24. MAGNETIC VISCOSITY OF SUBMARINE BASALTS, DEEP SEA DRILLING PROJECT, LEG 37

C. Plessard and M. Prévot, Laboratoire de Géomagnétisme du Parc Saint-Maur 4, Avenue de Neptune, 94100 Saint-Maur (France)

INTRODUCTION

Magnetic viscosity or magnetic after effect is the increase or decrease of magnetization with time in a constant (eventually zero) applied field.

These studies on the magnetic viscosity of submarine basalts have two main objectives:

1) to estimate the intensity of the induced magnetization carried *in situ*. Usually, it is assumed that the induced magnetization is given by χH where χ is the magnetic susceptibility measured in a short time (less than 1 min in most cases) and H the intensity of the geomagnetic field at the site of drilling. This assumption is wrong if the growth of the induced magnetization with time is important. In this case, the induced magnetization resulting from the influence of the geomagnetic field since the beginning of the Brunhes epoch (0.7 m.y.) can be rather higher than the magnetization measured in short times.

2) to determine the relative importance of the viscous remanent magnetization (VRM) with respect to the primary remanent magnetization and the behavior of the VRM when affected by alternating magnetic fields. As VRM is probably the most important secondary magnetization in submarine lavas (Lowrie et al., 1973), both these points are of particular interest for interpreting the paleomagnetic data obtained from these rocks.

EXPERIMENTAL PROCEDURES

For the entire collection (40 samples), we have determined the viscosity index v (Thellier and Thellier, 1944) which is equal to the ratio of the VRM obtained during 2 weeks in the geomagnetic field to the "stable" natural remanent magnetization (NRM) measured after a long storage (at least 2 weeks) of the sample in a free-field space. The measurements have been carried out with a "bit sample spinner magnetometer" (Thellier, 1967).

The intensities of the viscous magnetizations of these samples being weak, further experiments have been made with an astatic magnetometer (Pozzi and Thellier, 1963) especially built for studies of magnetic viscosity. This apparatus requires cylindrical samples with well-defined dimensions (length 7 cm, maximum diameter 1.7 cm). Because the shape of the DSDP samples was not suitable for this instrument, we crushed the samples and slightly pressed the powder (the grain size of which was a few millimeters) into a sample holder with the correct dimensions. The grain size of most titanomagnetites in these samples being less than 1 mm, we may suppose that the grain size of the magnetic minerals is not modified. Twenty samples, which were intended for purposes other than magnetic studies, were not available for crushing and could not be studied further. The 20 powdered samples were exposed to a 450-oe alternating magnetic field (peak value) before further experiments. This treatment was performed to destroy any remanent magnetization and to obtain an initial state:

1) reproducible (each experiment being carried out twice for verification). Note that thermal demagnetization does not lead to a magnetically stable body, the magnetic viscosity decreasing sharply with increasing elapsed time following thermal demagnetization (Plessard, 1971).

2) comparable to the initial state considered for theorectical purposes (Néel, 1951).

The change with time or "traînage" of the induced and remanent magnetizations has been studied for viscous magnetizations given in a 10-oe constant field applied for 20 min. Measurements are valid between 5 sec and 20 min after the constant field is applied (growth of the induced magnetization) or removed (decrease of the remanent magnetization). Using the method of least squares, two functions have been fitted to each set of data (both for the increase of induced magnetization and for the decrease of remanent magnetization): a linear function ($\sigma = a \log t + b$) and a parabolic function ($\sigma = a \log^2 t + b \log t + c$). We define also a parameter k given by $k = \triangle\sigma_1/\triangle\sigma_2$ where $\triangle\sigma_1$ and $\triangle\sigma_2$ are, respectively, the increase (or decrease) of magnetization when time increases from 5 sec to t_m and from t_m to 20 min (Figure 1) with $\log t_m = 1/2$ (log 5 sec + log 20 min). If k differs from 1, the "traînage" (increase or decrease) deviates from a logarithmic function. For volcanic rocks, all the parameters characterizing the "traînage" of the viscous magnetizations are proportional to the intensity of the applied field within the range 0 to 15-20 oe. This fact allowed us to calculate the various parameters for $h = 0.5$ oe (Table 1).

