J Geophys (1985) 57:59–64

Journal of Geophysics

Deep drilling through the accreting plate boundary of Asal, Southern Afar: palaeomagnetism and magnetic properties of basaltic cores

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Abstract. Palaeomagnetic and rock magnetic investigations have been carried out on unoriented samples from two deep vertical boreholes in the axial valley of the Asal Rift (Republic of Djibouti). The deepest samples (1280 m), submitted to temperatures of 200° C and long-term hydrothermal alteration, show low intensity values of magnetization (0.6 ± 0.2 Am^{-1}), in contrast to normal values of oceanic layer 2A, and pure magnetite as magnetization carrier. Thermal demagnetization, low-temperature saturated magnetization, high-temperature spinner experiments and optical examination show that: (1) There is evidence of thermal overprinting which did create a secondary component in the present day field direction; this direction is thermally locked-in during extraction from the borehole. (2) The use of this magnetization to orientate the core together with vectorial analysis of thermal demagnetization diagrams of the NRM reveals a high blocking temperature primary component with reverse polarity. (3) This contrasts with all previous surface palaeomagnetic surveys in the Asal Rift where only normal polarity directions have been found; it agrees, however, with an age of about 1 MY for the early stage of rifting at the present place as suggested from propagating rift theory in this area.

Key words: Magnetic properties – Basalt – Asal Rift – Hydrothermal alteration – Multivectorial magnetization

Introduction

The magnetic structure of the oceanic crust has been well explained by Vine and Matthews (1963) through the interpretation of marine magnetic anomalies. Dredged samples and submarine surveys have enabled us to state in more detail the magnetic structure of the crust, allowing us to give some constraints on the surface layers. Intensive studies have been carried out in some local areas of the mid-Atlantic Ridge at 45° N (Brooke et al., 1970; Irving, 1970; Ade-Hall et al., 1973) and the Famous area (Prévot et al., 1976). They could not, however, offer data needed for the vertical distribution of magnetic properties. With the next phases of crustal sampling (IPOD and DSDP programmes) data were obtained up to 600 m depth in basaltic layers 2A and 2B. A direct test of the Vine and Matthews hypothesis was possible (Johnson and Merrill, 1978) but increased complexity has arisen from the results (Hall, 1976), in particular when polarity inversion appeared in a vertical drilled section of the oceanic crust (Ryall et al., 1977; Johnson and Merrill, 1978). Magnetic properties of deep intrusive layers of the oceanic crust have been obtained from comparison with geothermal deep drilling in Iceland (Kristjansson and Watkins, 1977), obducted ophiolite suites (Stern and Elton, 1980; Banerjee, 1980) or sea floor dredgeholes (Kent et al., 1978).

These comparisons, however, may not always be justified as Iceland might not have true oceanic crust (Gibson, 1979) and there is evidence that most ophiolite suites have undergone metamorphism during obduction. Dunlop and Prévot (1982) have emphasized this difficulty. Their new data on magnetic properties on drilled submarine rocks from legs 30, 37 and 45 led them to propose a new magnetic layering of the oceanic crust where magnetite is the main magnetic carrier of all layers. They even show that deep crust and upper mantle are possible candidates to oceanic magnetic anomalies, an exciting hypothesis which has since been challenged.

In the search for the sources of magnetic anomalies over the Republic of Djibouti territory, a region where pseudo-oceanic crust has long since been recognized (Barberi and Varet, 1974; Lepine et al., 1972; Needham et al., 1976; Ruegg, 1975), aeromagnetic mapping was done by CNRS, France (Courtillot et al., 1980) and paleomagnetic surveys undertaken (Galibert et al., 1980; Courtillot et al., 1984). We report here results of magnetic properties of samples from two ancient deep geothermal holes in that same area.

During a geothermal survey in the Republic of Djibouti the "Bureau de Recherches Géologiques et Minières" (BRGM) drilled two boreholes close to Lake Asal in a volcano-tectonic axis known as the Asal Rift (Varet, 1978). This tectonic area is a unique example (together with Iceland) of an emerged spreading segment at the West of the Gulf of Aden near the Red Sea. The Asal Rift is at the westernmost segment of the Carlsberg ridge (Laughton, 1966), making a transition (Fig. 1a) between the oceanic domain of the Tadjourah gulf and the Afar depression (Lepine et al., 1972; Ruegg, 1975; Richard, 1979). Though morphological and structural evidence shows a similarity to a low-rate spreading ridge (Needham et al., 1976), the magmatism (Stieltjes, 1973; Richard, 1979) is transitional, the tholeitic trend appearing in most recent times. The rifting process studied during the last volcano-tectonic crisis in 1978 (Ruegg et al., 1979), first compared to the one previously studied in Iceland (Bjornsson et al., 1979), is considered as a typical example of a propagating rift (Courtillot

