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MAGNETISM OF THE MID-ATLANTIC RIDGE CREST NEAR 37°N FROM FAMOUS AND DSDP RESULTS: A REVIEW

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Abstract. —Comparison of magnetic properties of pillow basalts from the Rift Valley (FAMOUS area) and from the Crest Mountains (site 332 of DSDP Leg 37) of the Mid-Atlantic Ridge near 37°N shows that major differences in magnetic structure and properties of the oceanic crust occur between these two sites.

Mean effective intensity of magnetization of the pillow basalt layer drops from 1.4 x 10^{-2} emu cm^{-3} (14 A m^{-1}) at the axis to about 0.4 x 10^{-2} emu cm^{-3} (4 A m^{-1} at site 332. While the magnetic anomaly over the spreading center may be accounted for by a magnetized layer less than 500 m thick, deeper seated material contributes to the magnetic anomalies over the Crest Mountains.

The large reduction of the intensity of magnetization of the magnetized layer appears to be a general feature resulting from low-temperature oxidation (maghemitization) of titanomagnetite. The effect of maghemitization is a reduction by 2/3 to 3/4 of the remanence intensity, accompanied by a comparable decrease of the Q ratio. Correlative increase of Curie temperature and decrease of saturation magnetization agree with experimental data for synthetic titanomagnetites. However, contrary to previous conclusions deduced from magnetic studies on submarine basalts, almost no changes in susceptibility and coercivity parameters result from maghemitization. It is also pointed out that maghemitization of the top of layer 2A runs over too long a time constant to account for the occurrence of the "magnetization high" found in the FAMOUS Rift Valley. This feature corresponds to eruptions of fine-grained olivine-rich basalts, which are on the average twice as magnetic as the surrounding plagioclase or pyroxene-rich basalts. The high remanence of olivine-rich basalts results from their smaller magnetic oxide grain size. A similar relationship between petrology and magnetism is also observed for Leg 37 basalts at site 332.

The thickness of the highly magnetized layer found at the ridge axis is less than the approximately 1 km thick pillow basalt layer (2A). This implies that some process strongly reduces the intensity of magnetization of the pillows at depth. A moderate elevation in temperature resulting in a rapid and intense maghemitization seems to be the best explanation. At Leg 37 sites the isotherm corresponding to the mean Curie temperature (300°C) is at least at 2 km depth, which indicates that the whole layer 2 can contribute to the magnetic anomalies.

Within the FAMOUS Rift Valley the mean inclination of magnetization fits the dipole inclination, while anomalously shallow inclinations are commonly observed at DSDP and IPOD sites from the Mid-Atlantic Ridge Crest. This is in agreement with tectonic models of rifted mid-oceanic rises, which assume block tilting within or at the edges of the rift valley as a result of normal faulting. However, tectonic rotations required for explaining paleomagnetic result for Cretaceous North Atlantic IPOD sites may indicate a more complex structural evolution of the upper part of the oceanic crust.

Introduction

FAMOUS (French American Mid-Ocean Undersea Study) and DSDP (Deep Sea Drilling Program) Leg

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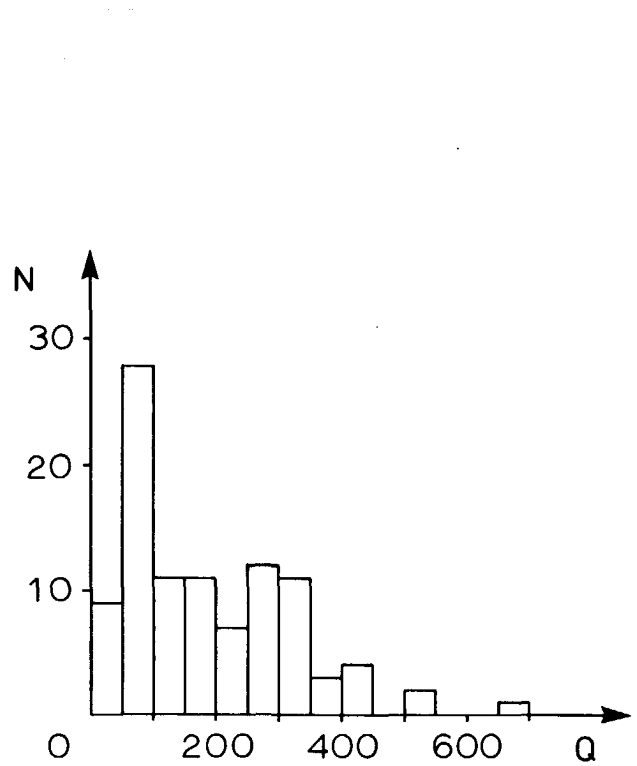

Fig. 2. Histogram of the Q ratio of 103 pillow basalts of the FAMOUS rift valley.

37 yielded large collections of pillow basalts that have been studied in great detail. The extensive magnetic results obtained provide a unique opportunity to compare the magnetism of the upper part of the oceanic crust at and near a ridge axis, in the present-day accretion zone and at 30 km from the spreading center.

The FAMOUS program was mainly devoted to the study of the Rift Valley near 37°N. This area was extensively sampled either by dredging (Needham and Francheteau, 1974) or by using manned submersible (Bellaiche et al., 1974; Arcyana, 1975; Ballard et al., 1975). Figure 1 shows the location of the dredge stations where most of the rocks studied magnetically by the French team (Lecaille et al., 1974; Prévot et al., 1976; Prévot and Lecaille, 1976) were recovered. A total number of about 160 samples was studied, including 120 large samples about 300 g in weight. Experiments include weak-field susceptibility and natural remanent magnetization (NRM) measurements, alternating field treatment, magnetic hysteresis studies, thermomagnetic analysis and electron microprobe analysis (carried out on only 10 samples with titanomagnetite crystals large enough for such studies). Detailed experimental procedures and results will be given elsewhere (Lecaille and Prévot, 1979). Fission-track ages obtained by Storzer and Selo (1974, 1976) indicate these rocks are less than 0.1 m.y. old.

Another magnetic study has been carried out by Johnson and Atwater (1977) on rock samples from the Rift Valley, most of them recovered by submersibles. Their results are restricted to small specimens with mean magnetic grain size larger than 1 µm and include NRM and susceptibility measurements, alternating field treatment and thermomagnetic analysis. This sampling bias results in a systematic rejection of the specimens with mean grain size below the single-domain to pseudosingle domain threshold (about 1 µm for titanium-rich titanomagnetites, e.g., Day, 1977). There is therefore some doubt that the mean values they obtain for grain size-related magnetic parameters (intensity of remanence, susceptibility, Koenigsberger ratio, median destructive field) are really representative of the overall FAMOUS pillow basalts.

Regarding the Leg 37 cores magnetically studied by several authors (in Aumento, Melson et al., 1977) and in greatest detail by Hall and Ryall (1977), we will consider the data from holes 332A and 332B, the nearest site to the ridge axis, for comparison with FAMOUS results. Site 322 is located at 37°N, only 30 km west of the present-day plate boundary. Estimated age of the crust at this site is about 3.5 m.y. (Aumento, Melson et al., 1977).

The comparison of these two magnetically well documented sets of submarine basalts will be made in regard to three problems: (1) the contribution of pillow basalts to the observed magnetic anomalies; (2) the magnetic effects of the low-temperature oxidation (maghemitization) of titanomagnetites and (3) the relationship between petrology and magnetism of the basaltic layer.

Pillow basalts as a source of magnetic anomalies

The magnetic anomalies produced by pillow basalts depend on several magnetic parameters: Firstly, the Koenigsberger (or Q) ratio, the ratio of the intensity of remanence to the intensity of magnetization induced by the geomagnetic field at the site. As a first approximation, it may be considered that the Q ratio must be larger than one for the Vine and Matthews (1963) interpretation of magnetic anomalies to be valid. Secondly, we have to consider the characteristics of the remanent magnetization itself: intensity, polarity and direction.