The method used for the alternating field treatment of VRMs has been previously described (Biquand and Prévot, 1970). The VRMs studied here were obtained in a 3-oe field applied for 1 month. The AF treatment takes place half an hour after the sample is removed from the field. It has been shown that the demagnetization curves are not significantly different for $h = 3$ oe and $h = 0.5$ oe (Prévot, 1975).

VISCOUS INDUCED MAGNETIZATION (VIM)

We see from Table 1 that:

1) The various parameters can be quite different from sample to sample;

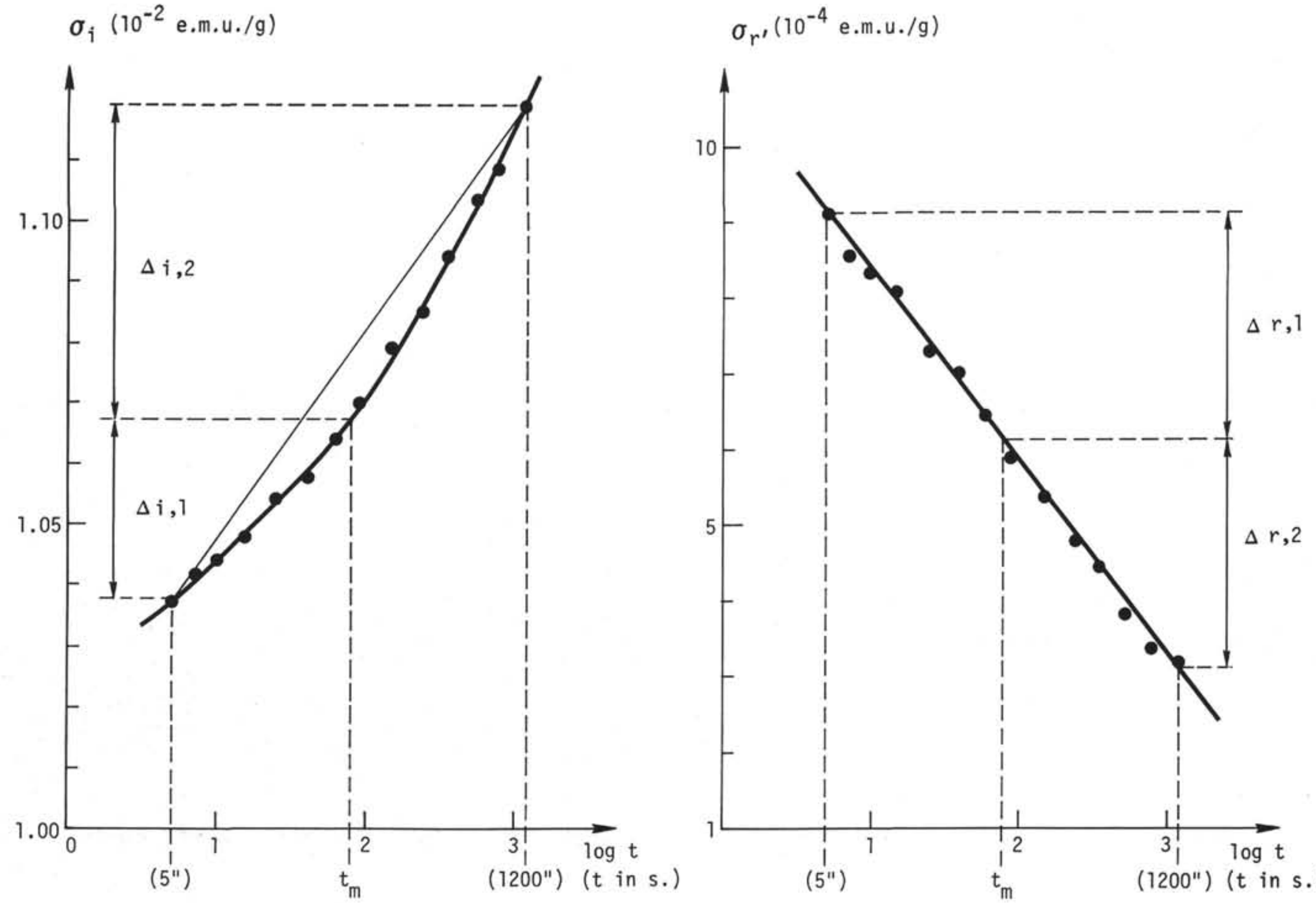

Figure 1. *Sample 332B-37-2, 102-105 cm. Variation with time of the induced (left) and remanent magnetizations (right). t is the time since the 10-oe field is applied and t' the time after this field is removed.*

2) For most of the samples, ratio $\Delta\sigma_i/\sigma_i$ is quite large.