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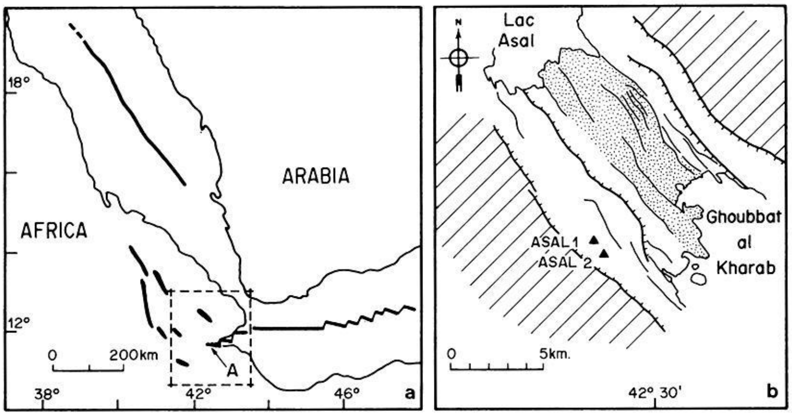

Fig. 1. a Sketch map of the Afar area with main tectonic trends: *black*: known spreading axis and active oceanic type volcanic ranges. *A* indicates the site of the Asal rift. **b** Locations of the two boreholes in the Asal rift. *Shaded area*: Dahla and stratoid basaltic trapps (8–1 M.Y. old). *White*: central zone, containing the Inner Floor (*dotted area*), after Needham et al. (1976)

et al., 1980; Courtillot et al., 1984). The affinity of the Asal Rift with an oceanic ridge should result in an oceanic-type magnetic structure of the crust and magnetic properties of samples from deep layers might help to elaborate magnetic layering models for this area and be useful for a comparison with true oceanic crust.

Geological setting of boreholes and sample description

The two boreholes named ASAL1 and ASAL2, were drilled by BRGM during the 1975 survey for detecting steam fields in this area. They lie inside the rift near its SW limit (Fig. 1b) and are both on the same tectonic block of the "Central zone" as described by Needham et al., 1976) by analogy with a rift valley of an oceanic ridge. During drilling operations the alkaline basaltic Stratoid and Dahla series which are, respectively, 1–4 MY and 4–8 MY old (Barberi et al., 1975; Richard, 1979) and outcrop only outside the rift, were encountered beneath the present tholeitic basalt. In situ temperature measurements for ASAL 2 yielded values above 220° C at a depth of 1260 m, indicating a strong temperature gradient at this site; a petrographic study of the two borehole cuttings (BRGM, 1975) indicates that samples have undergone increasing metamorphism with depth from zeolite to greenschist facies with chlorite and epidote below 1200 m. It is important to point out that this metamorphism is not a simple deep sea water circulation mechanism, as for surface layers of the oceanic crust (Bohlke et al., 1981), but results from hydrothermal alteration at temperatures of about 300° C.

Table 1 lists the different standard specimens obtained by drilling from fragments provided by BRGM and recovered in three different cores: (1) Core 1C2 (ASAL 1) is a rhyolitic flow with strong silica recrystallization; substitution of pyroxene by chlorite reported by BRGM (BRGM, 1975) was not observed in our samples. Coring was done from 450 to 453 m (90% recovered); we used fragments 1, 5, 11, 15, 18 and 21 spread along the 3 m of coring to get 16 specimens. (2) Core 2C1 (ASAL 2) is from an alkaline basalt with low chlorite content. Coring was done from 980 to 981.5 m (60% recovered); we used fragments 1 and 2 to get 6 specimens. (3) Core 2C2 (ASAL 2) is also an alkaline basalt having extensive chloritization, secondary silica calcite and epidote; it has a characteristic greenschist facies metamorphism. Coring was done from 1281 to 1284 m (60% recovered); we used fragments 1, 2 and 3 spread along the distance of coring to get 10 specimens. A total of 32 specimens were available for our study.

