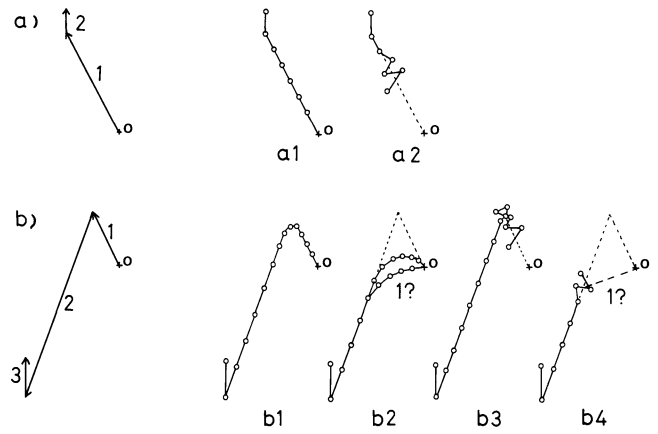

Fig. 6. Components of the NRM (schematic representation). Types of demagnetizations

pears, a secondary and a primary magnetization. In the best case, all components can be separated (b1). Usually the direction of the secondary vector can also be determined. This is not always the case for the primary. When the coercivity spectra overlap, one demagnetizes the primary as well as the secondary magnetization (b2). Many andesites show such a behaviour. Sometimes, especially in the tuffites, the directions begin to oscillate during the demagnetizing of the secondary magnetization (b4), or only at the begining of the demagnetizing of the primary (b3). In cases (b2, b3, b4), the directions obtained after demagnetizing are scattered and the mean direction does not give the direction of the characteristic magnetization. However at a homogenous site the planes defined by the secondary and the primary vectors must intersect along a common line which is the direction of the primary vector (Halls, 1976). This computation has always be done when the demagnetization did not show a clear primary vector such as that in cases (a1 and b1). An example is given by site 55 in Fig. 7.

6. Palaeomagnetic Properties of the Different Calc-Alkaline Volcanics

On many temperature versus intensity of remanence curve (Fig. 4) as well as on the thermomagnetic curves in high field (Fig. 5), we have observed an intermediate Curie temperature of about 300° C. The susceptibility curves also show an inflection at the same temperature. Similar thermomagnetic diagrams have been found for oceanic dredged basalts by Ade-Hall (1964) and Wasilewski (1968). Readman and O'Reilly (1970) obtained analoguous results with synthetic titanomaghemite in a vacuum. Ade-Hall and al. (1971) explain such thermomagnetic behaviour of continental basalts by a regional hydrothermal alteration. This alteration acts in an environment of the zeolite metamorphic facies and produces new magnetic phases.

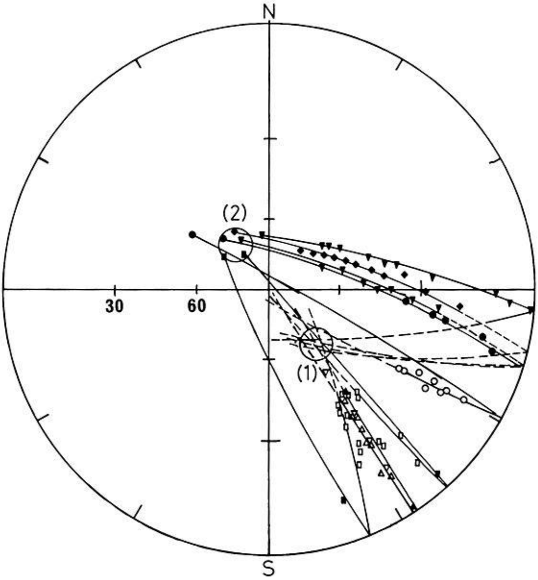

Fig. 7. Example (site 55) of secondary (2) and primary (1) magnetization directions. The primary direction is given by the intersections of the demagnetizing planes. Each symbol represents a specimen

We have observed zeolites on several thin sections of our samples, as has Baque (1974). Thus the hypothesis of Ade-Hall and al. (1971) may also hold for the calc-alkaline rocks of Sardinia. Regional hydrothermal alteration would be the most important creator of secondary magnetizations. However the effects vary with the petrographic nature of the rocks.