3) For all the samples the growth in magnetization with time is better expressed by a second-order function (Figure 1). The k_i parameter being lower than 1, except for Sample 332B-44-4, 24-26 cm, the extrapolated value of σ_i for t = 0.7 m.y. is greater than indicated by the usual logarithmic extrapolation.

4) Because of the importance of the growth of the induced magnetization with time, the extrapolated value of σ_{i_i} for t = 0.7 m.y. is generally several times greater than σ_{i_i} for t = 5 sec, the maximum difference corresponding to a factor of 20.

5) The geometric mean for the $\sigma_{NRM}/\sigma_{i(extr.)}$ ratio (Table 1) is about 3.5. Assuming the direction of the NRM is parallel (or antiparallel) to the Brunhes geomagnetic field, we deduce from this result that the global magnetization (equal to $\overrightarrow{NRM} + \overrightarrow{VMI}$ 0.7 m.y.) carried in situ by these basalts is statistically twice larger—or so—for normally magnetized blocks than for blocks with the opposite polarity. Clearly, calculation models for magnetic anomalies, which assume the same intensity of magnetization for both the normally and reversely magnetized crust, are unrealistic.

6) For most of the samples, and in spite of the strong increase of the induced magnetization with time, the intensity of the NRM is higher than the intensity of the induced viscous magnetization calculated for t = 0.7 m.y. For such samples the magnetic anomalies reflect some changes in the distribution of the remanent magnetizations on the sea floor. However, for 6 of the 20 samples studied, the VIM carried in situ is probably comparable to the natural remanent magnetization.

VISCOUS REMANENT MAGNETIZATION (VRM)

1) Except for Sample 332B-35-1, 46-49 cm the decrease with time of the remanent magnetization follows approximately a logarithmic function (k ≅ 1, Table 1)

2) The viscosity index v varies from less than 1% to 60% (Table 2). Extensive measurements on subaerial volcanic rocks have shown that v is log normally distributed (Prévot, 1975). The logarithmic mean value of v for the samples studied here is 3.4% (95% confidence interval for the mean: 2.2% to 5.3%). Note that the time duration in the geomagnetic field from the beginning of the Brunhes epoch results in a "natural" VRM which is probably 3 to 4 times greater than the VRM acquired within 2 weeks (Prévot, 1975; Prévot and Grommé, 1975). The mean magnetic viscosity of these submarine samples, probably 3.5 m.y. old, is much larger than that for the young basalts from the ridge axis (Lecaille et al.,

TABLE 1
Main Characteristics of the Viscous Magnetizations of DSDP Samples from Leg 37 (Hole 332B)