Table 1. Palaeomagnetic results. 1C2. 1a stands for Asal *1* borehole, coring *C2*, fragment n° *1* (BRGM) palaeomagnetic standard specimen *a*. *I*, inclination. *J*, intensity of magnetization in AM^{-1}. *H* and *T*: range of AF peak field and temperature giving the cleaned direction

Specimen number	N.R.M.		Inclination after cleaning		
	$I_{(°arc)}$	J_{NRM}	$H_{(mT)}$	$T_{(°C)}$	$I_{(°arc)}$
Asal 1					
1C2 1a	(82)	(0.71)	12–40		(82)
1b	(80)	(0.22)		125°–375°	(81)
5a	42	0.02	20–35		13
5b	18	0.03		450°	15
5c	13	0.02			
11a	1	0.03	30–50		15
b	5	0.03		150°–450°	14
c	12	0.04			
d	19	0.03			
15a	45	0.02	30–50		0
b	49	0.03			
18a	31	0.03	10–35		10
b	34	0.03			
21a	51	0.04	15–40		–
b	50	0.03		300°–400°	7
c	63	0.03			
$N=5$, $J_{NRM}=0.03\pm0.01$ Am^{-1}, $I_m=9°\pm6°$					
Asal 2					
2C1 1a	7	2.00	50–60		18
b	10	1.98		broken at 450°	9
2a	18	2.47	40–70		19
b	16	2.34		broken at 450°	18
c	18	2.43		broken at 375°	19
d	19	–	50–70		22
$N=2$, $J_{NRM}=2.2\pm0.3$ Am^{-1}, $I_m=17°\pm4°$					
2C2 1a	50	0.34	30–70		34
b	45	0.56		500°–700°	36
c	44	0.37			
2a	40	0.50	15–70		38
b	41	0.65		600°–700°	36
c	42	0.95		450°–580°	36
d	43	0.81			
3a	33	0.55	10–70		32
b	31	1.25		400°–600°	30
c	46	0.48			30
$N=3$, $J_{NRM}=0.64\pm0.2$ Am^{-1}, $I_m=34°\pm3°$					

Natural remanent magnetization and viscous remanent magnetization

Stability of the natural remanent magnetization (NRM) has been studied by the "storage test" using a 1-week period: samples are stored for 1 week with their vertical axes upward in the geomagnetic field and for another week with their vertical axes downward, in a position antiparallel to the first one. Subtraction and addition of the two NRMs measured after the two storages yield, respectively, the VRM (viscous remanence) acquired in 1 week in the laboratory and the NRM free of viscous component at this time scale (Dunlop and Prévot, 1982; Thellier and Thellier, 1944). The ratio VRM/TRM yields a mean viscosity of 12% for the rhyolites in ASAL 1 and lower than 5% for the two basaltic flows in ASAL 2 showing that short-term VRM is mall or negligible for the two basaltic flows but quite important for the rhyolitic flow. NRM intensities for all samples are given in Table 1; they show consistent results within the same fragment and in the same core except for fragment 1C2-1 which has disproportionately high NRM intensity and abnormal inclination, AF demagnetization of specimen 1C2-1a has shown the typical behaviour of an IRM component which might have been acquired during drilling, a process previously suggested by different authors (Dunlop and Prévot, 1982).

Rejecting these anomalous samples, we obtain mean intensities of 0.03 ± 0.01, 2.2 ± 0.3 and 0.64 ± 0.20 Am^{-1}, respectively, for cores 1C2, 2C1 and 2C2. Putting aside the rhyolite 1C2, which is not a major constituent of the crust in the Asal area, the last two results from the basaltic flows can be compared with data obtained in two previous surface samplings made on the Asal Rift, keeping in mind the limited number of samples we have. The mean NRM intensities of the two sets available are 2.7 Am^{-1} (Harrison et al., 1977) and 5.6 Am^{-1} (Galibert et al., 1980); we interpret the discrepancy between these surveys by a variable proportion of highly magnetized subaquatic flows and less magnetized aerial flows in the two samplings. Such differences in intensity have been pointed out by Prévot and Grommé (1975). The value of 2.2 ± 0.3 Am^{-1} found at 980 m in ASAL 2 for core 2C1 agrees well with these figures, which are all characteristic of layer 2A. On the contrary, core 2C2 at 1280 m with 0.6 ± 0.2 Am^{-1} has a much too low intensity. Two hypotheses may be considered to explain this result: (1) The variability of petrographic type. (2) The effect of high temperature in this area. If we consider the mean value 3.6 Am^{-1} (with bounds of 2.1 and 14.7 for the standard deviation) computed by Prévot and Grommé (1975) for young basaltic flows of variable type, our data is significantly lower.

