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A Note on the Palaeomagnetism of the Late Precambrian Malani Rhyolites near Jodhpur - India

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Abstract. Palaeomagnetic properties from a series of mainly rhyolitic lava flows from the Malani volcanic suite in Rajasthan-India, dated at 745 ± 10 my, were studied by means of alternating fields and thermal demagnetization methods.

The mean direction of the characteristic magnetization component, of both normal and reversed polarity: $D = 354.5°$, $I = +53.5°$, $\alpha_{95} = 8°$, $N = 10$, (Pole: 80.5° N, 43.5° E, $dp = 8°$, $dm = 11.5°$) is in good agreement with earlier results obtained by Athavale *et al.* (1963). The fold test gives a positive result and the above mentioned mean direction from the Malani rhyolites is in agreement with other Precambrian data from the Indian subcontinent. Therefore, this mean direction is interpreted to represent the primary magnetization direction. The position and orientation of the Indian subcontinent about 745 my ago was more or less alike its present-day orientation, however, at that time India was situated at a slightly higher latitude.

Key words: Palaeomagnetism — Precambrian Malani Rhyolites — Malani Rhyolites — India.

Introduction

The Malani igneous suite, formed predominantly by rhyolites and some later intrusive granites, covers an area of several thousands of square miles in Western Rajasthan (India). The rhyolites, dated at 745 ± 10 my by Crawford and Compston (1970) are locally seen to overly unconformably Early Precambrian rocks of the Aravalli System. When the two are present together, the Malani rhyolites are covered with erosional disconformity by the probably Late Precambrian Jodhpur sandstones. Locally the Malani rhyolites are in a tilted position with dips, sometimes up to 70 degrees, assigned either to blockfaulting (Rutten, 1965) or to folding on a regional scale (Mukherjee, 1966).

Rutten has studied the Malani rhyolites in the area near Jodhpur (26 °N 73 °E), and found that the rhyolites in this area predominantly showed typical ignimbritic field characters. However, his conclusion was disputed by Mukherjee (1966).

A previous palaeomagnetic study of the Malani rhyolites was undertaken by Athavale *et al.* (1963) who collected their samples (60 in all) from subhorizontal flows only. Their results, obtained after alternating field demagnetization up to 200 Oe peak value and thermal demagnetization studies, showed a reasonably dense distribution of directions grouped around a mean direction $D = 353°$, $I = +56°$. The inclination of this mean direction is somewhat higher than the present local field direction in the sampling area ($D = 360°$, $I = +38°$). Athavale's *et al.* data seem to favour a counterclockwise rotational movement of the Indian subcontinent during Middle and Late Precambrian times as has been tentatively concluded from radiometrically dated palaeomagnetic results available (Klootwijk, 1974). However, in view of the slight variance between the palaeomagnetic direction of the Malani rhyolites, obtained by Athavale *et al.*, and the present local field direction it seemed appropriate to confirm the stability of the palaeomagnetic direction by means of some further tests, for instance the fold test not applied by Athavale *et al.* (1963). For this purpose a collection of oriented samples from the Malani rhyolites, sampled by the late Prof. Rutten from both subhorizontal and tilted flows in the Jodhpur area, was studied. In addition a study was made of the magnetic susceptibility anisotropy mainly in order to attribute some additional pro or contra arguments for the ignimbritic nature of the flows. These data will be discussed elsewhere.

Sampling and Laboratory Treatment

Altogether 45 handsamples (Table 1) were taken by Rutten (Fig. 1, 1965), from mainly rhyolites (11 sites) and in addition from a felsitic dyke (1 site) and a basaltic dyke (1 site). The samples were collected over the total height of the rhyolites each, some of which showed a tuffaceous top and a massive centre. Orientation of the samples was done in the field by means of a normal compass.

Initial natural remanent magnetization measurements were made with the samples cast in paraffine wax. For demagnetization treatment, a total of 106 cores of 1 inch diameter and 2.2 cm in heigt were drilled from these samples.

All remanent magnetization measurements were carried out on the astatic magnetometers of the Palaeomagnetic Laboratory, State University of Utrecht. From each site at least one specimen was progressively demagnetized by means of alternating fields in 11 to 18 steps up to 3000 Oe peak value. In addition at least one specimen from each site was progressively demagnetized by thermal methods in 23 steps up to zero intensity. The remaining specimens were partially progressively demagnetized in alternating fields (9 to 13 steps) or by thermal methods (11 to 18 steps). Directional analysis of the data was made according to standard techniques described elsewhere (Zijderveld, 1967). For data processing and map plotting, the CDC-6500 computer of the Academic Computer Centre Utrecht was programmed in Algol-60.