1. FAMOUS pillow basalts

The Q ratio is quite high (figure 2) with a geometric mean value of 151 (table 2). Individual Q ratios range from 20 to 680.

The mean Q value found by Johnson and Atwater (1977) for their specimens from the Rift Valley is about one order of magnitude smaller, due to their higher susceptibility (3.5×10^{-3} emu cm^{-3}), about 10 times that listed in table 2. Such a high susceptibility is difficult to accept for unoxidized pillow basalts. It is several times larger than the susceptibility of unoxidized massive flows (Johnson and Hall, 1978). However, the magnetic susceptibility of the latter should be higher, due to both a larger grain size and a higher content of magnetic minerals. We note also that the susceptibilities given in the same paper by Johnson and Atwater (1977) for samples dredged near DSDP site 332 are similarly one order of magnitude higher than the mean value for the pillow basalts drilled at this site (table 2).

There is therefore no doubt that the Q value is quite high and that the magnetic anomaly over this spreading center is not due to lateral changes of the induced magnetization carried by the pillow lava sequence.

It has been pointed out by Harrison (1976) that the arithmetic mean (and not the geometric mean) has to be used to estimate the intensity of remanence as a source of magnetic anomalies. The arithmetic mean value of the intensity of remanence of the pillow basalts is $1.9 \pm 0.3 \times 10^{-2}$ emu cm^{-3} (19 A m^{-1}). The histogram (figure 3) shows only one maximum, indicating that probably this mean value is meaningful. Johnson and Atwater (1977) found approximately the same value for a less extensive collection of rocks from the median valley.

Polarity and inclination of remanence have been determined for 18 partially oriented pillow basalts from the Rift Valley (Prévot et al., 1976; Johnson and Atwater, 1977). For most of the samples, the criterion used for orientation was the occurrence of frozen-in lava levels resulting in the formation of ledges assumed to be horizontal. During the diving operation in the FAMOUS area of the Mid-Atlantic Ridge near 36°50', field observations have shown (Ballard et al., 1975; Heirtzler, 1975) the existence of a series of ledges or shelves on the walls of collapsed feeder tubes. The outer surfaces of these tubes or pillows are glassy and the interior ledges or shelves are cryptocrystalline and not as glassy as the exteriors. Hence it is believed that cold sea water did not enter into the cavities defined by the ledges. These shelves and cavities are formed when the feeding lava is cut off intermittently at its source, permitting partial drainage of the remaining flow and quenching of lower lava levels within the cooling pillow (Ballard and Moore, 1977). The upper surface of the ledges is smooth while the bottom surface has a rugose texture due to the presence of septa and lava stalactites (Prévot et al., 1976). The cavities between shelves vary in width from a few centimeters to about twenty centimeters and are often elongated in a preferential direction (Fig. 4). However, the cavities are not always continuous but may be interrupted by internal walls (Bideau et al., 1977). Usually several levels of cavities may be seen in a single pillowed flow. In the interior of the pillows, a series of elongated cavities with a smoother floor and a more rugose roof gives an indication of the vertical at the time of cooling. Hence in order to orient a fragment of such a pillow basalt showing cavities, the vertical at the time of cooling is taken to be normal to the flattish ledge or normal to a line of small elongated cavities. In both cases the polarity of the vertical is deduced from the relative position of the smooth and rugose surfaces of the cavities (Prévot et al., 1976).

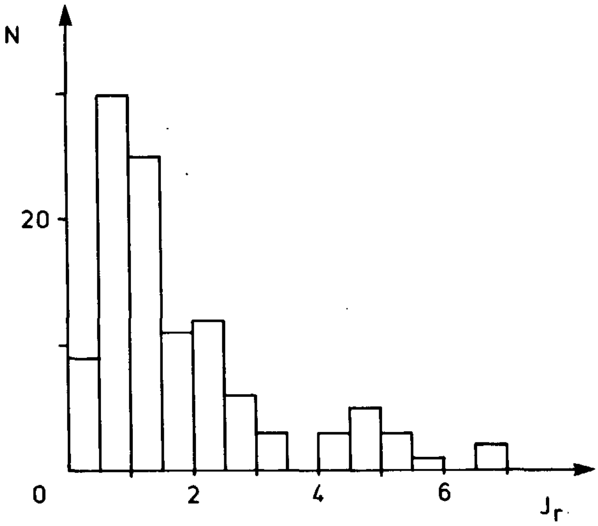

Fig. 3. Histogram of the intensity of magnetization J_r (natural values) of 111 pillow basalts of the FAMOUS rift valley (10^{-2} emu cm^{-3}).

The difficulties with this method of rock reorientation are related to the facts that the cavities are often irregular in shape, that the ledges may be missing, and/or the cavities may be scarce. Thin sections made across the pillow fragments from the surface to the interior show only textural variations accompanied by an increasing degree of crystallinity towards the inner part of the flow. However, the most significant variations are found within the first 3 centimeters from the surface. Examples of reorientation using the method of the cavities were tested on various types of basalts recovered by dredging and by submersibles from the ocean floor. Plagioclase-pyroxene-rich basalts (ARP 73-10-02, ARP 74-17-40), olivine basalt (ARP 74-11-17, CH 31-DRI-111), and plagioclase-rich basalts were used (Fig. 4).

This criterion has been used for 13 samples. For the remaining samples, two were collected by Alvin divers from outcrop, then reoriented according to diver description after the return to the surface. The other three samples were drilled and reoriented assuming the drilling barrel was vertical and the pillows did not move after cooling. Figure 5 shows the location and polarity of oriented samples.

The nine samples studied by Prévot et al. (1976), broadly distributed within the median valley, are normally magnetized. The mean inclination is equal to 56° ± 10° (s.d.), which corresponds to the expected inclination for an axial centered dipole at this latitude. Similarly, Johnson and Atwater (1977) found a mean inclination equal to 53° ± 8°. But a major difficulty arises from the fact that two of their nine samples, all collected within the median valley, exhibit a negative inclination.

One of the two reversely magnetized samples was oriented from cooling levels as described above. This criterion provides an unequivocal determin-