Similar studies in Iceland (Kristjansson, 1972; Wood and Gibson, 1976) did not yield a clear answer, but the prime importance of hydrothermal circulation in lowering the proportion of magnetic minerals has been pointed out (Ade-Hall et al., 1971; Kristjansson, 1972). However, we must not forget the low number of samples we have worked with.

Alternating field and thermal demangetization

Table 1 gives the absolute value I of the NRM inclination (we know the vertical direction of each fragment of cylindrical shape but not which face is up or down). For core 1C2 (ASAL 1) we get variable values, rather high, relative

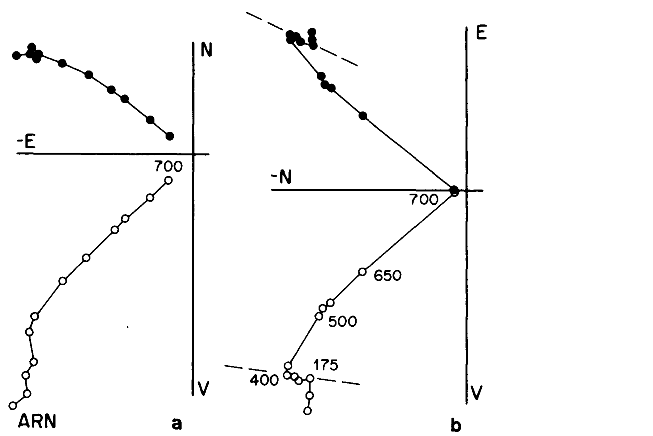

Fig. 2a, b. Zijderveld (1967) diagrams. **a** AF cleaning of sample 2C2.1a; **b** Thermal treatment of sample 2C2.1b. *Full symbols*: horizontal projection; *open symbols*: vertical projection. *Dotted lines*: *B* component

to the expected dipole inclination (22°) at the latitude of Asal. However, except for fragment 1 which might have acquired an IRM during drilling, after AF and thermal demagnetization the mean inclination is lowered to $9° \pm 6°$, a value compatible with secular variation if we consider it as an instantaneous record of the field direction from one flow unit. For core 2C1 a stable direction is defined for each specimen with coercive force above 40 mT and high unblocking temperatures giving a mean inclination, after cleaning, of $17° \pm 4°$. The decrease of magnetization is small during heating; this corresponds to a stable direction up to 400° C after which most samples break up, preventing higher temperature steps being done.

Core 2C2 shows very different behaviour during both types of demagnetization. Thermal cleaning allows the separation of three components (Fig. 2b) while, on the other hand, AF cleaning (Fig. 2a) shows only one direction corresponding to the one with high unblocking temperatures. Table 1 gives the inclination of the high-temperature/high-field component, defined in the range 10–70 mT or unblocking temperatures greater than 400° C. The corresponding mean inclination of this component is about 34°. The characteristics of the three components of magnetization are the following: (1) Component A with unblocking temperatures greater than 400° C and a mean inclination of about 34°. (2) Component B with shallow inclination of about 4° and unblocking temperatures in the range 175°–400° C. (3) Component C with steep inclination, defined by unblocking temperatures lower than 175° C (Fig. 2b) which probably represents the viscosity acquired during 1 year of storage in the laboratory field. The B component is sometimes poorly defined when the two blocking-temperature spectra of B and A do overlap; nevertheless, the result is that B is roughly antiparallel to A (Fig. 2b). We shall come back to this result later on.

Rock magnetism

Opaque minerals were identified by microscope observation of polished sections and thermomagnetic analysis. J_s–T curves were obtained with a vertical type balance in a field of about 0.1 T and samples heated in vacuum. Acquisition of isothermal remanence magnetization (IRM) in fields up to 1.2 T, observation of transition temperature using a Di-