Results

The intensity of initial remanence ranged between 10^{-6} to 10^{-3} emu/cm^3 with a mean around 2.10^{-4} emu/cm^3. Q-values generally exceeded unity with the exception of samples from site 14 which showed Q-values between 0.3 and 0.7 (Table 1).

The initial specimen directions reveal a prominent northern concentration with moderate downward dips (Fig. 1 A, 2 A 2). A minor concentration of initial directions, pointing south-southwest and upwards, was made up by the two reversely magnetized sites 15 and 16 (Fig. 1 A, 2 A 1). In general the initial specimen directions grouped rather well within each site, with site 13 showing a much larger initial scatter.

AF-Demagnetization

Upon alternating field demagnetization it appeared that in most sites mainly one single component was present (Fig. 3 A). However, pilot specimens especially from sites 13 and 16 showed a more or less distinct local field component of rather small intensity, i.e. 10 to 20% of the initial intensity which could be eliminated at 250 to 400 Oe peak value (Fig. 3 G, 3 K). Sample 13 A reveals a notable behaviour (Fig.

Table 1. Initial measurements

Site	Constitution	Samples	Specimens	Mean direction (degrees)		α_{95} (degrees)	k	Intensity[b]	Q-value	Anisotropy % (K_{max}/K_{min}^{-1}) $\times 100\%$
RI– 2	rhyolite (26°18′N 73° 1′E)	7	15	359	+61.5	8.5	54	1– 48	0.4–23	1.5–3.3
RI– 3	rhyolite (26°18′N 73° 1′E)	4	14	20	+51	15	39.5	84–234	9.7–40	0.6–1.9
RI– 4	rhyolite (26°18′N 73° 1′E)	3	13	57	+60.5	—	—	1.4–27	1.1–21	3.3
RI– 5	rhyolite (26°18′N 73° 1′E)	1	3	14	+61.5	—	—	116–117	14–22	1.2
RI– 7	rhyolite (25°48′N 72° 10′E)	4	9	344	+35	20.5	20.5	79– 82	0.9–1.2	2.2–3.2
RI– 8	felsitic dyke (25°48′N 72° 10′E)	2	4	341	+41.5	—	109	50– 53	0.7	2.7–2.9
RI–10	rhyolite (25°48′N 72° 10′E)	5	10	349.5	+47.5	11	71.5	77–148	1.2–3.5	0.9–2
RI–11	basaltic dyke (25°48′N 72° 10′E)	2	6	341.5	+24.5	—	4	77–177	0.9–1.6	1.2–1.7
RI–12	rhyolite (25°48′N 72° 10′E)	3	9	340.5	+53.5	22.5	30.5	204–254	1.8–2.1	1.9–3.7
RI–13	rhyolite (25°40′N 73° 9′E)	5	17	51	+46	45	4	83–488[a]	0.9–3.2	1.5–2.5
RI–14	rhyolite? (26°7′N 73° 3′E)	4	6	6	+53.5	27	12.5	9– 26	0.3–0.7	3.1–6.3
RI–15	rhyolite (26°7′N 73° 3′E)	3	8	227	–25	23	30	673–944	5.5–7.6	3.2–3.6
RI–16	rhyolite (26°7′N 73° 3′E)	2	3	211	–16	—	14	66–325	0.9–3.5	2.2–3.6

[a] Specimens of sample RI 13 A showed much higher initial intensities, between 2827 and 3405 $\times 10^{-6}$ emu/cm^3 and Q-values between 18.6 and 20.6.

[b] In units of 10^{-6} emu/cm^3.

