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Magnetic inclination of basaltic lavas from the Mid-Atlantic Ridge near 37°N

DURING the course of the French–American Mid-Oceanic Undersea Study (FAMOUS), many samples of basaltic pillow lava were collected from the axial region of the Mid-Atlantic Ridge near 37°N. The vertical axes and the tops of nine of these samples have been determined fairly accurately, allowing calculations of magnetic inclination at the time of the cooling of the lavas to be made with reasonable confidence.

According to modern conceptions of seafloor creation, basalts from the axial regions of the mid-ocean ridges should be young, and therefore magnetised in approximately the same direction as the present geomagnetic field. But the few magnetic measurements that have been made on basalts collected irrefutably on the crustal block responsible for the existence of the axial magnetic anomaly have yielded conflicting results[1-5]. Normal polarity has been found in samples from the Reykjanes Ridge[1] and from the Mid-Atlantic Ridge near 45°N (refs 2–4), but mixed or reversed polarities were found in two of six basalt cores drilled within the Rift Valley at the same latitude[5]. The mean magnetic inclination at a site cannot be reliably calculated if the number of satisfactorily reoriented samples is too small or if the direction of magnetisation is erratic within a single pillow or between samples. Although these conditions seem to have been met for samples dredged from 45°N (ref. 4), the mean magnetic inclination is 20° lower than expected.

Three of the samples discussed here (CH 31-DR 1-111; CH 31-DR 2-122; CH 31-DR 4-200) represent material dredged during the RV Jean Charcot CH 31 cruise of 1972 (refs 6 and 7). The remaining six samples (ARP 73-10-02; ARP 74-10-15; ARP 74-11-17; ARP 74-13-24; ARP 74-14-31; and ARP 74-17-40) were collected by a telemanipulated arm operated from the bathyscaphe Archimède during the FAMOUS diving programmes of 1973 and 1974 (refs 8 and 9). The locations of the sampling sites are shown in Fig. 1. Six samples were collected in the axial part of the Rift Valley, the remaining three come from the region of the intersection of the Rift Valley and Transform Fault 'A' near 36°57′N. The age of the samples can be inferred from a variety of methods.

The oxygen isotope ratio for a rock from dredge haul CH 31-DR 1 indicates that the material is very fresh, having suffered no noticeable seawater contamination (G. Pineau, M. Javoy and J. Bottinga, personal communication). Samples from dredge CH 31-DR 2, dated on a relative scale by measurements of the thickness of the palagonite–manganese coating[10] are dated at less than 170,000 yr BP. No age determination is available yet for samples from dredge CH 31-DR 4.

The youngest rock of the set of Archimède samples in the inner floor of the Rift Valley is probably ARP 74-10-15, which exhibited fresh glass on the chilled margin, followed by ARP 74-11-17, which was sampled in a talus pile barren of sediment, and which showed very little preserved glass. Both are olivine basalts[7,9] representing the youngest eruptives in that section of the Rift Valley, probably emplaced

Table 1 Magnetic properties of specimens of pillow lavas from the rift valley of the Mid-Atlantic Ridge near 37°N