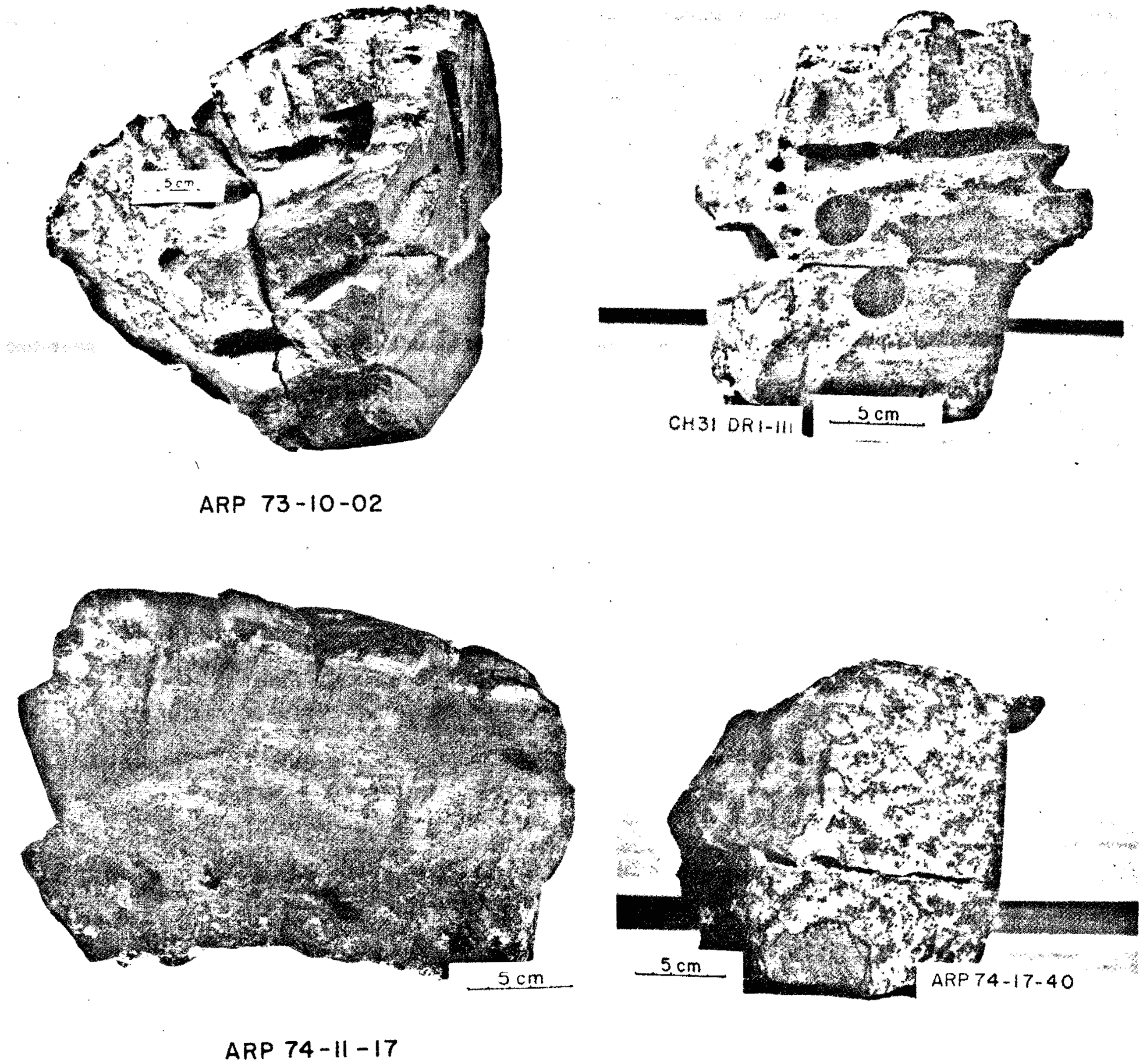

Fig. 4. Selected pillow flows showing oriented cavities with ledges. Samples ARP 74-11-17, and CH 31-DR 1-111 are olivine basalts. Samples ARP 73-10-02 and ARP 74-17-40 are plagioclase-pyroxene-rich basalts. The vertical is taken to be normal to a line defined by the elongation of the cavities. All the samples are from the inner floor of the Rift Valley near 36°50'N except for sample ARP 74-17-40 which was collected in transform fault "A".

ation of the horizontal plane but the determination of up and down is less sure, being based only upon differences in rugosity between supposed downward and upward-facing walls of the cavities. The second reversely magnetized sample was drilled. In the absence of direct visual inspection of the site, the possibility that this sample was recovered from a talus pile cannot be ruled out. Other possible interpretations are self-reversal or recording of some geomagnetic excursion.

In view of the indirect methods which have to be used for reorienting submarine pillow basalts, the occurrence of 16 normally magnetized samples from a total of 18, strongly suggests that in this part of the FAMOUS Rift Valley (Rift Valley 2, according to Macdonald 1977) the pillow basalts are normally magnetized, in agreement

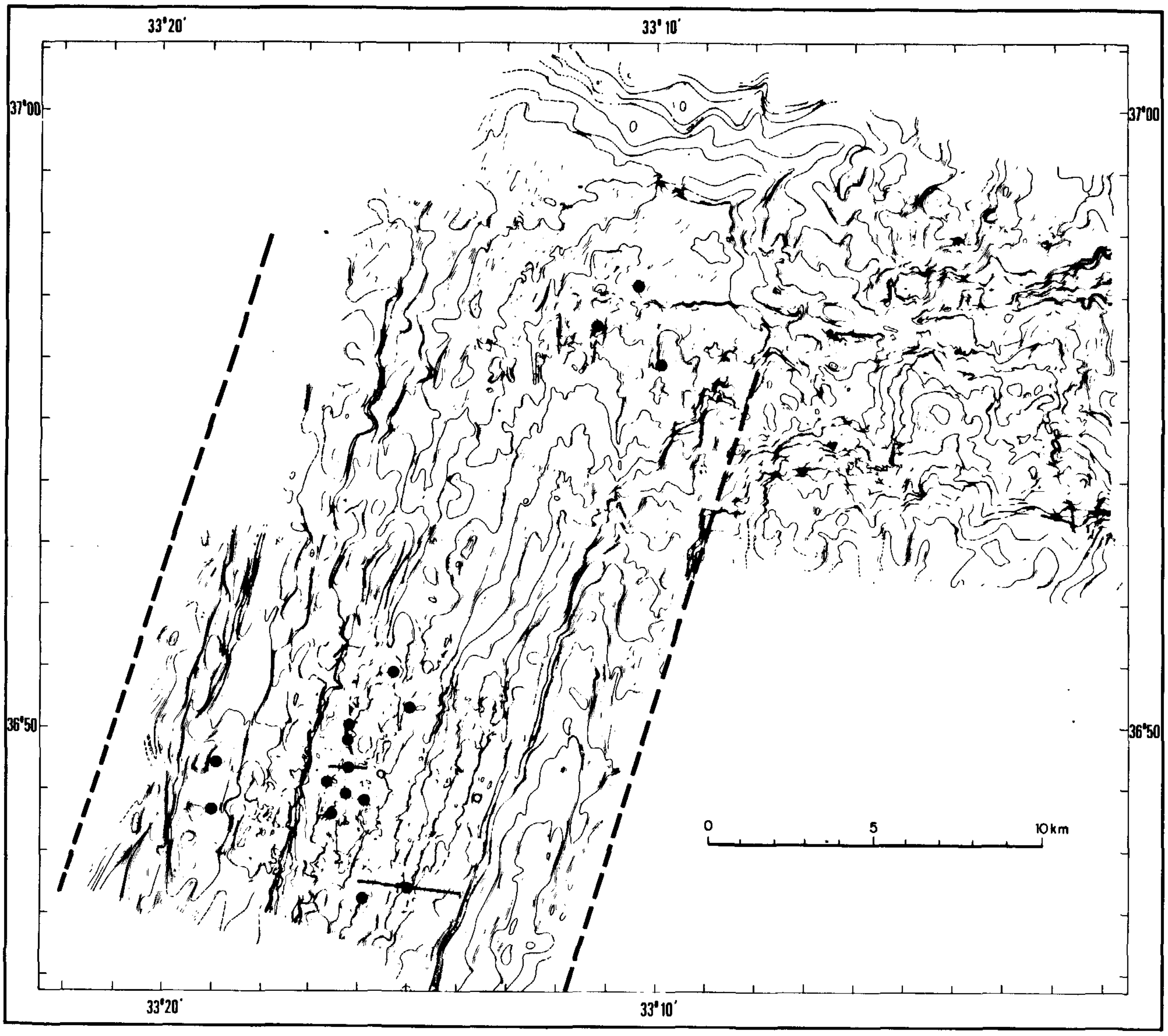

Fig. 5. Location and polarity of oriented samples from the median valley (from Prévot et al., 1976, and Johnson and Atwater, 1977). Black dots: positive inclination; circles: negative inclination. Heavy lines with black dots correspond to dredge hauls samples. Boundaries of the crust formed during the Brunhes epoch are indicated by heavy dashed line.

with their Brunhes age. Similarly, paleomagnetic studies of the Afar rift valley--which is interpreted as an accreting plate boundary--showed that all samples are normally magnetized (Harrison et al., 1977; Smith and Sichler, personal communication).

Assuming that the fraction of non-magnetic material is 0.2 at the ridge axis (Salisbury, personal communication) and that the standard deviation of the directions of NRM is 20° (Marshall and Cox, 1971), the overall mean intensity of magnetization of the pillow-lava layer is 1.4×10^{-2} emu cm^{-3}. A magnetized layer less than 500 m thick is enough (Lecaille et al., 1974) to account for the amplitude of the axial anomaly at 37°N (Needham and Francheteau, 1974). Hence the pillow basalt layer is responsible for the magnetic anomaly observed at the axis of the Mid-Atlantic Ridge near 37°N.