Table 1 (continued). After alternating field or thermal demagnetization

Site	Samples[a]	Specimens[b]	Mean direction (degrees)		α_{95} (degrees)	k	Strike and dip (degrees)	Site mean direction after dip correction (degrees)	
RI– 2	6 (1)	14 (4)	3.9	+62.5	6.5	133	subhorizontal		
RI– 3	4	13 (4)	23.5	+52.5	5.3	297.5	subhorizontal		
RI– 4	2	2 (1)	3.2	+65.2	—	23.5	subhorizontal		
RI– 5	1	3 (2)	16.5	+62.5	1.5[c]	5070	subhorizontal		
RI– 7	4	8 (3)	340	+45	12.5	55	subhorizontal		
RI– 8	2	3 (1)	339	+48	—	14	intruded into RI7		
RI–10	5	9 (2)	346.5	+52	6	162	subhorizontal		
RI–11	2	5 (3)	342.5	+46	—	47	intruded into RI10		
RI–12	3	6 (3)	353	+61	7	316	200E/12W	337	+54.5
RI–13	4	13 (6)	87	+42	4	490.5	188E/51W	345	+81
RI–14	4	6 (3)	356	+57	12.5	54	195E/46W	320	+27.5
RI–15	3 (1)	6 (3)	213	—30.5	12	430.5	195E/46W	182	—33
RI–16	2	2 (1)	211	—25.5	—	207	210E/65W	189	—11.5

[a] Between brackets number of samples rejected, because of uninterpretable demagnetization graphs.
[b] Between brackets number of specimens treated by thermal methods, all other specimens were demagnetized in alternating fields.
[c] Unit weight given to specimen directions.

Table 1 (continued). Mean direction after cleaning

Number of sites (degrees)	Mean direction (degrees)		α_{95}	k	Pole position (degrees)		dp (degrees)	dm (degrees)
Before dip corr: 10[a]	0.5	+54.4	9.5	26				
after dip corr: 10[a]	354.5	+53.5	8	35.3	80.5°N	43.5°E	8°	11.5°

[a] Sites 13, 14 and 16 are excluded.

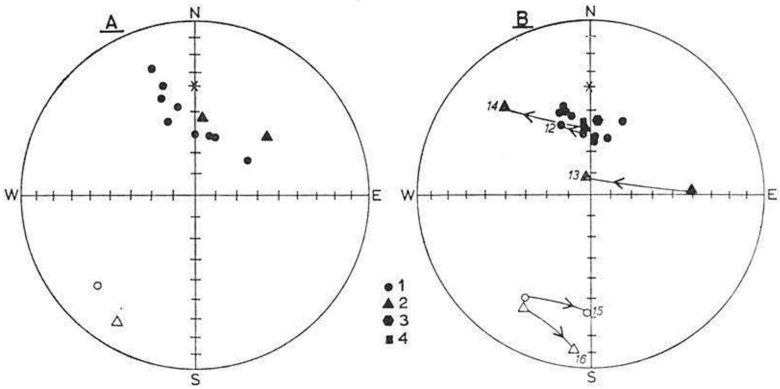


Fig. 1. Stereographic projection of site-mean directions: A initial directions: B after demagnetization treatment. Site-mean directions from sites 12 to 16 are shown before and after correction for the local dip of the strata, both directions combined by arrowed full lines. Dots denote directions pointing downwards, Circles denote directions pointing upwards. The asterisk denotes the present local field direction at the sampling locality, dipping downwards

Legend: 1. Accepted site-mean directions.
2. Site-mean directions excluded for computation of the mean-site direction (sites 13, 14 and 16).
3. Mean-site direction before application of a correction for local dip of the strata.
4. Idem after correction for the local dip of the strata

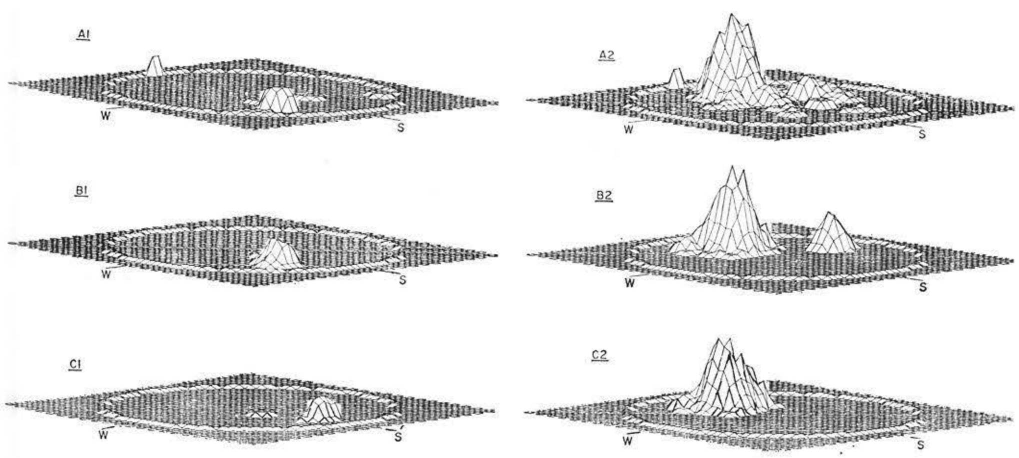


Fig. 2. Density distribution of remanent magnetization directions, represented as a three dimensional perspective view of an equal area projection. The view is taken from the southwest. The rim on the figures represents the outline of the equal-area projection