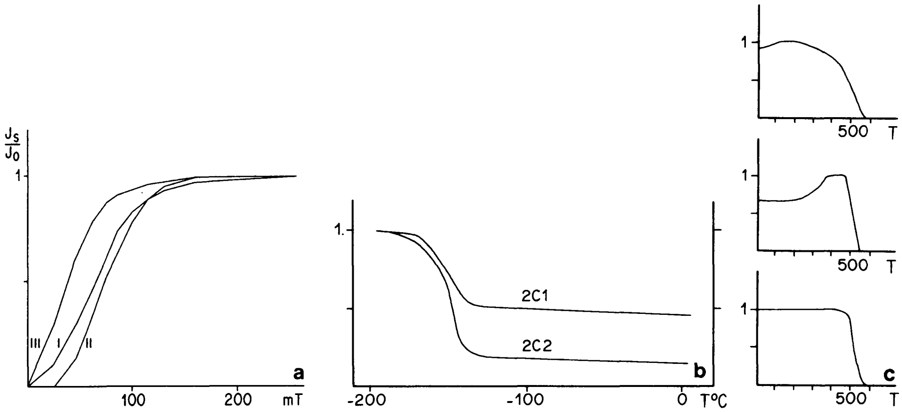

Fig. 3. **a** SIRM acquisition for core 1C2 (I), 2C1 (II) and 2C2 (III). **b** SIRM behaviour at low temperatures for core 2C1 and 2C2. **c** J_s–T curves for cores 1C2 (*top*) 2C1 (*middle*) and 2C2 (*bottom*)

gico high/low temperature spinner and X-ray diffractometry were also used to better extimate the magnetic carriers.

Opaques for cores 1C2 and 2C1 are abundant and have a mean size of 10 μm. The grains consist of primary titanomagnetite (TTM) with scarce exsolved lamellae of ilmenite ("trellis" intergrowths). Early stages of maghemitization can be observed, the minerals having only suffered a slight alteration at the time of emplacement. The J_s–T curve for 2C1 shows a particular behaviour with enhancement of magnetization below the Curie point (Fig. 3c); the external field, too low for saturation, explains the maximum, a characteristic of the Hopkinson effect (Dunlop, 1974) which may be an indication of abundance of mono-domain grains. The reversible curve indicates no or minor chemical transformation during heating and a Curie point near pure MT. IRM acquisition curves (Fig. 3a) show that 2C1 remanence in a field of 50 mT is only 20% of the saturation remanence (SIRM) which is, however, always obtained in fields lower than 200 mT.

The behaviour of SIRM at low temperature has been studied following the method given by Nagata et al. (1964) for the separation of the magnetite and hematite phases. After the sample was magnetized, both at room and liquid-air temperature (−160° C in our experience), continuous recording of the variation of magnetization shows that a transition at −150° C exists during warming up to 20° C (Fig. 3b). This is characteristic of almost Ti-free MT. The relatively small decrease of SIRM at −150° C, however, might indicate abundant SD grains. The absence of a transition a −20° C on the other hand is evidence of lack of hematite at least in coarse grains. X-ray determination of the lattice parameter has been carried out on one sample from core 2C1 giving $a = 8.35$ Å, a value characteristic of maghemite or substitute TTM.

Core 2C2 is totally different; opaques are scarce and have a mean size of a few μm. The grains are interstitial in small veins and consist of secondary magnetite. X-ray determination of the lattice parameter yields an unlikely low and poorly defined value of $a = 8.27$ Å. Saturation remanence is obtained in a field below 150 mT compatible with MT/TTM grains. Hematite is never apparent in 2C2 although unblocking temperatures greater than 580° C have been observed in one sample (Fig. 2).

To summarize, MT with low Ti content appears to be the major constituent of the magnetic minerals in all samples. Hematite was not observed directly, but thermal demagnetization occasionally exhibited $T_b > 600°$ C. For 2C2, secondary MT crystallized during hydrothermal alteration, a temperature of 300° C being high enough for this process to take place (Cann, 1979). The origin of MT observed in 1C2 and 2C1, however, at a depth where temperature was much lower is not understood. The samples do not show any alteration and there is no indication for deuteritic oxidation. The MT looks like primary MT.

Interpretation of the results of core 2C2

Rock magnetic studies show the presence of secondary magnetite in 2C2 as the only visible magnetic mineral. The effect of hydrothermal alteration on TRM may explain the result observed during thermal demagnetization: if all primary minerals have broken down as indicated by microscope observation, the original TRM has been replaced by CTRM (component A) with grains which may be locked at temperatures of the order of 230° C. If, on the contrary, primary magnetic minerals still subsist, but are small enough and not visible (for instance, inclusion of MT into silicates would protect them from alteration), part of TRM subsist in component A. In both cases the B component is a PTRM carried by secondary grains which remain unlocked at 230° C. The acquisition of magnetization is the following: (1) Acquisition of primary TRM (component A). (2) Stepwise burial of the flow with evolution of the Asal Rift; in situ temperature increases slowly, up to 230° C with hydrothermal activity. This prolonged effect possibly destroys the primary magnetic minerals and secondary magnetic grains grow, some of them staying unblocked owing to that temperature. (3) Acquisition of TRM by the unblocked grains during uplift of the core and cooling in the present magnetic field ($I = 5°$), yielding the shallow inclination B component.