2. Leg 37 pillow basalts

The numerous magnetic studies carried out on Leg 37 basalts (Hall and Ryall, 1977a and b; Bleil and Petersen, 1977; Dunlop and Hale, 1977; Plessard and Prévot, 1977; Kent and Lowrie, 1977) showed large differences in magnetic properties with respect to the FAMOUS rocks.

The relatively high Q ratio of Leg 37 basalts (approximately equal to 35 according to Ryall et al., 1977) seems to indicate that--as found for FAMOUS rocks--the remanence dominates over induced magnetization. However, it must be noted that Leg 37 basalts are often magnetically viscous (Dunlop and Hale, 1977; Evans and Wayman, 1977; Kent and Lowrie, 1977; Plessard and Prévot, 1977) in contrast to FAMOUS basalts (Lecaille et al., 1974). Magnetic viscosity results in the fact that not only the remanence (viscous remanent magnetization or VRM) but also the induced magnetization (viscous induced magnetization or VIM) increases significantly with t, the time of application of the field. If we neglect short-lived geomagnetic excursions, the acquisition time to consider in nature is 0.7 m.y., the beginning of the Brunhes polarity epoch, except for younger rocks. The measurements carried out by Hall and Ryall (1977) using a high frequency susceptibility bridge, yield an induced magnetization definitely smaller than the induced magnetization carried in situ by the specimen. The actual mean Q value is therefore smaller than 35. Plessard and Prévot (1977) showed that the VIM of Leg 37 basalts increased almost linearly with log t. According to a tentative estimation of the intensity of induced magnetization for t = 0.7 m.y., they concluded nevertheless that for a large majority of their samples, the induced magnetization carried in situ is noticeably smaller than the NRM.

The properties of NRM are also quite different from those observed in the FAMOUS rift valley. The magnetic polarity is mostly reversed (Ryall et al., 1977) in accordance with interpretation of sea-surface magnetic profiles suggesting that site 332 is within the 3.32-3.78 m.y. old negative polarity block (Aumento, Melson et al., 1977). The approximately 100 m thick normally magnetized layer occurring at the top of hole 332A may correspond to a normal polarity event preceding the Gilbert-Gauss boundary (Aumento, Melson et al., 1977). The mean inclination is shallower by a much as 25°-30° from the expected dipole value suggesting considerable tectonic tilting (Ryall et al., 1977; Harrison and Watkins, 1977). The effective intensity of the drilled basaltic layer is only 0.37×10^{-2} emu cm^{-3} (Ryall et al., 1977), about four times weaker than that calculated for the rift valley. Hence, contrary to our conclusion for the FAMOUS Rift Valley, the layer responsible for magnetic anomaly at site 332 probably exceeds the accepted thickness of 2 km for layer 2 (Ryall et al., 1977).

The low-temperature oxidation of titanomagnetites

1. Magnetic effects of maghemitization: comparison of FAMOUS and Leg 37 pillow basalts.

Low-temperature oxidation of titanomagnetites (maghemitization) is probably the main process explaining the decrease of the contribution of the pillow lava sequence to magnetic anomalies outwards from the ridge axis (Irving, 1970).

All evaluations of the magnetic effects of naturally occurring maghemitization are based on the assumption that the two specimens or the two rock units under comparison were identical before alteration. This can never be demonstrated. It may be hoped that a favorable situation for comparing two collections of pillow basalts would occur when the rocks were erupted at the same latitude from the same accreting plate boundary and close to each other in time. The FAMOUS and Leg 37 collections meet these conditions. Moreover, many petrographical similarities were noted between Leg 37 basalts and those in the FAMOUS area (Bryan and Thompson, 1977). We shall restrict the comparison between the FAMOUS and Leg 37 collections to pillow basalts. Hence, for Leg 37, we shall consider only the magnetic data of the petrological units identified as pillow lava sequences by Aumento, Melson et al., (1977). Because NRM intensity and Q ratio have a log normal distribution, we shall compare their geometric mean values.

Comparison of electron-microprobe and thermomagnetic data indicates that the FAMOUS pillow basalts contain only slightly oxidized titanomagnetites (table 1). This is demonstrated by the absence of significant difference between measured and calculated Curie points for most of the samples. The latter Curie point is deduced from chemical analysis, assuming that no oxidation occurred and using Curie point data for synthetic titanomagnetites (see review by Smith and Prévot, 1977, for pure titanomagnetite, and experimental data by Richards et al., 1973 for substituted titanomagnetites). Note that estimated uncertainties about calculated values are ± 30°C (Smith and Prévot, 1977).

Sample DR06-104A is certainly oxidized, and perhaps also samples DR02-102A$_2$, DR03-103 and DR03-105 B$_3$. Moreover, the mean calculated Curie point of the samples is about 40° lower than the mean measured Curie point for the entire collection (table 2). This suggests a slight maghemitization of the FAMOUS pillow basalts, the mean oxidation index z being about 0.2 according to Readman and O'Reilly's (1972) data for synthetic titanomaghemite.

The Leg 37 pillow basalts are largely maghemitized as demonstrated by the irreversibility of the thermomagnetic curves of most of the samples (Bleil and Petersen, 1977; Dunlop and Hale, 1977; Hall and Ryall, 1977b; Schwarz and Fujiwara, 1977; Murthy et al., 1977; Kent and Lowrie, 1977) and the high mean Curie point (table 2).

For most of the magnetic parameters (except Curie temperature and saturation magnetization), the estimation of the magnetic effects of maghemitization requires the two suites of rocks under consideration to contain titanomagnetites with the same grain size. The condition seems fulfilled here, as shown by the absence of significant difference in the H_{rc}/H_c ratio (remanent coercive force to coercive force) for FAMOUS and Leg 37 pillow basalts (table 2). The J_{rs}/J_s and H_{rc}/H_c ratios found may

Table 1 Average chemical composition and Curie point of titanomagnetite from FAMOUS pillow basalts (rift valley)

Sample number	n	Fe	Ti	Al	Mg	Mn	Cr	Si	x	Θ	Θ_c
DR 02-102 A_2	23	53.0 ± 0.1	13.4 ± 0.1	1.5 ± 0.2	0.4 ± 0.2	0.4 ± 0.1	0.1 ± 0.1	0.2 ± 0.1	0.64	105 ± 15	80 ± 30
DR 03-103	5	54.6 ± 0.7	11.5 ± 0.1	1.2 ± 0.2	0.3 ± 0.2	0.1 ± 0.01	0.01± 0.01	0.6 ± 0.1	0.56	180 ± 20	160 ± 30
DR 03-105 B_3	5	54.0 ± 0.4	12.7 ± 0.5	1.2 ± 0.1	0.5 ± 0.2	0.4 ± 0.1	0.1 ± 0.01	0.5 ± 0.1	0.61	172 ± 22	130 ± 30
DR 03-112 B	16	52.8 ± 1.1	13.0 ± 0.6	1.4 ± 0.2	0.4 ± 0.1	0.4 ± 0.1	0.1 ± 0.1	0.5 ± 0.2	0.63	100 ± 15	95 ± 30
DR 06-100 G_4	20	53.3 ± 0.9	12.5 ± 0.4	1.5 ± 0.1	0.3 ± 0.2	0.4 ± 0.1	0.1 ± 0.1	0.7 ± 0.3	0.61	113 ± 13	105 ± 30
DR 06-102 A	20	52.1 ± 0.8	12.8 ± 0.7	1.1 ± 0.1	0.3 ± 0.1	0.5 ± 0.4	0.03± 0.01	0.3 ± 0.1	0.64	117 ± 13	105 ± 30
DR 06-104 A	23	54.2 ± 0.3	13.1 ± 0.3	1.1 ± 0.2	0.2 ± 0.1	0.4 ± 0.2	0.03± 0.02	0.6 ± 0.1	0.63	212 ± 12	115 ± 30
DR 06-106	16	55.4 ± 0.8	12.4 ± 0.9	1.1 ± 0.2	0.2 ± 0.1	0.4 ± 0.1	0.3 ± 0.2	0.5 ± 0.2	0.59	144 ± 18	145 ± 30
DR 09-111 A	20	55.5 ± 0.5	12.7 ± 0.5	1.2 ± 0.1	0.2 ± 0.1	0.3 ± 0.2	0.01± 0.01	0.4 ± 0.1	0.60	122 ± 14	130 ± 30
DR 10-100 B_2	22	53.9 ± 0.3	13.2 ± 0.5	1.2 ± 0.2	0.4 ± 0.1	0.5 ± 0.1	0.01± 0.01	0.5 ± 0.2	0.63	99 ± 15	110 ± 30

n, Number of analyzed grains (three spots from each grain); mean metal content is given in weight percent with standard deviation;

x, molecular percentage of ulvöspinel of the pure and non-oxidized equivalent titanomagnetite (Prévot and Mergoil, 1973); Θ and Θ_c are respectively the measured and calculated Curie points in °C (calculation method is given in the text).