A1: Initial specimen directions, upper hemisphere.
A2: Idem, lower hemisphere.
B1: Specimen directions after demagnetization treatment, upper hemisphere.
B2: Idem, lower hemisphere.
C1: Specimen directions after demagnetization treatment, and correction for local dip of the strata. Specimens from the rejected sites excluded, upper hemisphere.
C2: Idem, lower hemisphere

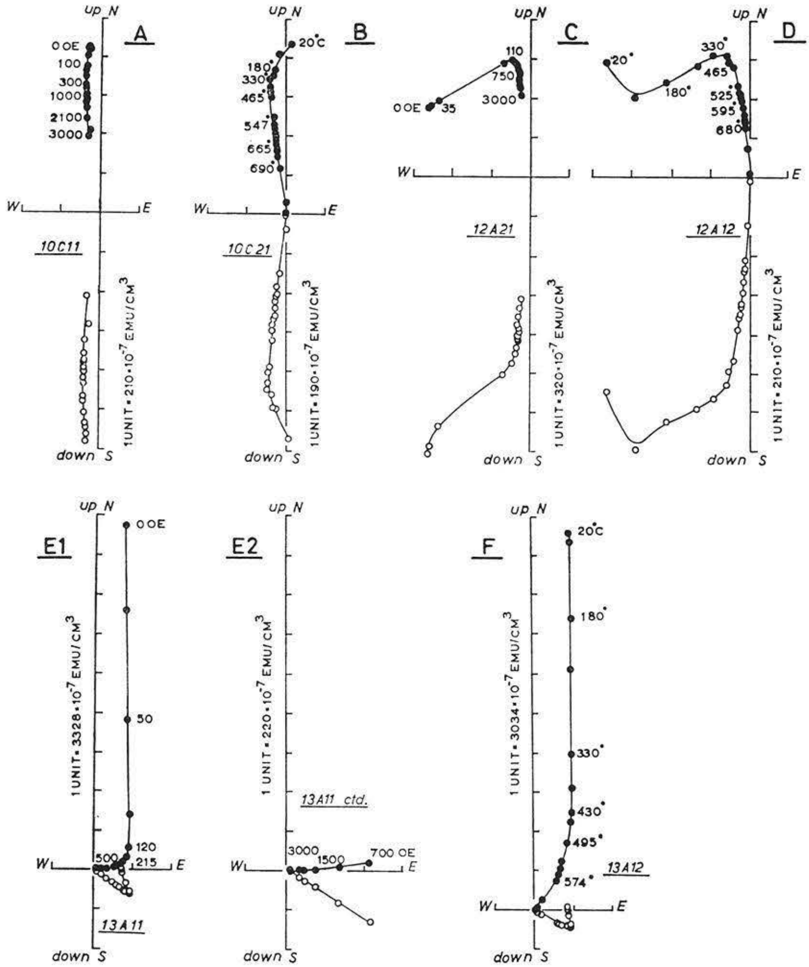
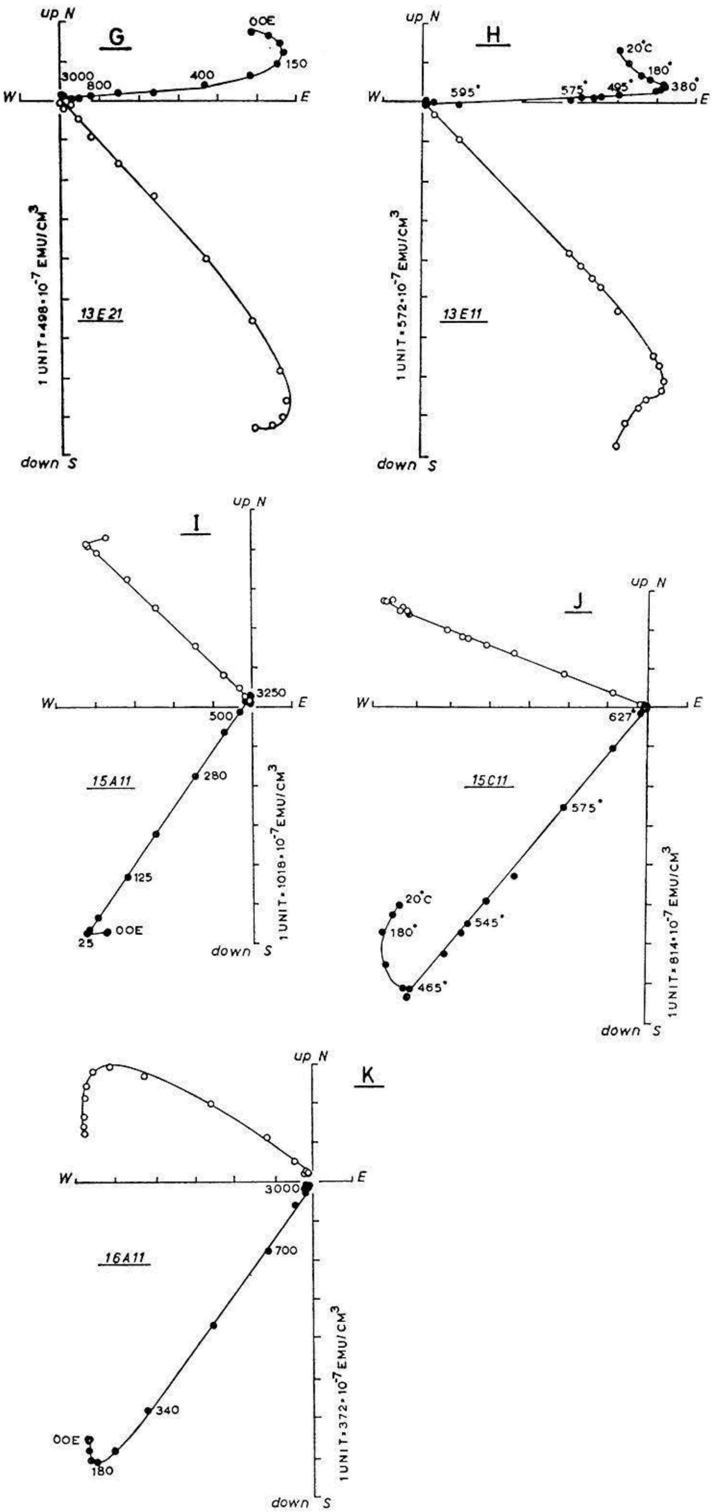