Thermal overprinting has been theoretically studied (Pullaiah et al., 1975) for synthetic minerals (magnetite and hematite); the corresponding diagrams allow us an estimate of the duration of heating, assuming his amplitude and the blocking temperature for laboratory heating times. Whole rock applications are critical as they rely on the assumption of the NRM to be TRM with constant mineralogy through time (either magnetite or hematite in the cases studied by Pullaiah) but have already been attempted (Schwarz, 1977; Van der Voo et al., 1978; Buchan and Schwarz, 1980). The simple magnetic mineralogy of the

Table 2. Characteristic direction of magnetization for core 2C2 computed after undirect orientation of the samples (see text)

Sample number	Declination	Inclination
2C2 1b	169.9	–35.8
2C2 1c	212.3	–35.5
2C2 1d	162.1	–32.2
2C2 2b	221.1	–36.3
2C2 2c	173.2	–35.7
2C2 2d	183.5	–36.7
2C2 3b	136.4	–29.9
Mean direction $N=7$	179.1	–37.7 $k=12$ $\alpha_{95}=15.4$

Asal samples allows us to use the magnetite diagram (Pullaiah et al., 1975); blocking temperatures given by thermal cleaning are about 400° C (disappearance of the B component) for roughly 5 min heating. These two parameters, carried back onto the diagram, yield a heating time of about 1 MY at 230° C (in situ temperature).

If we assume a constant temperature through time and no evolution of the magnetic grains which is hardly probable, the residence time we found of 1 M.Y., which gives the age of the hydrothermal circulation responsible for the alteration, is coeval with the Asal Rift formation. An age of 1 M.Y. for the Asal Rift is in agreement with other results deduced from tectonic and microtectonic studies (Arthaud et al., 1980). The B component, whose presence has been explained, is therefore parallel to the present magnetic field at Asal ($D=0°$, $I=5°$); we can now fully orientate the samples (Watts and Van der Voo, 1976). We have only to apply a vertical axis rotation to make the apparent B declination equal to zero. Table 2 gives the directions of A components obtained for seven samples and the mean direction (179/−38°). This result must be used carefully, owing to multiple errors caused by core rotation during uplift or overlap of blocking temperature spectra leading to bad determination of B, for example. Nevertheless, the A component undoubtedly represents a reversed direction of the earth's magnetic field.

Conclusions

The core 2C2 from the deepest borehole (ASAL 2) in the inner floor of the Asal Rift, taken at a depth of 1280 m, has been submitted to in situ temperature of about 220° C. This process results in a multivectorial magnetization for core 2C2 as PTRM was locked in the present field direction during extraction of the core from the borehole, as shown by the direction of component B revealed by thermal demagnetization.

The resulting intensity of magnetization of core 2C2 (0.6 ± 0.2 Am^{-1}) is anomalously low compared to oceanic basalts from layer 2A. Although limited to a small number of samples available from core 2C2, this result would suggest a negligable contribution of deep sources to aeromagnetic anomalies that have been mapped in this area. We suggest that surface palaeomagnetic survey data might be used in inversion models at least for the inner floor of the Asal Rift. In fact, correlation of palaeomagnetic polarity with the sign of the aeromagnetic anomalies over the older (1–4 MA) area between Lakes Asal and Abbe are in favour of a simple vertical structure of the magnetic crust in the area (Courtbillot et al., 1984).

Use of the B component of magnetization, parallel to the present field, to fully orientate the samples shows that the primary magnetization of basalt from core 2C2 has a reversed direction. This contrasts will all surface flows in the rift which have normal polarity (Galibert et al., 1980; Harrison et al., 1977) corresponding to recent Brunhes-age volcanic activity as illustrated by the last volcanic crisis of 1978 (Ruegg et al., 1979). A reverse direction, on the contrary, fits with a pre-Brunhes age of the last phase of rifting at that place, when rifting propagated from the Ghoubbat straights to the present Asal area, as suggested by Courtillot et al., (1984).

Acknowledgements. This research was suggested to us by J. Varet from B.R.G.M. and funded by a grant from D.G.R.S.T., N°. 76,7.1326.

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Received October 29, 1984; Revised March 22, 1985
Accepted March 28, 1985