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Palaeomagnetism of Tertiary Volcanic Rocks from the Ethiopian Southern Plateau and the Danakil Block

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Abstract. Remanent magnetization of 92 samples (22 sites) collected from Oligocene basalts from the Ethiopian southern plateau (location 9.1°N, 41°E) yields a palaeomagnetic pole at 75.1°N, 170.3°E with $A_{95} = 6.4°$ after AF-cleaning. This pole agrees with the Eocene-Oligocene pole for the western plateau. — Palaeomagnetic data of 125 samples (26 sites) from Early Pliocene basaltic rocks from the Danakil block (12.7° N, 42.5°E) yield a pole at 79.5°N, 258.8°E with $A_{95} = 2.6°$. The deviation of this pole position from other Miocene Pliocene poles for Africa is consistent with the hypothesis of 10° counter-clockwise rotation of the Danakil block since the Early Pliocene. On theoretical grounds however this amount of deviation may also be caused by not having completely averaged out secular variation due to insufficient sampling.

Key words: Palaeomagnetism — Africa — Afar Triangle.

Introduction

Previous palaeomagnetic investigations on Tertiary basaltic rocks in Ethiopia have been carried out by Brock *et al.* (1970) in the western plateau, by Megrue *et al.* (1972) on basaltic dikes in the area of the western and southern plateau, by Burek (1970) in the Danakil Block, and in the French Territorium of Somaliland (T.F.A.I.) by Pouchan and Roche (1971). In this paper palaeomagnetism of basaltic rocks from the southern plateau and from the Danakil block (see Fig. 1) is presented.

Volcanism in the Ethiopian rift and plateaus and in the Afar depression has been reviewed by Mohr (1971). Generally the plateau regions of Ethiopia consist of flood basalts which belong mainly to the alkali basalt series.

Radiometric age determinations (K-Ar ages) in the southern plateau has been carried out in most cases on dike intrusions into basaltic or non-basaltic host rocks (Megrue *et al.* 1972). Three dike samples at the road from Diredawa to Harrar (Fig. 1) have an average age of 31 My (35, 30, 28 My). Four samples from dikes at the road from Asbe Tafari to Harrer have an average age of 18 My (11, 15, 18, 28 My), and one basaltic host rock sample (in which the dike with 15 My was intruded) has an age 35.5 My. Similar ages were found further South near Goba with an average of 17.2

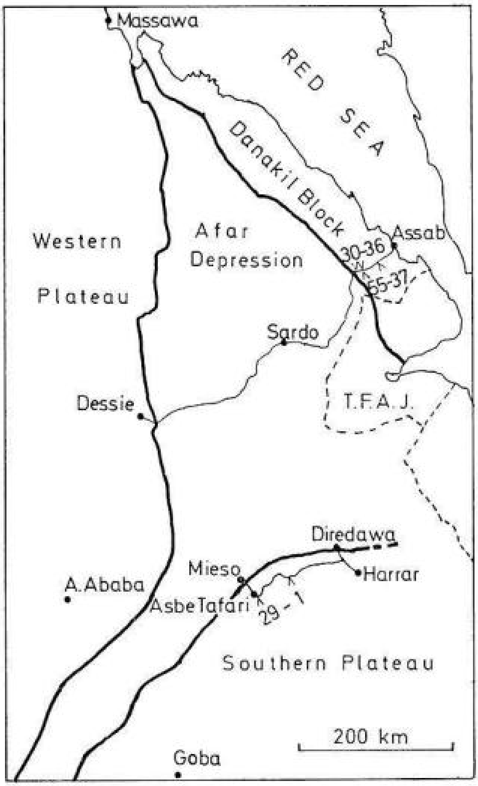

Fig. 1. Map of Ethiopia showing location of sites. Numbers refer to site numbers

My for 7 dike samples and 30 My for one basaltic host rock (Megrue *et al.*, 1972). Most of our samples were taken from basalt flows, only very few from dikes. It is therefore suggested that an Oligocene age (40—25 My) can be attributed to most of the collected samples. Some samples may be of Miocene age (25—10 My).