Fig. 3. Demagnetization diagram of specimens cleaned in alternating fields (A, C, E1, E2, G, I, K) or by thermal methods (B, D, F, H, J), The points represent successive positions – in orthogonal projectional – of the end of the resultant magnetization vector during progressive demagnetization. Circles denote projections on the vertical east-west plane. Dots denote projections on the horizontal plane. Numbers denote successive oersted peak values of the applied alternating fields or successive peak values of the applied temperatures. Compare the alternating field and thermal results from both specimens (in most cases specimens from the same sample) from the same site

3E1, 3E2). In this sample the initial intensity of remanence was about 10 times higher than that of the other samples from this site, mainly due to a very large present field like component which constituted about 85% of the initial intensity. The characteristic direction, determined after removal of this present field like component, is of the same intensity and nicely groups with similar characteristic directions from the other samples of this site (Table 1).



G
up N
down S
W
E
OOE
150
400
800
3000
13 E 21
1 UNIT = 498 · 10⁻⁷ EMU/CM³
H
up N
down S
W
E
20°C
180°
380°
495°
575°
595°
13 E 11
1 UNIT = 572 · 10⁻⁷ EMU/CM³
I
up N
down S
W
E
3250
500
280
125
25
OOE
15 A 11
1 UNIT = 1018 · 10⁻⁷ EMU/CM³
J
up N
down S
W
E
627°
575°
545°
465°
180°
20°C
15 C 11
1 UNIT = 814 · 10⁻⁷ EMU/CM³
K
up N
down S
W
E
3000
700
340
180
OOE
16 A 11
1 UNIT = 372 · 10⁻⁷ EMU/CM³

Fig. 3. G-K

In some specimens from sites 7, 12, 14 and 15 dispersed components of slight intensity and probably of viscous origin could be removed up to 50 to 200 Oe peak value (Fig. 3C, 3I). Sites 7, 8 and 14 specimens showed a very fast intensity decrease of the characteristic component (Fig. 4A, 4B). In all studied specimens from the Malani rhyolites an accurate characteristic component could be determined. In case of sites 2, 3, 4, 5, 10, 11 and 12, this component had a rather high coercivity spectrum so that it could not become eliminated completely at 3000 Oe peak value (Fig. 3A, 3C, 3E2, 3G, 3I, 3K), the highest alternating magnetic field available at our laboratory.