Location*	Sample number	Specimen	J_0†	MDF	I_{s_0}§	I_s§	θ¶	I_c‖	I_c**
1	CH 31-DR1-111	U (G)	23.4	834	68.7	68.3	2.2	67.2	67.2
		L	220	325	63.8	66.1			
2	CH 31-DR2-122	U	173	243	66.1	65.4	1.5	64.7	64.7
		L (G)	64.5	311	64.2	63.9			
3	CH 31-DR4-200	U (G)	16.9	130	53.2	50.4	3.7	50.0	50.0
		L	109	554	35.2	49.6			
4	ARP 73-10-02 (1)	U	405	181	45.1	43.3	8.9		
		L	170	122	41.3	47.9			
	ARP 73-10-02 (2)	U	288	113	54.7	53.9	3.7	53.7	53.7
		L	171	153	52.5	53.5			
5	ARP 74-10-15 (1)	U (G)	108	495	56.7	55.7	2.3	56.5	56.5
		L	503	226	51.7	57.3			
	ARP 74-10-15 (2)	U	246	300	48.6	55.8	11.2		
		L	455	226	59.9	60.2			
6	ARP 74-11-17 (1)	U (G)	43.5	877	70.1	70.4	0.9	70.7	
		L	348	141	71.4	70.9			
	ARP 74-11-17 (2)	U (G)	33.5	806	69.6	69.2	0.7	69.5	70.5
		L	319	156	69.1	69.7			
	ARP 74-11-17 (3)	U (G)	56.8	849	69.9	70.2	2.5	71.2	
		L	262	170	68.7	72.3			
7	ARP 74-13-24 (1)	U	99.0	444	44.7	43.4	13.8		
		L	67.2	229	23.9	30.7			
	ARP 74-13-24 (2)	U	92.2	474	43.1	46.2	13.5		
		L	62.0	141	29.0	36.7			
	ARP 74-13-24 (3)	U	107	433	44.1	45.1	9.2		
		L	65.8	181	24.3	36.6			
8	ARP 74-14-31 (1)	U (G)	17.7	693	47.4	47.4		47.3	
		L	54.1	523	44.3	47.1			
	ARP 74-14-31 (2)	U (G)	28.3	543	50.9	50.7	4.6	48.7	48.0
		L	78.1	331	42.5	46.7			
	ARP 74-14-31 (3)	U (G)	33.9	639	47.6	49.1	7.4		
		L	49.5	475	49.3	48.2			
9	ARP 74-17-40 (1)	U	106	83	42.1	42.1	1.8	41.7	
		L	99.8	192	25.1	41.2			40.7
	ARP 74-17-40 (2)	U	117	85	58.5	40.0	2.2	39.7	
		L	153	113	41.3	39.3			

* Location refers to numbered sites in Fig. 1. Sample number is eventually followed by core number (in brackets); U, upper specimen; L, lower specimen; G, glass on specimen.
† J_0, mean intensity of magnetisation before cleaning (10^{-4} e.m.u. cm^{-3}).
‡ MDF, median destructive field in peak oersted.
§ I_{s_0} and I_s are magnetic inclinations before and after cleaning, respectively.
¶ θ, angular deviation between the directions of magnetisations of the two specimens from the same core.
‖ I_c, mean inclination of core.
** I_p mean inclination of pillow. I_s, θ, I_c and I_p calculated after a.f. demagnetisation.

within the past 10,000 yr (refs 10 and 11). The age of sample ARP 73-10-2 is bracketed between 30,000 and 100,000 yr on the basis of these palagonite-manganese coatings[10]. Fission-track dating (D. Storzer, personal communication) shows that this sample was formed less than 50,000 yr ago.

The remaining three Archimède samples (ARP 74-13-24; ARP 74-14-31; and ARP 74-17-40) come from the axial portion of Transform Fault 'A' in the region close to its intersection with the Rift Valley. Sample ARP 74-13-24 was taken 4 km east of the axis of the Rift Valley segment on a small north–south ridge which structurally is part of the Rift Valley wall. Its age should be about 270,000–300,000 yr according to spreading rates for the eastern limb of the Rift Valley, calculated from magnetic profiles[6,12]. Sample ARP 74-14-31, with a ropey surface showing flow direction, has a preserved glassy crust and a palagonite layer overlain by a thin manganese coating. Samples at this site, on the edge of a tension gash associated with the left lateral shear of Transform Fault 'A' (ref. 9), are the youngest specimens collected in the Transform Fault. This estimate is supported by a fission-track age (D. Storzer, personal communication) of less than 45,000 yr. Sample ARP 74-17-40, closest to the accreting plate boundary, has textural and structural features similar to those of rocks determined to be intrusives from field evidence. It was sampled on a tectonic scarp which exhibits a layered sequence (possibly a truncated sill) 1.5 km east of the deep axis of the Rift Valley. Its age, inferred from spreading rates, should be less than 100,000 to 113,000 yr (refs 6 and 12). Spreading rate values averaged over the Brunhes Epoch may not necessarily, however, be applicable to an area which may be tectonically and volcanically active. Fission-track ages for this general region are all less than 300,000 yr (D. Storzer, *personal communication*).