In the tuffites one distinguishes two types; those which constitute a good palaeomagnetic material and the others. In the first type the opaque grains are small. They correspond to samples which show a Q=constant trend (Fig. 2). In the case of monodomain grains, remanence and susceptibility are due to the same grains and when the number of grains increases, J and K increase together and Q remains constant. So it is possible that in our case the monodomain grains are dominant. Their demagnetizing curves indicate a great coercivity and a Curie temperature between 500° and 580° C. The demagnetizing process allows the determination of the primary direction. In the second type, which is the more usual, the opaque grains are rather big (0.1 mm). The viscosity is important. The demagnetizing process reveals essentially a secondary magnetization which can be attributed to hydrothermal alteration. The coercivity is weak but at 16 kAm^{-1} (200 Oe) the remanence begins to oscillate and it is often impossible to obtain the primary direction. Similar difficulties arise after heating up to 300° C. Sometimes the demagnetizing curves look like typical (a1) curves. Nevertheless the latter considerations show that the vector would only be composed of a secondary magnetization and the primary would have completely disappeared.

The andesites show many types of behaviour and to discuss how they are distinguished would take to long. Only one distinction can be made: some of the NRM correspond to type (a), others to type (b). The first (samples 43111, 43112 on Fig. 4) do not present any difficulty. The others are more

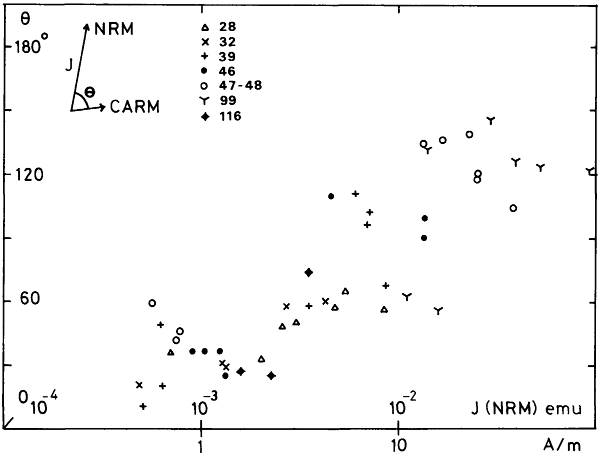

Fig. 8. Intensity of NRM (*J*) and angle (*θ*) defined by NRM and CARM

complicated. In Fig. 2 we noted that in a plot of *J* against *K*, *K* remains quite constant. For an intensity of the NRM higher than 1 A/m, we observed a correlation between the intensity *J* (NRM) and the angle *θ* defined by NRM and CARM (characteristic magnetization) (Fig. 8): *θ* increases as *J* increases. This means that a relatively strong secondary magnetization has been acquired in a reversed field to the TRM field. This is available for sites with normal and reversed polarity. For some specimens one can observe that *θ* increases with *J* as well as with the degree of alteration. When the NRM is strong (> 1 SI), the viscosity is weak and then the secondary magnetization is probably a chemical. The intermediate Curie temperatures allows us to attribute this chemical magnetization to the hydrothermal alteration. Often the primary direction can be defined, usually by the intersections of the demagnetizating planes. Nevertheless in some cases the secondary magnetization has a Curie temperature of up to 600° C. Such thermomagnetic curves can be explained by deuteric oxidation (Ade-Hall et al., 1971). Then it is often not possible to find a primary direction. As well as for tuffites a demagnetizing curve (a) can be a demagnetizing curve (b) (Fig. 6) for which the TRM has disappeared. So one confound the secondary chemical magnetization with the TRM.

The ignimbrites are by far the best material for palaeomagnetic studies in Sardinia. The weak viscous magnetization disappears quickly. When they exist the secondary magnetizations can be eliminated easily.