Thermal Demagnetization

The normalized thermal intensity decay curves in sites 2, 3, 4, 5, 7, 10, 11 and 12 specimens (Fig. 4C) reveal the existence of a thermally discrete component (Irving and Opdyke, 1965) of great stability which disappears above 650 °C (Fig. 4C). The

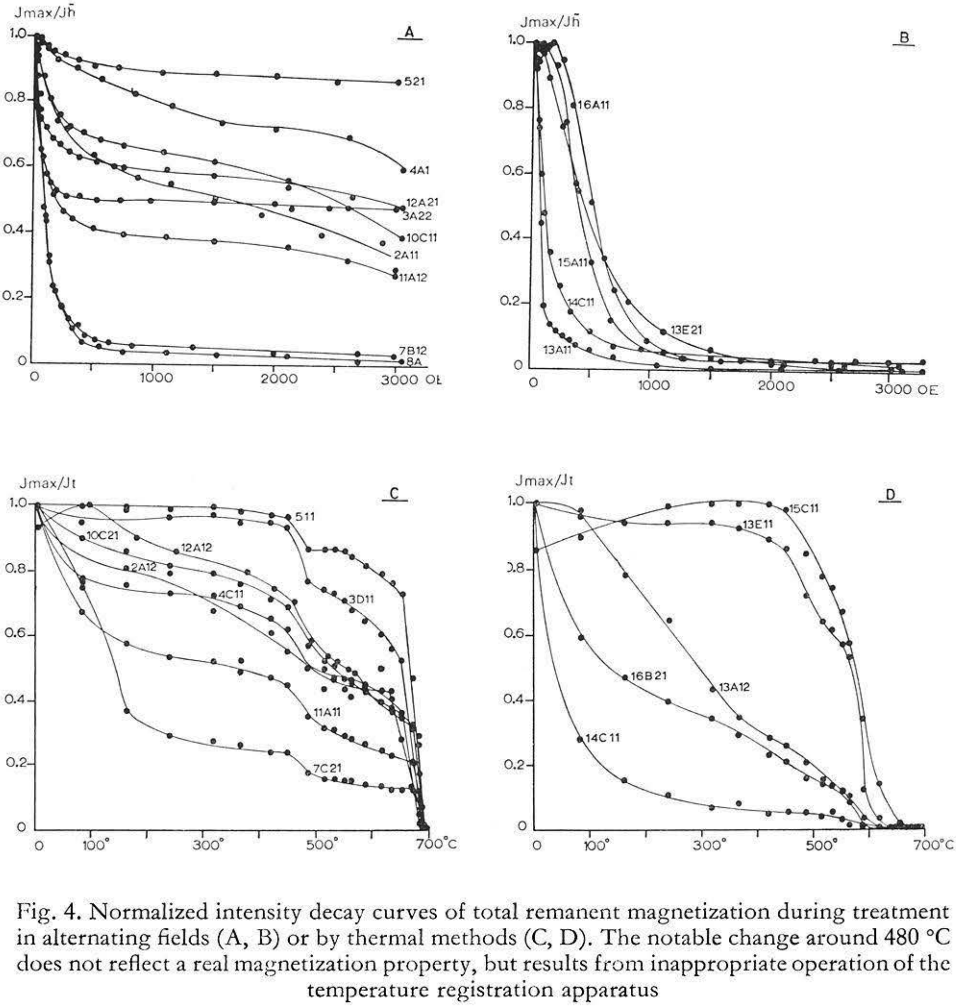


Fig. 4. Normalized intensity decay curves of total remanent magnetization during treatment in alternating fields (A, B) or by thermal methods (C, D). The notable change around 480 °C does not reflect a real magnetization property, but results from inappropriate operation of the temperature registration apparatus