On the combined evidence of fission-track dating, calculated opening rates, palagonite and manganese thickness, and field observations, it seems certain that all the reoriented rocks were emplaced during the Brunhes Epoch, so that a proper scheme of reorientation should reveal that the samples are all normally magnetised. Any negative inclinations could be attributable to eruptives that cooled during the Laschamps (reverse) geomagnetic excursion, which may have occurred between 10,000 and 15,000 yr BP,

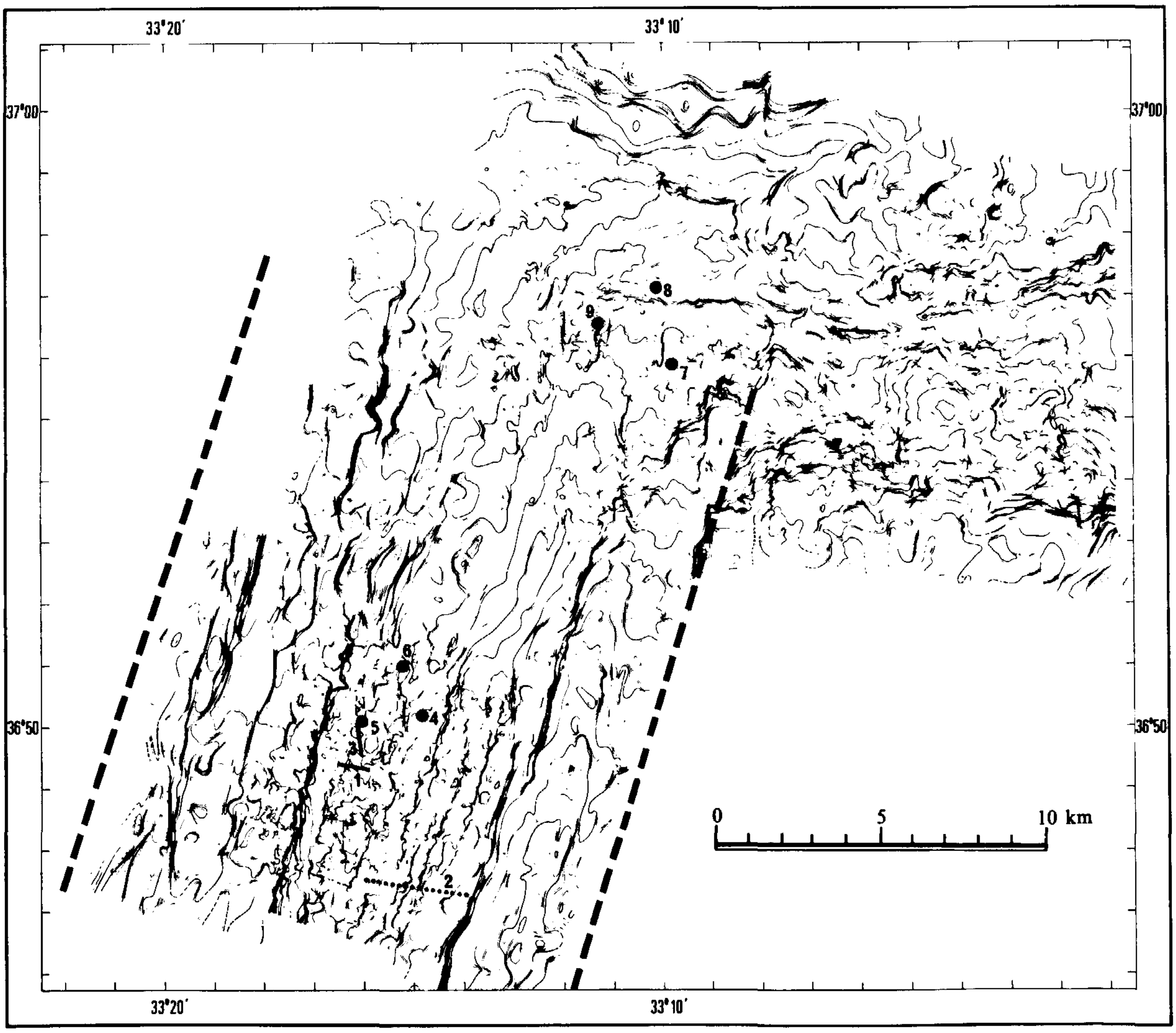

Fig. 1 Bathymetry of parts of the Rift Valley and Transform Fault "A" (21) showing sampling sites (Table 1) and boundaries (heavy dashed lines) of the crust formed during the Brunhes Epoch[6]. The sampling sites are taken from refs 6, 8 and 9. The location of dredge 2 (dotted line) is only indicative. The numbered locations refer to the first entry in Table 1. The Rift Valley sites are all clearly within the Brunhes block and should therefore have normal polarity.