7. Directions of the Remanent Magnetizations and Interpretation

All informations on the directions of secondary and primary magnetization are given in Table 1. These directions which have been judged representative for a site are illustrated in Fig. 9.

Table 1. *Site*, site number; *Loc*, topographic maps, 1/25 000e; ×, longitude; *Y*, latitude; *Dip*, direction and dip of max. slope; *d*, method of demagnetizing (Fig. 4); *a*, primary (1) or secondary (2) magnetization; *s*, Fisher statistic (F) or intersect of the demagnetising planes (C); N/N_0, number of samples taken for the mean direction computation (N) and total number of samples (N_0); $\mu/n/n_0$, number of specimens taken for the mean direction computation (μ), number of specimens

Site	Loc.	X	Y	Dip	d	a
3	Castelsardo	8 44 28	40 53 19	0 à 7NO	b1	2 1
4	Castelsardo	8 45 55	40 54 11	5N320	b3a1	2?
6	Castelsardo	8 44 54	40 53 35	10N320	b3a1	2?
36	Castelsardo	8 44 38	40 53 54	15N320	a1	1
37	Castelsardo	8 44 46	40 53 49	15N320	a1	1
67	Castelsardo	8 45 10	40 53 30	7N230	b3b4	2 1 1
120	Castelsardo	8 43 08	40 54 45	10N10	a1b4	2 1 1
121	Castelsardo	8 43 41	40 54 45	10N0	a1b4	2
122	Castelsardo	8 43 41	40 54 45	10N0	b4b3	2 1?
123	Castelsardo	8 43 41	40 54 45	10N20	b4b3	2 1?
124	Castelsardo	8 45 19	40 53 34	5N280	b3b4	2 1 1
126	Castelsardo	8 45 03	40 53 30	5N320	a1b4	2?
127	Castelsardo	8 45 23	40 53 37	5N280	b3	2 1 1
128	Castelsardo	8 45 48	40 53 46	5N260	b4a1	2 1
1	Castelsardo	8 46 10	40 53 51	6N240	b1	2 1
2	Castelsardo	8 46 20	40 53 54	7N265	a1	1
7	Castelsardo	8 46 50	40 54 14	–	b1b2	1
8	Castelsardo	8 46 34	40 54 24	15N170	a1b1	2 1
125	Castelsardo	8 49 43	40 53 37	7N270	a1	1
10	Oschiri	9 06 54	40 42 43	–	a1	1
13	Oschiri	9 07 12	40 43 13	10N250	a1b2	1 1
118	Costa Paradiso			~0	a2	1
119	Costa Paradiso			~0	a2b3	1

which possess the considered magnetization (*n*), total number of specimens (n_0); *D*, declination; *I*, inclination; *R*, *k*, α_{95}, Fisher statistic parameters; β, defines the cone in which μ magnetization planes intersect; *b*, direction taken in account in Fig. 9; *PS*, petrographic and stratigraphic denomination (chapter 2)