blocking temperature range indicates that hematite is the characteristic magnetization carrier as was to be expected from the high coercivity values for this component as deduced during alternating field studies (Fig. 4A). Pilot specimens from sites 13, 15 and 16 reveal a thermally discrete component with blocking temperatures between 500 °C and 600 °C (Fig. 4D). In accordance with the alternating field results (Fig. 4B) this suggests that in these sites magnetite is probably the characteristic magnetization carrier. Pilot specimens from most of both groups of sites also reveal the existence of a thermally distributed component with a series of blocking temperatures varying between room temperature and 650 °C (Fig. 4C) or 500 °C (Fig. 4D) respectively. The orthogonal demagnetization graphs in analogy with the AF-results reveal that this thermally distributed component can be assigned either to a distinct local field component as shown for a site 13 pilot specimen (Fig. 3F, 3E1, 3E2) or to dispersed components, probably of viscous origin (Fig. 3D, 3C).

The magnetic properties of site 14 specimens form a notable exception. The thermal analysis of specimen 14C11 (Fig. 4D) reveals the existence of a thermally distributed component only, which is easily eliminated during thermal demagnetization or alternating field demagnetization (Fig. 4A). Upon storage in the earth magnetic field this pilot specimen quickly acquires a considerable magnetization component. After alternating field treatment up to 3000 Oe, the intensity of remanent magnetization of this pilot specimen 14C11 was diminished from an initial intensity of 220.10^{-7} emu/cm^3 to 7.10^{-7} emu/cm^3. However, after storage in the earth magnetic field for about 1 month, the intensity of remanent magnetization was increased again up to 140.10^{-7} emu/cm^3. Therefore, the results of the thermal analysis in accordance with the low Q-value (Table 1) and the low stability of magnetic remanence suggest that the characteristic magnetization component in site 14 samples might be of secondary origin as will be discussed later on.

Discussion

The characteristic directions obtained after demagnetization in alternating fields or by thermal methods are in very good agreement with each other as can be seen from the comparable graphs of pilot specimens (Fig. 3) and from the three-dimensional density distribution representation of specimen directions (Fig. 2B1, 2B2). Note the distinctly improved grouping of sample directions after demagnetization treatment (Fig. 2B1, 2B2, Table 1).

Before dip correction the site-mean directions, obtained by giving unit-weight to sample-mean directions, for sites 2 to 12 show a fairly good concentration of normal polarity directions, pointing northwards with a downward dip of about 50 degrees (Fig. 1B). Sites 15 and 16 show mean directions of reversed polarity which, before application of a moderate dip (Table 1) are not exactly opposite to the normal polarity concentration. Note the mean direction of site 13. In this site the internal consistency of the characteristic directions is greatly improved after elimination of a secondary present field component of variable intensity, but before correction for the considerable dip of the strata (Table 1), this mean direction is distinctly aberrant from one of the concentrations mentioned above.

The tectonic position of the flows has been measured by Rutten (1965) from "the parallel, vague, fluidal structure", supposed to be originally subhorizontal in ignimbrites, and from columnar structures in the flows standing at right angles to the fluidal structure. According to Rutten's field studies, most of the flows were in a sub-horizontal position but the flows from sites 12 to 16 appeared to be tilted sometimes up to 70 degrees (Table 1). Therefore, the fold test could be applied to the mean directions from these sites and the resultant configuration is shown in Fig. 1 B. A slight correction only had to be applied for site 12, but after a moderate correction for sites 13, 15 and 16 the concentration and opposite alignment of the normal and reversed groups is decidedly improved (Fig. 1). However, in case of sites 13 and 16 it must be concluded from Fig. 1 B that the tectonic control is not sufficiently accurate. Dip measurements of these flows range between 50 and 70 degrees. So it is clear that slight errors in strike measurements after dip correction will result in considerable deflections of inclination of the palaeomagnetic vector. (Fig. 1 B). Nevertheless, the distinct tendency for improved grouping of site-mean directions after dip correction plainly indicates the fold test to be positive.

It was discussed before that the characteristic magnetization component of site 14 specimens was of very low stability. For this site, the fold test gives a negative result (Fig. 1 B). It must be concluded that the magnetization of this particular site presumably is of secondary origin.

The site-mean directions from sites 13, 14 and 16 are not included in the computation of the mean-site direction. The data from all accepted sites together (Table 1, Fig. 1 B) result in a mean-site direction: $D = 354.5°$, $I = +53.5°$, $\alpha_{95} = 8°$, $N = 10$, which is in very good agreement with the data from Athavale *et al.* (1963): $D = 353°$, $I = +56°$, $\alpha_{95} = 10°$, $N = 9$. The positive fold test result as obtained in the present study, indicates that the characteristic magnetization direction is definitely of pretectonic origin and most probably of primary origin as can be concluded from the agreement with other Precambrian data from the Indian subcontinent (Klootwijk 1974, Fig. 5, Athavale *et al.* 1963, 1970).