The basalts in the sampling area near Assab (see Fig. 1) cover the basement of the Danakil horst. According to Mohr (1971) these are of Miocene or Pliocene age. The only available radiometric age determination on a basaltic flow is about 60 km NW of the sampling area and yields an age of 6.7 My (Barberi *et al.*, 1972a). Therefore an Early Pliocene age may be attributed to our collected samples.

Sampling and Measurements

Samples with 2.5 cm core diameter were taken with a portable drilling machine. From the southern plateau 119 cores from 30 sites were sampled

Table 1. Site mean palaeomagnetic results after AF-cleaning of Ethiopian southern plateau basalts (location is at 9.1°N, 41°E)

Site	N	AF (Oe)	D°	i°	α_{95}	k	Pole position °N	Pole position °E	
(1)	2	160	36.3	—37.1	>45				
2	4	200	213.9	—20.5	5.2	303	56.5	126	
3	3	320	16.1	+ 0.2	8.3	221	71.6	159	
(4)	1		unstable						
5	5	350	346.9	— 8.3	23.7	11	71.4	265	
6	4	220	10.8	+ 3.3	9.6	91	76.9	164	
7	2	320	0.3	+ 0.5	38	45	81.1	219	
8	3	180	201.7	—12.7	10.2	146	68.3	137	
9	7	170	190.7	+25.2	16.5	14	65.2	195	
10	3	300	14.4	—15.8	19.1	42	67.5	181	
11	4	220	33.7	— 1.4	6.5	198	54.9	145	
(12)	2	300	254.9	—56.7	28.4	79	17.4	95	
13	5	300	194.4	+14.3	4.9	240	68.2	179	
14	2	200	197.9	+17.5	18	200	64.6	175	
15	2	330	336.9	—16.7	14.1	315	61.0	274	
16	4	330	355.9	—24.8	8.7	112	67.5	231	
16a	5	330	35.3	— 7.7	11.7	43	52.4	150	
(17)	3		unstable		>45				
(18)	3		unstable		>45				
(19)	3		unstable		>45				
20	12	170	184.6	+ 2.7	6.5	44	78.5	197	
21	5	300	176.1	+ 5.4	19.4	16	77.5	239	
22	3	310	42.6	+12.5	2.8	1870	47.7	131	
(23)	8	300	262.5	+ 7.5	9.4	35	6.7	136	
(24)	5	300	223.8	—50.6	6.4	144	43.7	96	
25	4	350	185.3	—11.5	7.3	158	83.7	163	
26	4	200	7.3	+ 8.2	23.4	16	81.1	165	
27	5	300	192.3	—12.7	6.9	122	77.5	142	
28	3	300	176.8	—20.8	6.7	330	86.4	339	
29	3	240	197.5	—18.8	20	38	72.7	128	
All normal:									A_{95}
11 sites			11.1	— 4.8	13.5	12.3	74.0	176.6	10.2
All reversed:									
11 sites			191.8	— 3.0	11.4	16.8	76.0	163.2	8.6
All sites:									
22 sites			11.4	— 0.4	8.4	14.4	75.1	170.3	6.4

Sites in brackets were omitted for the mean values. N number of samples, AF peak value of alternating field cleaning, D declination, i inclination, α_{95} and A_{95} radius of the 95% circle of confidence for the directions and the poles, k precision parameter.

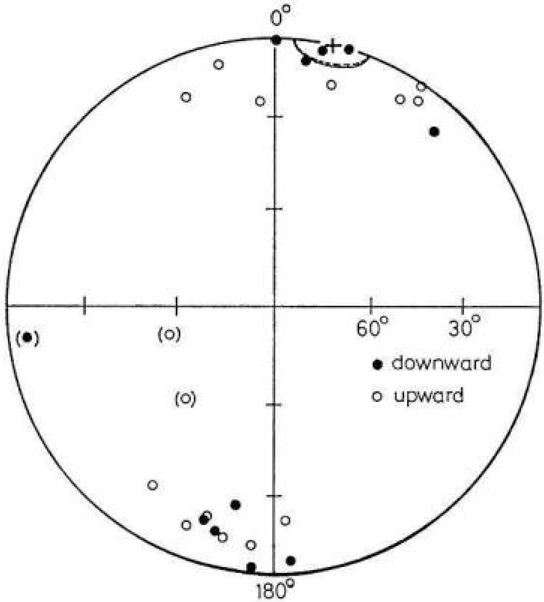

Fig. 2. Stereographic projection of mean site directions of remanent magnetization after alternating field cleaning for amples from the southern Ethiopian plateau. + = Overall mean with the 95% confidence circle (unit weight for each site). Directions in brackets were ommitted because of intermediate pole positions (pole latitude <45°)

along the road from Asbe Tafari to Harrar ca. 6—55 km from Asbe Tafari (Fig. 1). — From the Danakil block 127 cores were collected from 27 sites along the road from Assab to Sardo ca. 35—58 km from Assab.