Table 2 Comparison of average magnetic properties of FAMOUS (rift valley) and Leg 37 (holes 332A and 332B) pillow basalts

	FAMOUS	Leg 37
θ (°C)	159 ± 9 (N=86)	294 ± 14 (N=69)
z	$\simeq$ 0.2	0.7 ± 0.04 (N=69)
J_s (emu cm^{-3})	0.87 ± 0.11 (N=53)	0.40± 0.04 (N=85)
J_r (10^{-2} emu cm^{-3})	$1.44\{^{1.23}_{1.68}$ (N=103)	$0.366\{^{0.312}_{0.428}$ (N=85)
k (10^{-4} emu cm^{-3})	2.99 ± 0.34 (N=103)	2.41 ± 0.22 (N=84)
Q	$1.51\{^{129}_{178}$ (N=103	$39.5\{^{32.9}_{47.6}$ (N=84)
J_{rs}/J_s	0.41 ± 0.03 (N=53)	0.54 ± 0.12 (N= 8)
H_{rc}/H_c	1.43 ± 0.07 (N=51)	1.41 ± 0.14 (N=20)
H_c (Oe)	297 ± 42 (N=53)	253 ± 31 (N=20)
H_{rc} (Oe)	407 ± 74 (N=51)	353 ± 50 (N=20)
MDF (Oe)	359 ± 51 (N=53)	303 ± 25 (N=85)

θ, Curie point; z, degree of oxidation; J_s, saturation magnetization; J_r, natural remanent magnetization; k, initial susceptibility; Q, Koenigsberger ratio ($\frac{J_r}{kH}$ with H=0.42 Oe); J_{rs}, saturation remanent magnetization; H_{rc}, remanent coercive force; MDF, Median destructive field of NRM. Error bars indicate the 95% confidence interval for the average (brackets for log normally distributed parameters). Leg 37 data from Bleil and Petersen (1977), Dunlop and Hale (1977), Hall and Ryall (1977a and b) and Murthy et al. (1977). Note that the MDF of the FAMOUS pillow basalts is about 80% higher than that found by Johnson and Atwater (1977) for a collection restricted to samples with a mean titanomagnetite grain size larger than 1 µm (see text).

be interpreted as corresponding to small pseudo-single domain grains (Lecaille and Prévot, 1979).

Magnetic effects of maghemitization are as follows:

i) Large decreases of saturation magnetization, remanence and Q ratio occur (table 2).

The decrease in spontaneous magnetization is compatible with the trend observed at 0°C for synthetic titanomaghemites (Prévot, 1973).

It must be pointed out that J_r and Q changes are overestimated because the shallow-reversed primary remanent magnetization of Leg 37 basalts is often reduced in intensity by overprinted normally direc-

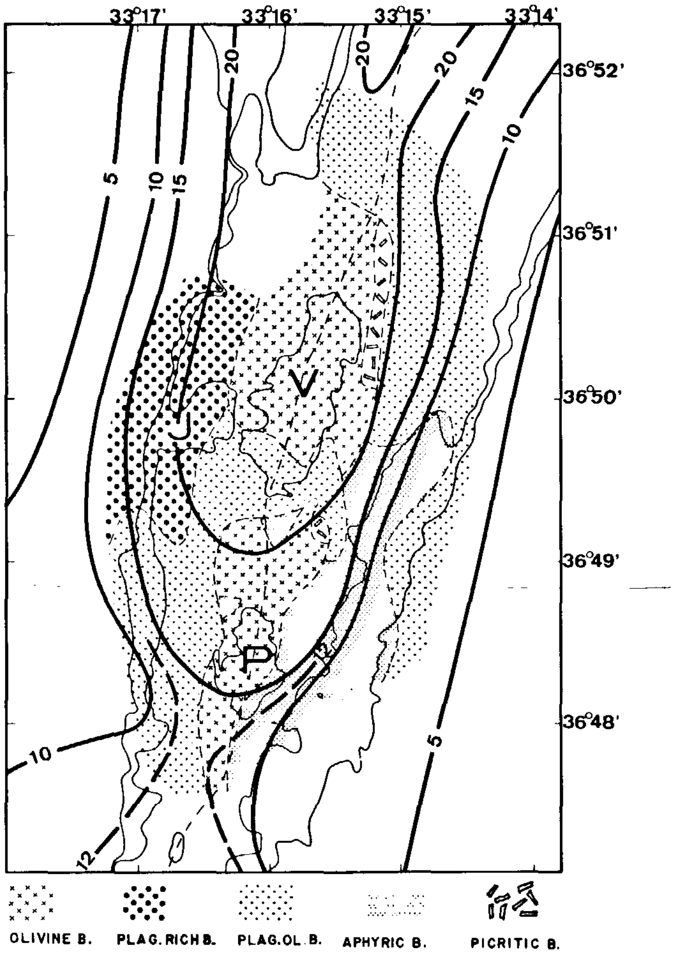

Fig. 6. Generalized distribution of five basalt types in the FAMOUS rift valley (from Hekinian, Moore and Bryan, 1976) with superimposed magnetization calculated from the inversion solution of near-bottom magnetic profiles (5 A/m contour interval; from Macdonald, 1977). Letters indicate topographic highs: V, Mount Venus; P, Mount Pluto; J, Mount Jupiter. The fields of plag. ol. basalts (plagioclase-olivine-pyroxene basalts) and of the aphyric basalts refers here to the pyroxene-rich basalts discussed in the text. The picritic and the olivine basalts correspond to the olivine-rich basalts.

ted VRM (Bleil and Petersen, 1977; Ryall et al., 1977). Prévot and Grommé (1975) showed that for subaerial basalts with a viscosity index (Thellier and Thellier, 1944) comparable to that of Leg 37 basalts (Plessard and Prévot, 1977) the intensity of the VRM acquired since the beginning of the Brunhes epoch is, on average, equal to 1/5 of the intensity of the primary remanence.

ii) Quite small changes in susceptibility and coercivity parameters (H_c, H_{rc} and MDF) are observed (table 2).

It can be demonstrated from theory (Prévot et al., 1979) that maghemitization of single-domain grains results in a large decrease in coercivity and a large increase in susceptibility whereas the opposite trends are expected for true multidomain particles. The later trends have been observed by Ade-Hall et al., (1976) for coarse-grained basalts from Leg 34.

The small changes observed here in coercivity-related parameters are probably a characteristic of small pseudo-single domain particles.