or during the Blake reverse event (or excursion) with an inferred duration of about 10,000 yr and a mean age close to 110,000 yr BP (see ref. 5).

The partial reorientation of samples from the sea floor is possible first, for cores, assuming that the axis of drilling is vertical (in practice, deviation from the vertical can reach 15°; ref. 5 and, second, for magnetically viscous samples, using various magnetic tests; refs 2, 13 and 14), (these methods should obviously be applied only to rocks whose viscosity has been established; they cannot be used for the samples discussed here because their viscosity index is too small[15]); third, for pillow-lavas exhibiting one or more volcanic features considered to be criteria of polarity[1-4].

The last method is the only one which gives indications of the orientation of the pillow-lava during cooling because it is independent of possible subsequent changes of position.

De Boer *et al.*[1] have listed four volcanic features thought to be diagnostic of vertical and top: the flattened-oval shape of pillows; the location of necks interconnecting pillows at their bases; stemlike extensions commonly at the bases of pillows; and basal stalactites on the concave side of a crust from lava tunnels or tumuli. Of these, the last seems to be the most reliable (see, for example, ref. 16) but it can give only a polarity and cannot give the vertical because the position of the lava crust with stalactites on the tumulus or tunnel cannot be known *a priori*. In another study[4], the horizontal was assumed to be parallel to the equatorial plane of the pillow but the assumed error of 20° (ref. 4) is probably too low, because the method relies strongly on questionable conceptions of how pillows form[16], and assumes that the pillow cooled on a horizontal surface. A further possibility, that of using surface glass coating as a guide to the original orientation, is not reliable because pillows often curl during their formation.

An improved criterion of orientation came from field observations made from the American submersible Alvin in the inner floor of the Rift Valley in the FAMOUS area[17-19]. It was noted that, on the tops of lava flows, series of ledges commonly occur along the inner walls of collapsed feeder tubes. The ledges record the various levels at which lava flowed through the tubes[17] much as rings in a bathtub register successive water levels[18]. These frozen-in lava levels were observed to be nearly horizontal *in situ*, and they provide a reliable guide to sample orientation for palaeomagnetic studies[19]. The nine samples for which measurements are reported here are the only ones among all the rocks sampled by the French team in the FAMOUS area showing the 'bathtub ring' criterion or a modification of the criterion. Some examples are shown in Figs 2 and 3.

In sample CH 31-DR 4-200 (Fig. 2*b*), a small flattish ledge occurs near the core of a pillow exhibiting a glassy margin. The upper surface of the ledge is very smooth and contrasts with the overlying, subparallel wall, which has a rugose texture imposed by the presence of small septae and lava stalactites. The vertical is taken normal to the flattish ledge and the polarity is given by the relationship between the rugose stalactite-bearing surface and the smoother, upward-facing surface. The flattish glassy surface is tilted about 30° from the horizontal.

The angular discrepancy between the glassy surface and the horizontal is more extreme in the case of sample ARP 73-10-02 where the glassy surface is nearly vertical (Fig. 2*c*). In the interior of the pillow a series of elongate cavities with smooth flattish floors and more irregular roofs gives a good indication of the vertical at the time of cooling.

In sample ARP 74-11-17 (Fig. 2*d*), the glassy surface is on top and nearly horizontal. The vertical is taken to be normal to a line of small, elongate, asymmetric cavities. The true vertical could deviate slightly, because the cavities seem to be *en échelon* (Fig. 3) and the vertical axis could have been taken perpendicular to the parallel long axes of the cavities. The polarity is not, however, in doubt and is given by both the asymmetry of the cavities and by the lava stalactites on a large surface (Fig. 3).