s	N/N_0	$\mu/n/n_0$	D	I	R	*k*	α_{95} β	b	PS
F	5/5	8/8/11	352	58	7,9147	82	6	2	M_1t
F	5/5	8/8/11	328	58	7,9742	272	3	1	
F	4/4	6/7/7	359	57	5,9825	287	4	2?	M_1t
F	3/3	6/6/6	358	54	5,8936	47	10	2?	M_1t
F	5/5	5/5/5	358	48	4,9914	468	4	1	M_1t
F	6/6	6/6/6	353	−14	5,9768	216	5	1	M_1t
F	6/6	8/8/14	298	62	7,7963	34	9	2	M_1t
F	6/6	11/11/14	164	−28	9,8562	9	16		
C	6/6	11/14	143	−56			10	1	
F	7/7	13/13/15	349	50	12,6846	38	7	2	M_1t
F	2/7	2/4/15	106	−56					
C	3/7	3/15	130	−64			5	1	
F	6/6	9/9/9	331	64	8,9485	155	4	2	M_1t
F	5/5	6/6/9	335	60	5,9451	91	7	2	M_1t
F	4/5	6/6/9	353	60	5,9683	158	5	1?	
F	2/3	3/3/5	352	62	2,9925	268	7	2	M_1t
	1/3	1/1/5	7	63					
F	4/6	5/8/9	337	57	4,8682	30	14	2	M_1t
F	5/6	7/7/9	121	−70	6,9760	250	4		
C	6/6	8/9	131	−70			8	1	
F	5/5	5/5/5	5	56	4,9900	402	4	2?	M_1t
F	7/7	9/9/9	349	46	8,8032	41	8	2	M_1t
F	6/7	6/6/9	152	−59	5,8814	42	10		
C	7/7	9/9	159	−60			7	1	
F	6/6	10/11/11	330	54	9,6791	28	9	2	M_1t
C	6/6	9/11	148	−61			5	1	
F	5/5	6/6/6	314	58	5,9824	285	4	2	M_1t
F	5/5	5/6/6	286	53	4,9756	164	6	1	
F	5/5	7/7/7	287	54	6,9921	765	2	1	$\mathrm{M}_1\tau$
F	3/3	4/4/4	281	57	3,9369	48	13	1	$\mathrm{M}_1\tau$
F	2/5	2/3/6	305	65				2	
F	5/5	6/6/6	281	60	5,9889	452	3	1	$\mathrm{M}_1\tau$
F	7/7	7/7/7	166	−31	6,9919	747	2	1	$\mathrm{M}_1\tau$
F	6/6	9/10/10	164	−49	8,9674	246	3	1	τ
F	6/6	7/7/7	148	−38	6,9591	147	5		τ
C	6/6	7/7	150	−46			7	1	
F	6/6	6/6/6	144	−44	5,9931	727	2	1	τ
F	6/7	6/6/7	146	−44	5,9847	329	4	1	τ

Table 1 (Continued)

Site	Loc.	X	Y	Dip	d	a
5	Castelsardo	8 44 59	40 53 40	~15N320	a1b1	1
34	Castelsardo	8 44 49	40 53 47	~15N320	a1b1	2 1
15	Castelsardo	8 46 14	40 52 32	–	a1	
11	Castelsardo	8 43 24	40 52 18	–	a1b1b2	2 1
12	Castelsardo	8 43 23	40 52 26	–	a1b1b2	2 1
14	Castelsardo	8 44 30	40 52 57	–	b4	2
33	Nulvi	8 44 34	40 48 06	–	a1b1	1
32	Nulvi	8 47 01	40 46 53	–	b2b1	1?
66	Castelsardo	8 42 34	40 50 05	–	a1	1
38	Sorso	8 40 37	40 45 59	–	b4	2
39	Sorso	8 41 34	40 47 08		b3b4	1
40	Osilo	8 39 38	40 44 00	–	a1b3	2 1
116	Osilo	8 41 43	40 44 15	–	a1b2	1
129	Osilo	8 39 21	40 44 04	–	b2b3b4	2 1?
130	Osilo	8 40 29	40 44 56	–	b2	1? 1?
115	Chiaramonti	8 45 00	40 41 07	–	b1b2b4	1
41	Chiaramonti	8 44 59	40 40 42	–	b3b4	2 1 1
90	Bosa	8 31 40	40 17 28	–	b4	1 1
30	Bosa	8 30 52	40 18 32	–	a1b2	1
31	Bosa	8 30 05	40 18 40	~0	a1b2	1
26	Padria	8 35 11	40 22 05	–	a1	1
27	Padria	8 35 17	40 22 05	–	b1b2	1 1
50	Sindia	8 35 49	40 19 53	–	a2b3	1
63	Romana	8 38 58	40 28 38			
64	Romana	8 39 08	40 28 52	–	a2	1
65	Romana	8 39 58	40 28 24	–	b3b4	1 1
43	Banari	8 39 41	40 33 42	–	a1	1