2. Development with time of maghemitization

At some spreading centers, and in particular within the FAMOUS rift valley 2, deep tow magnetic profiles indicate the occurrence of a "central anomaly magnetization high" (Klitgord, 1976; Macdonald, 1977). In the rift valley 2 it is described as a sharp, narrow maximum in crustal magnetization occurring near the axis of the inner floor and coinciding with large volcanic features such as Mount Pluto and Mount Venus (Fig. 6). According to Klitgord and Macdonald the magnetization high indicates the youngest eruptions on the sea-floor. The less magnetized surrounding lava flows are supposed to be older, their weaker magnetization being interpreted as a result of weathering. In other words, maghemitization is supposed to occur intensively within the rift valley. Only direct magnetic measurements can verify this hypothesis. From a comparison of preliminary magnetic data for "axial basalts" (dredged within 1 km from the axis: dredge hauls 1, 4, 5, 8, 9, 11 and 12) and for "more distant basalts" (dredge hauls 2, 3, 6 and 10), Prévot and Lecaille (1976) concluded that the magnetization high cannot result from an alteration process. The more complete data now available (Table 3) confirms their conclusions:

1) The axial basalts are about twice as magnetic as the more distant basalts. In other words, direct magnetic measurements are compatible with intensity variations deduced from deep-tow profiles.

2) This change in intensity of remanence cannot be explained by any maghemitization process because of the absence of change in Curie temperature and the larger saturation magnetization (which decreases through maghemitization) of the more distant basalts.

It is obvious therefore that such a magnetization high is not necessarily a marker of the most recent extrusions on the sea floor and may not be useful in detecting present plate boundaries.

Relationship between petrology and magnetism of the basaltic layer

1. FAMOUS pillow basalts

The idea that the magnetization high could be due to petrological variations of the magma at the time of eruption came from the observation that highly

Table 3 Comparison of average magnetic properties of the axial basalts and the more distant basalts from the median valley of the Mid-Atlantic ridge (FAMOUS area)

Location	θ	J_s	k	J_r	Q
Axial basalts	160 ± 10°C	0.755 ± 0.145	2.50 ± 0.40	$1.98\left\{\begin{matrix}2.39\\1.64\end{matrix}\right.$	$241\left\{\begin{matrix}277\\210\end{matrix}\right.$
	(N=57)	(N=30)	(N=57)	(N=57)	(N=57)
More distant	155 ± 14°C	1.10 ± 0.15	3.63 ± 0.53	$0.978\left\{\begin{matrix}1.18\\0.813\end{matrix}\right.$	$78.2\left\{\begin{matrix}94.7\\64.6\end{matrix}\right.$
basalts	(N=46)	(N=23)	(N=46)	(N=46)	(N=46)

Legend: see table 2

magnetic hills found in the inner floor (Fig. 6) of the FAMOUS Rift Valley correspond mainly to olivine-rich basalt while plagioclase and pyroxene-rich basalt occurs on the eastern and western walls (Bougault and Hekinian, 1974; Hekinian and Hoffert, 1975; Hekinian, Moore and Bryan, 1976; Arcyana, 1977; Bryan and Moore, 1977).

To test this hypothesis, thin sections from each of the 120 large samples studied magnetically were examined and half of the samples were chemically analyzed. We compare the magnetic properties of two groups of basalts:

- olivine-rich basalts (Bougault and Hekinian, 1974) which include both olivine and plagioclase as early formed mineral phases. These are aphanitic, aphyric or slightly phyric basalts. The picritic basalts, which are less common, will be considered here as olivine-rich basalts.
- pyroxene-rich basalts (plagioclase-pyroxene-olivine basalts) and plagioclase-rich basalts (moderately phyric and highly phyric plagioclase basalts). The pyroxene-rich basalt may contain small amount of olivine.

Results listed in table 4 show that the intensity of remanence of olivine-rich basalts is statistically twice as large as other basalt types. This does not result from any difference in the chemical composition of the titanomagnetite, as attested by the absence of any difference in the mean Curie temperature. Neither can the difference in remanence intensity be due to changes in the magnetic oxide content. On the contrary, titanomagnetites are more abundant within the group with the smallest intensity of remanence as shown by their higher saturation magnetization (which is proportional to the oxide content). The difference in intensity of remanence may result either from changes in the intensity of the paleofield or from a variation in the grain size of the magnetic minerals. For titanomagnetites, the intensity of the thermoremanent magnetization decreases within the pseudosingle domain range when particle size increases, the total diminution in intensity corresponding to a factor of ten (Day, 1977). We think that the difference in intensity of remanence between olivine-rich basalts and pyroxene-rich or plagioclase-rich basalts is mainly due to a statistical grain size difference, the smallest magnetic oxide grains being found in the olivine-rich basalts. This view is substantiated by the trends of the grain size-dependent magnetic parameters (H_c, H_{rc}, MDF and Q) which all indicate that, statistically, the finest titanomagnetites occur within the olivine-rich basalts (Table 4). Microscopic observations lead to the same conclusion.

It must be pointed out that this correlation between magnetism and petrology is only valid at a statistical level. Moreover, it is not an unequivocal relationship: within each of the two magnetically different groups, basalts which are petrologically quite distinct coexist. The differences in magnetic properties observed are in fact related to the textural features of the rocks rather than to their petrology as a whole.

Figure 7 shows a ternary diagram giving the relative amount (vol %) of phenocrysts, matrix minerals and mesostasis in the rock. The term mesostasis as used here refers to the glassy portion and the cryptocrystalline (< 0.02 mm in length) material not identified under a high power microscope. The matrix minerals range between 0.02 and 0.9 mm in length and include plagioclase laths, pyroxene, and olivine granules. The phenocrysts consist mainly of cumulate plagioclases having a grain size larger than 1 mm in length. On the same diagram the value of the coercive force H_c is superimposed for each sample. It is apparent that the largest coercive forces (corresponding to the finest grains) are found for the least crystalline rocks, which are the olivine-rich basalts.

Table 4 Average magnetic properties of olivine-rich pillow basalts and plagioclase or pyroxene-rich pillow basalts from the FAMOUS area (median valley)

	olivine-rich basalts	plagioclase or pyroxene-rich basalts
θ	162 ± 12 (N=35)	159 ± 13 (N=45)
J_s	0.690 ± 0.150 (N=28)	1.05 ± 0.13 (N=23)
Q	$234 \left\{ \begin{matrix} 193 \\ 284 \end{matrix} \right.$ (N=52)	$98.5 \left\{ \begin{matrix} 88.3 \\ 121 \end{matrix} \right.$ (N=45)
H_c	368 ± 76 (N=28)	250 ± 55 (N=23)
H_{rc}	502 ± 113 (N=28)	314 ± 80 (N=22)
MDF	393 ± 69 (N=28)	323 ± 80 (N=23)
J_r	$2.01 \left\{ \begin{matrix} 1.64 \\ 2.48 \end{matrix} \right.$ (N=52)	$0.995 \left\{ \begin{matrix} 0.818 \\ 1.21 \end{matrix} \right.$ (N=45)

Legend: see table 2

2. Leg 37 pillow basalts

Petrographic studies of Leg 37 basalts led to the recognition of petrological types similar to those found in the FAMOUS area (Bryan and Thompson 1977; Dimitriev and Aumento, 1977). Using these studies and geochemical data from Aumento, Melson et al. (1977) we were able to classify Leg 37 pillow basalts from hole 332B into the two groups previously defined: olivine-rich basalts and plagioclase or pyroxene-rich basalts.

Table 5 shows that the relative variation of the magnetic parameters between these two groups are the same as those found for the FAMOUS pillow basalts; olivine-rich basalts are about twice as magnetic as plagioclase and pyroxene-rich basalts. Again, this cannot result from variations of oxide content (oxide content is lower in the olivine-rich basalts) and has to be attributed to the smaller magnetic oxide grain size (attested by a larger median destructive field) in the olivine-rich basalt.

The fact that low-temperature oxidation affects these two groups of basalts to the same degree is demonstrated by the absence of any significant difference between the two mean Curie points. Hence maghemitization does not modify the relative contribution of olivine-rich basalts and of plagioclase or pyroxene-rich basalts to magnetic anomalies.