Rutten's (1965) field evidence in favour of a general ignimbritic origin of the Malani rhyolites near Jodhpur has been disputed by Mukherjee (1966). It was found by Ellwood and Watkins (1974) that the susceptibility anisotropy data of ignimbrites constitute a notable exception among extrusives. According to their preliminary data, ignimbrites are exceptional in that they are characterized by well grouping principal susceptibility axes. In the present collection of the Malani rhyolite samples, very well grouping principal susceptibility axes were found also. So, following Ellwood and Watkins, these data can be interpreted as further evidence for the ignimbritic nature of the Malani rhyolites in the Jodhpur area. These susceptibility anisotropy data were obtained by means of a rotating sample susceptibility anisotropy bridge, recently constructed at the Palaeomagnetic Laboratory (Mullender and Van den Berg, in preparation: A rotating sample susceptibility bridge), and will be discussed in greater detail elsewhere (Klootwijk *et al.*, in preparation).

Some deflection of the NRM direction due to planar fabric of the Malani rhyolites might be expected. In view of the presumably ignimbritic nature of the Malani rhyolites, we may apply the conclusion reached by Grommé *et al.* (1972) on NRM deflections in the Bishop Tuff ash flow in California (Dalrymple *et al.*, 1965; Grommé *et al.*, 1972). From the uniformity of NRM directions throughout the variably welded Bishop Tuff and its xenolithic inclusions, Grommé *et al.* have concluded that a deflection of NRM due to compaction or welding, does not seem to occur in general

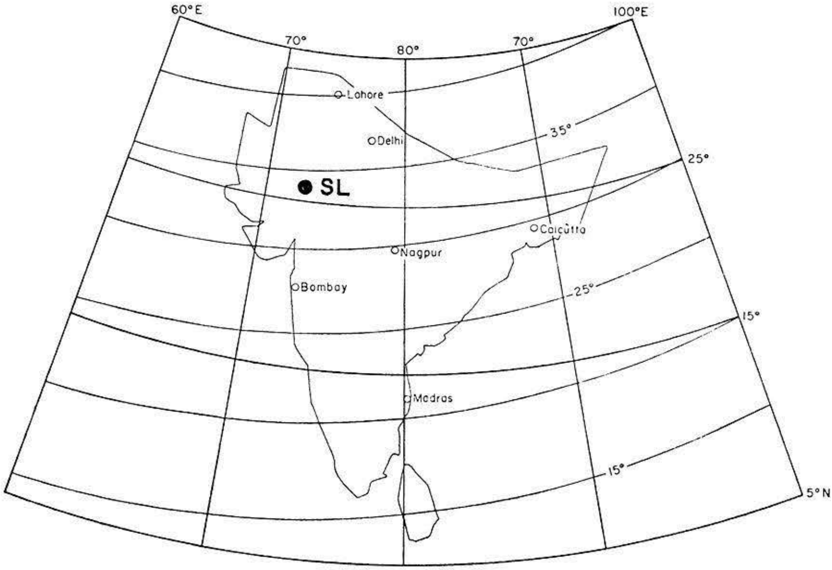


Fig. 5. Palaeolatitude map for the Indian subcontinent as deduced from the Malani rhyolite palaeomagnetic data. The pattern is computed according to the central axial dipole field formulae. SL denotes sampling locality

in ash flows. Welding and compaction in normal ash flows obviously takes place at temperatures above the blocking temperature of the magnetic constituents. This is supported by experimental data from Ross and Smith (1961) who have found welding temperatures between 580° and 750 °C or perhaps 900 °C.

The low value of the susceptibility anisotropy in the Malani rhyolites (generally less than 3%, Table 1) seems to exclude a significant deflection of the NRM direction due to anisotropy effects as well. So the obtained mean-site direction can be taken to represent the ambient magnetic field direction during the time of extrusion.

Interpreted in accordance with other Indian Precambrian data (Klootwijk, 1974), the present result reveals a position and orientation of the Indian subcontinent about 745 my ago, more or less like its present-day orientation. However, at that time, India was situated at a slightly higher latitude, as shown by the palaeolatitude map (Fig. 5).

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