Sample ARP 74-14-31 shows a superposition of two, approximately horizontal, ropey lava surfaces (Fig. 2*a*). A confirmation of the field determination is provided by an elongate cavity below the upper ropey crust and by well developed stalactites on the bottom of the sample.

Suitable samples for reorientation could not be found in the collection made from the diving saucer Cyana, because of their small size. Similarly, only the very large dredge samples could be used with any confidence.

One to three vertical cores, about 10 cm long, were drilled through each of the nine samples of reoriented pillow lava basalts. The upper and the lower parts of each core were sawn flat, giving two specimens of about 30 g. All 36 specimens were submitted to magnetic study, including alternating field treatment up to 850 oersted (Table 1). In several cases, the intensities of magnetisation and the median destructive field (MDF) were quite different from one specimen to another, even within a single core. In particular, the glassy parts of a sample are systematically much less magnetised than non-glassy parts. The very high coercivities shown by the glassy portions of the samples probably reflect in part the smaller grain size. As previously pointed out[22] the between-specimen variability indicates that large samples (or the averaging of results from several specimens from each pillow) are generally required to obtain significant data on the intensities of magnetisation of submarine extrusives.

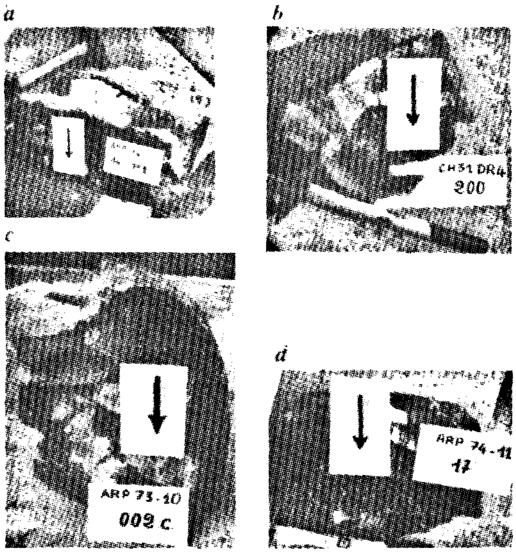

Fig. 2 Four selected pillow lavas displaying characteristic features for reorientation (see text). Arrows, vertical-downward at the time of cooling. *a*, ARP 74-14-031; *b*, CH 31-DR-4-200; *c*, ARP 73-10-02C; *d*, ARP 74-11-17.

All of the specimens have a positive magnetic inclination. The alternating field treatment induced small changes in direction, probably by the removal of weak parasitic magnetisations acquired during drilling. Because the samples are not viscous, no significance can be attached to the sign of the inclination change during cleaning. In some cases, the directions of magnetisation after cleaning remain significantly different for the upper and the lower specimen from a single core. In particular, the upper part of pillow ARP 74-13-24 is characterised by a magnetic inclination 10–15° higher than that of the lower part of the pillow.

Fig. 3 *a*, Close-up of cavity alignment in sample ARP 74-11-17 (Fig. 2 *d*); *b*, stalactite-bearing surface (vertical-upward into picture) at the base of ropey lava ARP74-14-031 (shown in Fig. 2); *c*, close-up of horizontal cavity below upper ropey surface of sample ARP 74-14-031 (Fig. 2*a*).

This may indicate variations in space of the geomagnetic field at the site of cooling, because of disturbances caused by the neighbouring lavas. The large inclination found for sample ARP 74-11-17 may be real and result from secular variation. Alternatively, it may be the result of a small error in the orientation, as discussed above.

In calculating the mean inclination of a pillow we have rejected data obtained from cores exhibiting a deviation larger than 5° in their directions of magnetisation (after cleaning) between the upper and the lower part of the pillow.

The overall mean magnetic inclination, calculated from the mean values for eight pillow basalts, is equal to 56°. It corresponds exactly with the inclination of the present geomagnetic field (International Geomagnetic Reference Field, 1965), which is the same as the inclination of an axial dipole field. At two drill sites of DSDP leg 37, west of the FAMOUS area, natural remanent inclinations were also found to be close to the dipole value for the area and to match this local anomaly sense[20] although anomalons shallow inclinations were found at a third site.

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