The remanent magnetization was measured with a fluxgate spinner magnetometer. All samples were subjected to AF-cleaning with peak fields between 100 and 400 Oe according to results from AF demagnetization of pilot samples from each site.

Southern Plateau

Results for the plateau samples after AF cleaning are given in Table 1, the site mean directions and the overall mean with its circle of confidence are shown in Fig. 2.

Site 1, 4, 17, 18, and 19 were ommitted because of very large within-site scatter, which could not be adequately reduced by AF-cleaning ($\alpha_{95} > 45°$). Site 12, 23 and 24 have intermediate directions (yielding a pole with latitude $< 45°$) and were discarded. Of the remaining sites 11 have normal and 11 have reversed polarity. The mean pole positions of normal and reversed

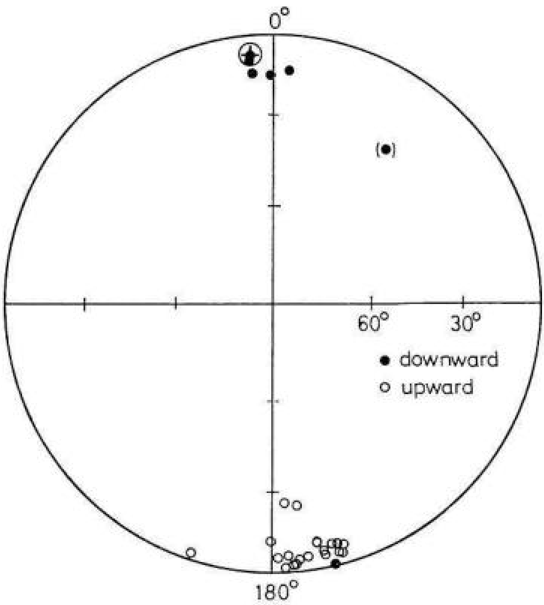

Fig. 3. Mean site directions after alternating field cleaning for sample from Danakil block. + = Overall mean with the 95% circle. Direction in brackets was ommitted because of intermediate pole position

sites coincide. Giving unit weight to each site direction the overall mean direction of normal and reversed sites is D = 11.4°, i = — 0.8° with $\alpha_{95} = 8.4°$. This yields a pole position at 75.1°N and 170°E with $A_{95} = 6.4°$ ($dp = 4.2°$, $dm = 8.5°$).

The stability of the natural remanence against AF cleaning was relatively weak in most cases. On demagnetization in 300 Oe the original intensity has droped to one third in average, in some cases to one tenth of the initial value. After AF cleaning the intensity varied between 20 and $400 \cdot 10^{-5}$ Gauss for the different sites.

Danakil Block

Results for the samples from the Danakil block after AF cleaning are given in Table 2, the directions of magnetization in Fig. 3. Site 40a was discarded because of intermediate direction. Of the remaining 26 sites 5 have normal remanent magnetization (these sites are located nearest to Assab) und 21 are reversed. The circles of confidence of the mean pole positions of normal and reversed sites overlap. The overall mean direction of magnetization is D = 353.8°, i = 8.4° with $\alpha_{95} = 3.4°$. This yields a pole positions at 79.5°N, 258°E with $A_{95} = 2.6°$ ($dp = 3.4$. $dm = 1.8°$). —

Table 2. Site mean palaeomagnetic results after AF-cleaning of Danakil block basalts (location is at 12.7°N, 42.5°E)