IV Conclusions

Extensive magnetic studies carried out at the Mid-Atlantic Ridge Crest near 37°N show that the magnetic properties of the pillow basalt layer are

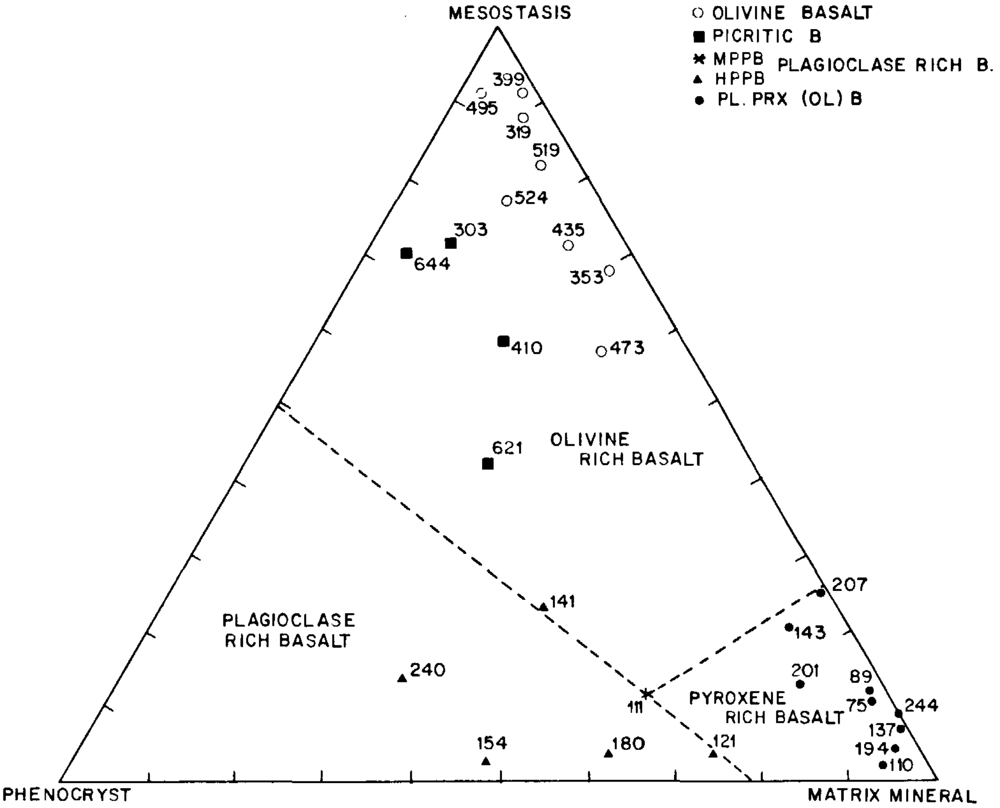

Fig. 7. Ternary diagram of the relative amount (vol %) of phenocrysts, matrix mineral and mesostasis (see text for precise definitions). Number indicates coercive force of the sample (Oe). Olivine basalts and picritic basalts are olivine-rich basalts. Plagioclase-rich basalts are divided into moderately phyric plagioclase basalts (MPPB) and highly phyric plagioclase basalts (HPPB). PL. PRX (OL)B are called pyroxene-rich basalts in the text. See text for references about these different types of basaltic rocks found in the rift valley.

petrology dependent and change notably with time as a result from sea-floor weathering and tectonic tilting. In addition the thickness of the magnetized layer increases rapidly outwards from the ridge axis. All these features seem to be typical of the behavior of the basaltic layer of the oceanic crust.

1. A relationship between petrology and magnetism was first suggested by Vogt and Johnson (1973) in order to explain high-amplitude anomalies zones located close to some postulated "hot spots". Chemical and magnetic studies of rocks from the Reykjanes Ridge (de Boer, 1973; Day et al., 1979), the Galapagos spreading center (Vogt and de Boer, 1976) and high-amplitude zones in the Juan de Fuca area (Vogt and Byerly, 1976) seem to support this conjecture. The highest magnetizations of these Fe-Ti enriched basalts are supposed to result from a larger titanomagnetite concentration, contrary to our observations in the FAMOUS area. However, the rock magnetic study carried out on seven pillow fragments from the Galapagos spreading center showed a poor correspondence between the titanomagnetite abundance and the remanence intensity (Anderson et al., 1975). These workers suggest that in addition to having twice as much titanomagnetite, the samples from the Galapagos rift zone have five times more intense remanence than the samples from the Costa Rica ridge because the former have a greater proportion of smaller grains. As it is true for the magnetization high in the FAMOUS rift valley, variations in the grain size of the magnetic minerals seem essential to interpret the high-amplitude anomalies zones found in other parts of the oceans.

2. Maghemitization of titanomagnetite is probably the major cause for the decrease in the amplitude of magnetic anomalies outwards from the ridge axis. However, according to the Curie temperatures of the rocks collected within the FAMOUS Rift Valley, the maghemitization of the top of the basement is a progressive process. Samples collected as far as 4 km west of the axis yield Curie temperatures near 150°C (Johnson and Atwater, 1977), which is not significantly different from the mean value at the axis (table 4). This confirms our

Table 5 Average magnetic properties of olivine-rich pillow basalts and plagioclase or pyroxene-rich pillow basalts from Leg 37 (hole 332B)

	olivine-rich basalts	plagioclase or pyroxene-rich basalts
θ	294 ± 9 (N=65)	305 ± 14 (N=78)
J_s	0.305 ± 0.023 (N=65)	0.429 ± 0.066 (N=78)
Q	74.5 { 63.6 / 87.2 (N=50)	34.7 { 28.6 / 42.2 (N=49)
MDF	370 ± 31 (N=49)	254 ± 30 (N=49)
J_r	0.488 { 0.423 / 0.561 (N=50)	0.270 { 0.222 / 0.327 (N=49)

Magnetic data from Hall and Ryall (1977a and b), petrological classification from Dmitriev and Aumento (1977). Legend: see table 2.

conclusion that the magnetization high found in the FAMOUS Rift Valley 2 does not result from an alteration process and cannot be used a priori as a marker of the present plate boundary.

From the FAMOUS area to DSDP 332 site, the mean intensity of NRM decreases by a factor of 4. Taking into account the reducing of NRM of reversely magnetized Leg 37 basalts due to VRM overprinting, the reduction of the intensity of the primary remanent magnetization must be slightly less, probably between 2/3 and 3/4. There is an excellent agreement between intensities of remanence measured and intensities calculated from direct modeling of near-bottom magnetic anomalies at 37°N (Macdonald, 1977). In both cases the intensity decreases from 2 x 10^{-2} emu cm^{-3} right at the axis (effective average intensity of remanence of axial basalts) to about 0.4 x 10^{-2} emu cm^{-3} for 3.5 m.y. old crust (holes 332).

The 2/3 to 3/4 reduction due to maghemitization is the same as that found by Prévot and Grommé (1975) for dredged basalts from the whole North Atlantic basement. The larger decrease observed at 45°N (Irving, 1970) probably results from some combination of maghemitization and local variations in magnetic oxide content and/or size, between basalts from the median valley and from the flanks (Prévot, 1973). It is worth noting that moderately magnetized pillow basalts have also been recovered within the median valley at 45°N (Ade-Hall et al., 1973).

3. Tectonic rotations due mainly to normal faulting at the edges of the median valley have been suggested by Van Andel (1968) and Van Andel and Bowin (1968). Another geologic model by Moore et al. (1974) assumes that the subsidence of the ridge center induces a substantial tilting (of 20° to 40°) towards the rift-valley axis. The paleomagnetic data so far obtained in the North Atlantic strongly support such models. It has been frequently observed at DSDP and IPOD sites that, even after cleaning, the mean magnetic inclination of the magnetic units differs from the value expected from paleolatitude: sites 332A, 332B, and 333A (Ryall and Hall, 1977); sites 395 and 396 (Johnson, 1979), site 396B (Petersen, 1979); sites 407, 408, and 410A (Luyendyk, Cann et al., 1977), site 317D (Donnelly, Francheteau et al., 1977) and site 418A (Flower, Salisbury

et al., 1977). Expected and anomalous inclinations, which generally differ by 20 to 30°, have been observed several times in a single hole.