s	N/N_0	$\mu/n/n_0$	D	I	R	*k*	α_{95} β	b	PS
F	7/7	8/8/8	356	−17	7,9472	133	5	1	α
F	6/6	7/8/10	4	45	6,8843	52	8	2	α
F	5/6	9/10/10	358	−13	8,9258	108	5	1	
	1/3	2/2/5	331	20					α
	2/3	3/3/5	357	34					
F	2/5	4/5/9	297	48	3,9502	60	12	2	α
F	3/5	4/4/9	330	53	3,9339	45	14	1	
F	4/6	5/5/10	347	41	4,9571	93	8	2	α
F	4/6	5/5/10	332	49	4,9773	177	6	1	
F	5/5	8/9/9	134	− 7	7,9619	184	4	2	α
F	5/5	8/8/8	322	11	7,9764	297	3	1	α
F	5/5	7/7/7	307	67	6,9604	152	5	1	α
F	6/6	9/9/9	123	−17	8,4866	598	2	1	α
F	6/6	8/8/10	358	48	7,9558	159	4	2	α
F	4/9	7/7/14	157	−36	6,9702	201	4		α
C	8/9	12/14	160	−35			8	1	
F	4/6	5/6/15	358	46	4,8163	22	17	2	α
F	5/6	9/10/15	321	55	8,7939	39	8	1	
F	6/7	6/7/7	343	53	5,9892	465	3	1	α
F	3/10	4/5/18	357	62	3,9954	659	4	2	α
F	8/10	12/12/18	316	67	11,8781	90	5	1?	
F	7/7	8/9/9	20	57	7,8026	35	9		α
C	7/7	7/9	8	50			10	1?	
F	6/6	7/7/8	8	47	6,9839	375	3	1	α
F	2/4	2/2/6	354	64			2		α
F	4/4	6/6/6	118	−21	5,6910	16	17		
C	3/4	4/6	155	−53			5	1	
F	5/6	9/12/12	146	−45	8,5469	18	13		α
C	5/6	9/12	148	−66			10	1	
F	6/6	9/9/9	139	−40	8,8844	69	6	1	SA_2
F	5/5	5/5/5	11	80	4,9659	117	7	1	SA_2
F	3/4	3/4/4	174	−41	2,9989	1812	3	1	SA_2
F	4/5	4/5/5	172	−32	3,9604	76	11		SA_2
C	5/5	5/5	182	−47			5	1	
F	5/6	6/8/8	183	−54	5,9805	257	4	1	SA_2
									SA_2
F	5/5	7/7/7	172	−56	6,9921	762	2	1	SA_2
F	2/4	4/4/9	100	−68	3,9792	144	8		SA_2
C	4/4	7/9	109	−68			8	1	
F	3/3	5/5	344	55	4,9978	1835	2	1	SA_2

Table 1 (Continued)

Site	Loc.	X	Y	Dip	d	a
17	Capo Marargiu	8 24 20	40 22 34			
18	Capo Marargiu	8 24 29	40 22 06	–	b4	2
19	Capo Marargiu	8 24 42	40 22 00	–	a1	
20	Capo Marargiu	8 25 07	40 21 30	–	b2b3b4	1
21	Capo Marargiu	8 23 33	40 20 20			
28	Capo Marargiu	8 24 00	40 22 11	–	a1b4	1?
29	Capo Marargiu	8 25 18	40 21 19	–	a1b2	1
46	Banari	8 40 02	40 30 25	–	a1	1
47	Romana	8 41 03	40 29 45	–	a1	1
48	Romana	8 41 13	40 29 54	–	b2b3	2 1 1
42	Banari	8 38 17	40 34 08	–	a1	1
44	Banari	8 39 34	40 34 56	–	a2b3	1
45	Banari	8 39 08	40 33 20	–	b3b4	2 1
98	Banari	8 39 43	40 34 42	–	b1b4	2 1 1
99	Banari	8 38 45	40 34 22	–	b3b4	1 1
22	Montresta	8 30 03	40 23 05	–	a1a2	1
23	Montresta	8 29 37	40 23 18	–	b2	1
24	Montresta	8 28 51	40 23 40	–	a2b2	1
95	Montresta	8 28 56	40 23 18	–	a1	1
54	Montresta	8 29 27	40 20 02	17N25	a1a2	1
92	Bosa	8 30 40	40 19 17	20N30	a1	1
93	Bosa	8 30 37	40 20 00	15N15	a1	1
94	Montresta	8 27 54	40 23 44	–	a1b2	1
96	Montresta	8 31 09	40 23 39	510N7080	a1	1
103	Itiri	8 27 38	40 37 13	15N80	a1	1
107	Valverde	8 23 18	40 33 47	0 15N350	a1	1
111	Pedra Ettori	8 23 43	40 26 24	∼0	a1	1
112	Pedra Ettori	8 23 43	40 26 24	∼0	a1	1
51	Torre Argentina	8 26 16	40 19 23	?	a1	1?