Site	N	AF (Oe)	D°	i°	α_{95}	k	Pole position °N	Pole position °E	
30	6	350	198.5	— 1.4	5.4	151	68.0	164	
31	5	250	180.2	—11.5	15.1	26	83.0	221	
32	3	300	177.0	—26.7	5.8	438	86.7	337	
33	5	350	173.7	—25.1	11.6	44	83.8	317	
34	5	330	175.2	— 1.7	8.1	88	77.1	245	
35	5	300	177.7	— 0.4	8.0	90	77.1	233	
36	5	400	176.1	— 7.2	15.1	27	80.0	246	
37	3	350	355.9	+14.7	6.5	356	83.7	254	
38	5	350	3.7	+13.5	5.6	187	83.0	190	
39	5	350	354.5	+ 8.7	6.8	125	80.0	255	
40	3	300	354.4	+10.3	9.1	183	80.6	258	
(40a)	2	300	143.1	+29.6	21	141	43.2	275	
41	5	330	359.0	+15.7	2.1	1300	85.0	234	
42	5	350	168.7	— 7.4	2.7	787	75.6	274	
43	6	350	179.1	— 6.7	8.8	75	80.5	228	
44	4	350	169.9	—10.7	5.8	249	77.5	277	
45	8	300	173.8	— 4.1	4.6	141	77.6	253	
46	5	350	165.5	— 4.2	8.8	76	72.0	277	
47	5	330	172.0	— 5.1	7.4	107	77.0	261	
48	5	300	166.7	— 9.1	6.3	146	74.5	282	
49	3	350	165.2	— 3.5	15.8	62	71.6	277	
50	5	320	174.7	— 5.8	10.4	55	78.8	251	
51	5	300	166.6	+ 0.4	5.4	196	71.4	269	
52	5	350	168.1	— 5.8	9.0	73	74.6	273	
53	5	380	176.3	— 2.4	12.7	37	77.8	240	
54	4	350	165.6	— 9.1	1.8	2600	73.5	284	
55	5	350	163.6	— 8.3	5.6	185	71.6	286	
All normal:									A_{95}
5 sites			357.4	+12.5	4.6	277	83.1	243.8	3.5
All reversed:									
21 sites			173.0	— 7.4	4.0	61	78.5	260.3	3.0
All sites:									
26 sites			353.8	+ 8.4	3.4	68	79.5	258.8	2.6

Site in brackets was omitted for the mean values. — Legend see Table 1.

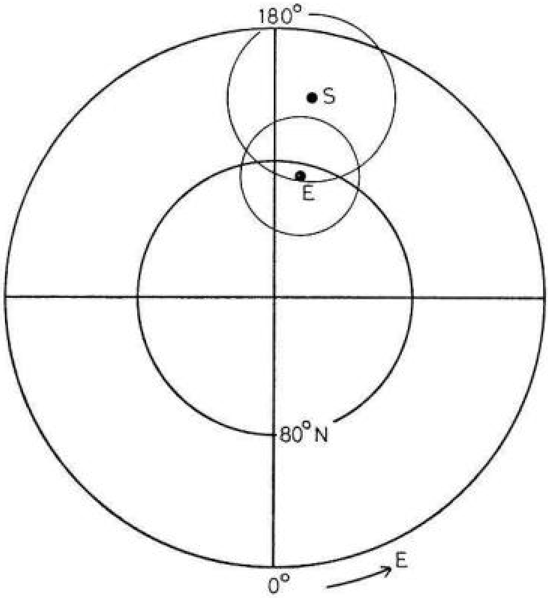

Fig. 4. Palaeopole positions with their respective circles of confidence for the Ethiopian plateaus. *E* Western plateau (location 9°N, 38.5°E) Eocene Oligocene (Brock *et al.*, 1970). *S* Southern plateau (location 9.1°N, 41°E) Oligocene (this paper)

After demagnetization in 300 Oe peak alternating field the natural remanence has decreased in average to about one half of its initial value. After AF cleaning the intensity varied between 100 and $1000 \cdot 10^{-5}$ Gauss for the different sites.