It is difficult to explain these anomalous inclinations by any non-dipole behavior of the geomagnetic field (secular variation or geomagnetic excursions or transitions) at the time of cooling because the probability of recording such directions is very low (Harrison and Watkins, 1977). Decisive geological and paleomagnetic observations in favor of tectonic rotations of crustal blocks have been reported recently (Donnelly, Francheteau et al., 1977; Flower, Salisbury et al., 1977).

The axis of spreading of the North Atlantic Ridge, trending approximately N-S, is more or less parallel to the horizontal component of the Upper Tertiary and Quaternay geomagnetic field. Rotations around the horizontal axis parallel to the ridge axis postulated by the two geological models reported above would reduce the magnetic inclination. The unexpectedly low inclinations frequently observed along the North Atlantic Ridge Crest (Ryall and Hall, 1977, Johnson, 1979; Petersen, 1979; Luyendyk, Cann et al., 1977) can therefore be readily explained by tectonic rotations.

Qualitatively different inclination discrepancies have been obtained for older oceanic crust. At the Cretaceous North Atlantic sites (IPOD megaleg 51-52-53) magnetic units with a mean inclination larger than expected dipole inclination were found, the difference being about 25°-35° (Donnelly, Francheteau et al., 1977; Flower, Salisbury et al., 1977) In such cases, horizontal rotation axes have to be more or less oblique with respect to the horizontal component of the paleofield. Taking into account the Cretaceous pole position for North America (Mankinen, 1978) and the 10-20° East strike of the ridge crest, rotations about axes parallel to the ridge crest can, at the most, increase the expected dipole 32° inclination to 43°-50°. This seems insufficient to account for the observed discrepancy. It may be suggested that large faulting occurred along directions oblique with respect to the spreading axis strike or that some rotations are due to large scale slumps rather than to normal faults (Francheteau, personal communication).

Another unsolved question is whether the postulated rotations parallel to the spreading center axis take place within (Moore et al., 1974) or at the edges of the median valley (van Andel and Bowin, 1968). The paleomagnetic data so far obtained for rocks collected within the median valley cannot settle this point because the magnetic inclinations calculated are in most cases relative to the horizontal plane at the time of cooling rather than to the present horizontal plane. Drilling within the rift valley is probably the only way to solve this problem.

An argument against the interpretation of anomalous inclinations in terms of tectonic rotation is that it would require extreme tilting of the blocks (Lowrie, 1977). Assuming that the rotation axis was in the plane of the paleofield vector, Harrison and Watkins (1977) found that the amount of rotation needed to account for the excessively shallow inclinations at the Leg 37 sites is 55°. However, the tectonic studies of the Afar accretion zone (Morton and Black, 1975) show that in several large areas extension tectonics resulted in normal faulting with blocks strongly tilted. Dip angles up to 60° and locally up to 90° have been observed. Probably as a result of successive stages of normal faulting, the faults were sometimes observed dipping at only shallow angles. In view of these results, there is no doubt that the tectonic complexity of the oceanic crust has been so far underestimated.

4. Thickening of the magnetized layer outwards from the ridge axis. It is now well established (Harrison, 1976) that the mean magnetic intensity of DSDP cores is several times less than the values calculated from magnetic anomaly profiles assuming the magnetized layer is only 500 m thick. DSDP sites recently studied along the MAR (Johnson, 1979, Petersen, 1979) confirms Leg 37 results (Ryall et al., 1977) that the magnetized layer is several kilometers thick away from the ridge axis. On the other hand, the high average magnetic intensity of the FAMOUS pillow basalts seems to indicate that the magnetized layer is less than 500 m within the median valley (Lecaille et al., 1974).

Three processes can result in a decrease of the intensity of remanence with depth at the MAR axis:

1. transition from pillow basalts to possibly less magnetic intrusive units.
2. geothermal gradient.
3. intense maghemitization at depth.

Regarding the first interpretation, the main transition between intrusive and intrusive rocks is supposed to correspond to the 2A/2B interface within layer 2 (Talwani et al., 1971). Fowler (1976) showed that beneath the median valley at 37°N layer 2A is about 1 km thick. Similarly, in a detailed geophysical study of the Reykjanes Ridge Crest Talwani et al. (1971) found that the thickness of the pillow basalts varies from 0.6 to 1.1 km in the crestal zone. This figure is to compare with the 400 m thickness they assign to the magnetized layer.

The second interpretation is that the bottom of the magnetized layer corresponds to the Curie point isotherm (160°C at the axis). This is supported by some thermal models of the oceanic crust. Sleep's (1975) study of the thermal structure of mid-ocean ridge axes suggests that the 300°C isotherm would be as shallow as 300 m at the axis of the MAR near 37°N. According to Sclater and Francheteau's (1970) cooling model of lithospheric plate, the variation of heat flow

q with age t of the site is given approximately by (Francheteau, personal communication):

$$q = \frac{12}{\sqrt{t}}$$

where q is in Heat Flow Unit (1 HFU=10^{-6} cal sec^{-1} cm^{-2}) and t in m.y. The thermal conductivity of pillow basalts being 4.0 mcal $°C^{-1}$ cm^{-1} sec^{-1} (Hyndman and Jessop, 1971; Hyndman et al., 1977) the depth of the 160°C isotherm can be calculated. This depth is approximately 400 m for t=0.5 m.y. and 500 m for t=1 m.y. At site 332, the calculated depth of the relevant 300°C Curie point isotherm is approximately 2 km, in agreement with Ryall et al.'s (1977) suggestion that the entire layer 2 contributes to the magnetic anomaly. As the plate cools the lower part of layer 2 becomes progressively magnetized. Such a cooling by conduction results in the formation of blocks of alternating polarity with broad sloping transition zones as described in Cande and Kent's (1976) magnetic model of layer 3. Such thermal models provide therefore a straightforward explanation of the thickening of the magnetized layer near the ridge axis.

There are however two major objections regarding this interpretation. The first one deals with the importance of nonconductive processes, in particular hydrothermal circulation, in the oceanic crust. Percolation by sea water extends down to several kilometers in depth (Ribando et al., 1976) and may cause significant loss of heat near the ridge axis (e.g. Talwani et al., 1971), which is not considered in Sclater and Francheteau's and Sleep's models. This idea led Cande and Kent (1976) and Kusznir and Bott (1976) to suggest that layer 2 as a whole is at 0°C at ridge axes. However, according to a numerical study of hydrothermal circulation in the oceanic crust (Ribando et al., 1976), percolation alters the spatial distribution of surface heat flow but not its mean value, unless circulating water leaves the porous crust as extensive hot springs with a temperature in excess of 50°C.

The second objection is that any rise in temperature will increase the reaction rate of maghemitization. It has been shown by Readman and O'Reilly (1970) and by Ozima (1971) that the reaction rate of maghemitization observed for 0.1 μm size titanomagnetites heated in air yields a time constant of the order of 10^6 years at 0°C, in agreement with the time dependence of maghemitization near the MAR axis (Irving, 1970; Johnson and Atwater, 1977). Pillow basalts at ridge axes are highly vesicular and are buried with trapped water, as shown by their very low seismic velocity (Talwani et al., 1971). As is true for the top of the oceanic basement, maghemitization at depth can proceed in the presence of sea water. Calculations following Ozima's (1971) procedure yield time constants of about 10^3 years at 50°C and a few years at 100°C for completion of maghemitization. Hence the lower boundary of the magnetized layer corresponds probably to a decrease in magnetization due to an intense maghemitization at depth at ridge axes. A further contribution comes from the decrease of the spontaneous magnetization as temperature increases. The geothermal gradient within the rift valley is therefore less important than the gradient needed to interpret the lower boundary of the magnetized layer in terms of the Curie point isotherm. However, depending upon the hydrothermal circulation pattern, and the depth of the eventually transient magma chamber (Nisbet and Fowler, 1978) at the ridge axis, the possibility remains that the lower part of layer 2A is heated at some places above its Curie point and becomes remagnetized as the plate moves away from the ridge axis.

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  par

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