s	N/N_0	$\mu/n/n_0$	D	I	R	k	α_{95} β	b	PS
									SA_1
F	5/5	6/8/8	148	−3	5,9278	69	8	2	SA_1
F	2/3	4/4/7	353	31	3,9801	151	7		SA_1
	1/3	3/3/7	323	35	2,9931	294	7		
F	5/5	7/7/7	156	−67	6,6712	18	14		SA_1
C	5/5	7/7	190	−62			10	1	SA_1
F	2/6	4/4/10	316	52	3,9012	30	17	1	SA_1
F	4/6	6/6/10	276	28	5,8210	28	13	2	
F	4/4	6/6/6	141	−68	5,9494	99	7	1	SA_1
F	9/9	9/11/11	163	−33	8,9396	132	4	1	SA_1
F	4/4	4/4/4	128	−49	3,9609	77	10	1	SA_1
F	4/4	7/7/7	316	3	6,8720	47	9	2	SA_1
F	4/4	7/7/7	124	−44	6,7191	21	13		
C	4/4	7/7	140	−35			5	1	
F	8/8	10/11/11	340	35	9,9757	372	3	1	SA_1
F	3/3	8/8/8	176	−54	7,9246	93	6	1	SA_1
F	2/8	3/3/11	274	56	1,9976	420	12	2	SA_1
F	5/8	5/6/11	318	52	4,9225	52	11	1	
F	5/5	5/6/7	317	63	4,9617	104	7	2	SA_1
F	3/5	3/3/7	145	−43	2,9973	760	4		
C	5/5	7/7	147	−57			5	1	SA_1
	1/7	1/7/14	343	38					
C	6/7	11/14	345	36			5	1	SA_1
F	4/4	5/5/5	160	−43	4,9978	1886	2	1	SA_1
F	4/4	4/4/4	145	−59	3,9909	331	5	1	SA_1
F	4/4	5/5/5	142	−45	4,9740	154	6	1	SA_1
F	6/6	6/6/6	151	−37	5,9855	346	4	1	SA_1
F	5/6	7/8/8	168	−30	6,9870	464	3	1	SI_1
F	6/6	6/6/7	153	−60	5,9800	251	4	1	SI_1
F	8/8	8/8/8	154	−40	7,9593	172	4	1	SI_1
F	4/7	4/7/7	150	−25	3,9742	116	8	1	SI_1
F	4/5	4/5/5	333	45	3,9851	202	6	1	SI_1
F	7/7	7/7/7	333	43	6,9909	661	2	1	(SI_2)
F	6/6	6/6/6	141	−43	5,9819	277	4	1	(SI_2)
F	6/7	6/8/8	141	−61	5,9909	551	3	1	SI_1
F	5/5	5/5/5	132	−52	4,9790	191	5	1	SI_1
F	5/7	7/10/10	7	58	6,9468	113	6	1	α

Table 1 (Continued)