Discussion

Western and Southern Plateaus

The circles of confidence for pole positions from Eocene Oligocene western plateau basalts and from Oligocene southern plateau basalts overlap (see Fig. 4). Similar pole positions were determined by Megrue *et al.* (1972) for Eocene Miocene dikes from the western plateau (pole at 86°N, 161°E, $A_{95} = 9°$) and Oligocene Miocene dikes from the southern plateau (82°N, 155°E, $A_{95} = 16°$). For the Territory of French Somaliland (but not for the southern end of the Danakil Block) Pouchan *et al.* (1971) determined for Eocene Miocene basaltic rocks a pole at 78°N and 137°E with $A_{95} = 6°$. The circles of confidence of all these mentioned pole positions from Ethiopia

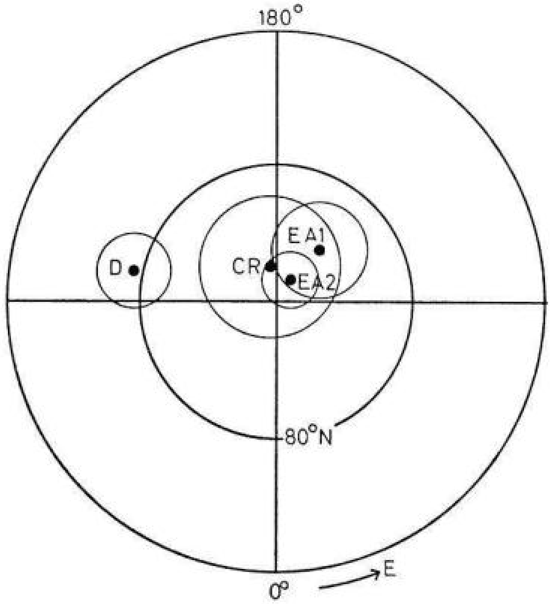

Fig. 5. A selection of Miocene Pliocene palaeopole positions for Africa and the Danakil block. *CR* Central Rift (location 0°N, 36.5°E) Miocene (Raja, 1968), *EA1* East African rift valley (1°S, 36°E) 0—7 My (Reilly 1970), *EA2* East African rift valley (1°S, 36°E) 7—14 My (Reilly, 1970), *D* Danakil block (12.7°N, 42.5°E) Early Pliocene (this paper)

overlap. Relativ tectonic movements between the southern and western plateau (if there are any) cannot be derived from the available palaeomagnetic data.

Danakil Block

In Fig. 5 selected Pliocene and Miocene pole positions for East Africa are compared with the Early Pliocene pole of the Danakil Block. The latter does not coincide with the others; the respective circles of confidence clearly do not overlap.

Interpretation of the Afar tectonics implies anticlockwise rotation of the Danakil Block in the time of formation of the Afar which started probably in the Lower Miocene (25—35 My B. P.) according to Barberi *et al.* (1972a). The angle of rotation however in uncertain. Burek (1970) estimated 30°, Barberi *et al.* (1972b) 18°$\pm$10° and Mohr (1972) about 35°. Very small angles of rotation have been postulated by Schäfer (1973 personal communication). Burek (1970) also determined an Early Miocene pole position for the Danakil Block at 46°N, 316°E consistent with counter-clockwise rotation in the order of 30°. Unfortunately this pole determination was restricted to two sites of volcanic rocks only.

Assuming a constant angular rotation rate since the beginning of the formation of the Afar these estimations imply an angle of rotation of 10° or less since the Early Pliocene. Starting with the determined Danakil pole (79.5°N, 258°E) a rotation of 10° yields a pole position at 81°N and 198°E, which brings the Danakil block pole closer to the other Late Tertiary African poles but no complete overlapping of all circles of confidence (see Fig. 5).

The palaeomagnetic method must be applied very carefully if the relative tectonic movements to detect are of a small scale (10° or less). If the time span sampled is not long enough with respect to palaeosecular variation then an apparent deviation of the mean pole position from the true pole positions may be the result. — Assuming both perfect measurement and perfect sampling of the secular variation cycle the angular standard deviation s of the mean direction is a measure for the magnitude of the palaeosecular variation. The angular standard deviation (due to palaeosecular variation) is about 19° for that latitude in Tertiary time according to Brock (1971). s (in degrees) is very nearly given by $81/k^{1/2}$ (k precission parameter, see Table 2). This yields $s = 9.8°$ for the samples from the Danakil block which is rather low. It is therefore possible that only a partial palaeosecular variation cycle is recorded what may be the reason for the deviation of the pole. — Although the palaeomagnetic observations seem to confirm the rotation hypotheses of the Danakil block, the conclusion is that much more detailed sampling must be carried out before all aspects in relation to secular variation can be excluded.

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