Site	Loc.	X	Y	Dip	d	a
52	Torre Argentina	8 26 16	40 19 23	10N180?–220	a1	1
53	Bosa	8 27 30	40 19 23	~0	b1b2	1
91	Bosa	8 28 34	40 17 46	~0	a1	1
97	Banari	8 37 36	40 34 24	~0	a1	1
131	Banari	8 41 15	40 31 00	–	a1b3	1
						1
132	Romana	8 35 48	40 29 33	–	a1	1
133	Banari	8 36 22	40 32 10	5N180	a1b1	1
134	Romana	8 37 02	40 25 50	–	a1	1
135	Romana	8 40 25	40 28 20	10N20	a1b2	1
55	Alghero	8 19 23	40 32 32	–	b3b4	2
						1
						1
106	Valverde	8 23 21	40 33 44	–	b3b4	1
						1
68	Carbonia	8 30 53	39 08 08	Variable	a1	1
69	Perdaxius	8 37 22	39 07 25	–	a1	1
70	Perdaxius	8 41 03	39 08 13	–	b3b4	2
						3?
						1
						1
71	Siliqua	8 49 08	39 15 52	–	a1	1
72	Villamassargia	8 40 22	39 15 36	–	b1b2	1
75	Perdaxius	8 35 43	39 09 51	–	b1b2	1
16	Sinis	8 26 08	39 54 30	–	a1b2	1
49	Sindia	8 34 56	40 18 06	~0	a1	1

In the andesites the measurement of slope was generally impossible. Nevertheless the scatter does not seem to be very much greater than that for the ignimbrites, the slope of which is known. For the latter the directions are coherent and hence the scatter can only be explained by secular variation of anomalous field directions during a reversal. Sites 1, 2, 7, 8 as well as some other sites investigated by de Jong et al. (1973) show the same directions grouping around N 280°–290° C which relate probably to the same layer. This group of directions is removed from the mean direction which is about N 330. Thus, the ignimbrites which cooled rather quickly, probably took on an anomalous field direction. This is probably also the case for some andesites like sites 33, 66, 5, 34.

A preliminary interpretation based on 55 sites was given by Edel and Lörtscher (1978). Their conclusion was as follows. In the lower andesitic and ignimbritic series (SA1, SI1), the NW directions dominate. In the upper andesite

Site	Loc.		X	Y	Dip		d		a
F	4/4	6/6/6	343 ? 346	64 ? 68	5,9955	1117	2	1	(SI$_2$)
F	4/6	6/6/11	338	58	5,9825	287	4	1	(SI$_2$)
F	4/4	4/4/4	340	63	3,9982	1686	2	1	(SI$_2$)
F	7/8	7/8/8	359	52	6,9803	305	3	1	(SI$_1$)
F	1/3	2/6/6	159	−35					SA$_1$
C	2/3	4/6	160	−35					
F	3/3	6/6/6	160	−56	5,9916	594	3	1	SA$_3$
F	4/4	4/4/4	328	48	3,9997	14235	1	1	SI$_2$
F	4/4	4/4/4	342	55	3,9994	5256	1	1	SI$_2$
F	4/4	4/4/4	457	58	3,9027	31	17	1	τ_3
F	4/5	7/9/10	323	65	6,9118	68	7	2	π
F	4/5	6/10/10	139	−40	5,8688	38	11		
C	5/5	8/10	140	−60			7	1	
F	5/7	8/10/13	116	−21	7,8122	37	9		π
C	6/7	10/13	147	−38			10	1	
F	7/7	8/9/9	26	36	7,8349	42	9	1	τ
F	6/6	9/9/9	179	−47	8,9515	164	4	1	α
F	4/8	7/10/17	325	52	6,7259	22	13	2	α
F	3/8	3/10/17	354	51	2,9757	82	14		
F	1/8	2/2/17	115	−55					
C	7/8	13/17	120	−60			10	1	
F	6/7	6/8/8	75	−55	5,9798	248	4	1	α
F	5/5	10/10/10	333	31	9,9378	145	4	1	α
F	5/5	7/7/7	130	−59	6,9520	125	5	1	α
F	5/6	5/6/6	198	−48	4,9907	430	5	1	β
F	4/4	4/4/4	4	56	3,9973	1132	3	1	β

series SA2, NW in addition to N directions were obtained. In the upper ignimbritic series (SI2, τ2) de Jong et al. (1973) and coulon et al. (1974) obtained a clear N direction (Fig. 9d). These results in comparison with petrographic data and some radiometric ages, are in favour of a rotation of Sardinia after 17 MY (Bellon et al., 1978).

Our new results generally agree with the first interpretation. But some contradictions appear. So, for some upper and lower ignimbrites we measured respectively NW and N directions. This means, if we did not measure an anomalous field direction, that, either our model does not fit, or the stratigraphy of the geologists is wrong. Before giving a definitive interpretation we await a new set of radiometric ages. The potassium-argon method, applied to individual minerals of our palaeomagnetic samples, will allow us hopefully to reach definite conclusions.

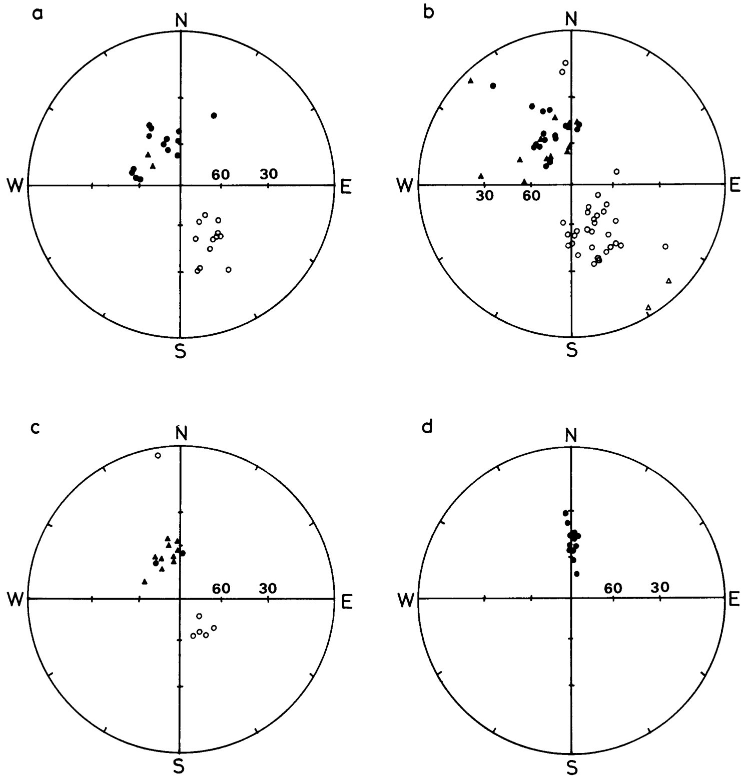

Fig. 9. Projection of the site mean directions in the ignimbrites (**a**), andesites (**b**) and tuffites (**c**) of the calc-alkaline Tertiary volcanics. Primary magnetizations (●) and secondary magnetizations (▲). Upper ignimbritic serie by de Jong et al. (1973) and Coulon et al. (1974) (**d**)

8. Conclusions

In the present paper we have described the different magnetic parameters as a function of the pertrographic nature of the calc-alkaline volcanics. Thermal treatment shows that most calc-alkaline volcanics underwent regional hydrothermal alteration. This results in the presence of secondary magnetizations, the importance of which vary with the petrography. They are very strong in the most tuffites, generally important in the andesites and negligible in the ignimbrites. Thus the palaeomagnetic study necessitates very detailed demagnetizations, especially with regard to the type of magnetization which is present. The directions of characteristic magnetization in the ignimbrites, which show no significant secondary magnetizations and for which the tectonic correction has been done, reveal significant secular variations and anomalous field directions during cooling of the lavas. Field reversals are numerous during Tertiary, and the anomalous directions of magnetization may have been induced during such reversal.

Except for the upper ignimbritic series SI2, the directions are generally NW, scattered around the mean direction $D=332$, $I=52$ with $N=79$, $k=22$, $\alpha_{95}=3°$. Soon, new radiometric ages of our samples will allow us to interpret the palaeomagnetic data from a geodynamic point of view.

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