Sample (Interval in cm)	Viscous Induced Magnetization σ_i	$\frac{\Delta\sigma_i}{\sigma_i}$	k_i	r_i	$\sigma_{i(\text{extr.})}$	Comparison of NRM and Induced Magnetization Q	$\frac{\sigma_{NRM}}{\sigma_{i(\text{extr.})}}$	Viscous Remanent Magnetization $\sigma_{r'}$	$\frac{\Delta\sigma_{r'}}{\sigma_{r'}}$	$k_{r'}$	mdf	Comparison "Trainages" $\frac{\Delta\sigma_i}{\Delta\sigma_{r'}}$
27-2, 4-6	3.48	0.13	0.90	1.2	6.85	28.7	14.6	0.38			85	
35-1, 4-7	21.4	0.17	0.85	1.3	55.1	0.47	0.18	3.89	0.66	1.1	48	1.4
35-1, 46-49	6.08	0.30	0.73	1.9	28.5	6.69	1.43	1.79	0.55	1.7	28	1.8
35-1, 104-107	4.51	0.32	0.73	1.9	22.5	5.68	1.14	1.54	0.55	0.73	18	1.7
35-1, 136-139	3.57	0.78	0.55	3.2	55.8	15.0	0.96	2.55	0.67	0.80	21	1.7
35-2, 29-32	2.73	0.81	0.44	4.0	53.8	9.12	0.47	2.30	0.69	0.81	16	1.4
35-2, 33-36	3.02	0.71	0.46	3.7	50.5	23.9	1.43	2.34	0.55	0.81	27	1.7
35-2, 91-94	4.26	0.16	0.57	2.1	16.4	11.3	2.93	0.73	0.56	0.91	24	1.7
35-3, 28-31	3.22	0.38	0.43	3.5	32.4	55.9	5.56	1.41	0.64	0.91	38	1.4
35-3, 81-84	4.11					42.8		0.63			92	
36-1, 104-106	4.86	0.14	0.70	1.7	13.9	28.0	9.78	0.76	0.66	0.97	92	1.3
36-2, 3-12	2.77	0.10	0.46	2.2	9.26	37.5	11.2	0.15			93	
36-2, 113-115	2.97	0.08	0.58	1.7	6.88	50.8	21.9	0.18			18	
36-2, 153-161	3.97	0.13	0.68	1.7	11.4	36.8	12.8	0.39	0.60	1.1	59	2.3
36-3, 143-145	2.66					50.4		2.39			75	
36-6, 66-68	5.64	0.18	0.78	1.5	17.1	20.9	6.90	2.07	0.76	1.2	33	1.3
37-1, 126-128	21.8	0.07	0.88	1.2	34.4	5.00	3.17	1.73	0.75	1.1	95	1.2
37-2, 43-45	5.75	0.39	0.71	2.1	45.3	33.4	4.30	2.12	0.71	1.2	75	1.5
37-2, 102-105	51.9	0.08	0.59	1.7	122	9.96	4.24	4.54	0.67	0.95	50	1.3
44-4, 24-26	15.6	0.12	1.1	0.82	21.0	12.8	9.52	2.09	0.66	1.2	54	1.4

Note: Magnetizations σ and $\Delta\sigma$ are given in 10^{-5} emu/g for h=0.5 oe; σ is the induced (σ_i) or remanent (σ_r') magnetization measured 5 sec after the field is applied or removed; $\Delta\sigma_i$ and $\Delta\sigma_r'$ are the variations of these two kinds of magnetization when the time increases from 5 sec to 20 min; k is defined in the text; r_i is the ratio of the induced magnetization calculated from the parabolic function to the induced magnetization calculated from the linear function, both for t = 0.7 m.y.; $\sigma_{i(\text{extr.})}$ is the value obtained from the parabolic function; Q is the Konigsberger ratio, given by $\frac{\sigma NRM}{\sigma_i}$; the median destructive field (mdf) is in oe peak, the parameters characterizing the "trainage" have not been calculated when $\Delta\sigma$ is smaller than 0.2 X 10^{-5} emu/g.

1974). This seems to indicate that the magnetic viscosity of submarine basalts results from some alteration process.

3) The behavior of VRM with respect to AF treatment is quite different from one sample to another one (Figure 2 and Table 2).

However the median destructive field (mdf, Table 1) is always smaller than the mdf for the NRM of nonviscous submarine basalts. As the growth of the mdf of VRMs seems to correspond only to a factor of 2 or so when t increases from 1 month to 0.7 m.y. (Prévot, 1975), the AF technique must be a quite efficient method for the magnetic cleaning of most of the submarine lavas.

4) If the VRM is due to thermal fluctuations, the grains carrying this magnetization would be large (multidomain ?) for the lowest mdf values and small (single domain ?) for the highest mdf values. Theoretically, this may be verified from the $\Delta\sigma_i/\Delta\sigma_{r'}$ ratio which is equal to 1 for single-domain grains (Néel, 1949) and to 2 for multidomain grains (Néel, 1951). For subaerial lavas it has been found (Prévot, 1975) that this ratio varies indeed from 1 for high mdf values (150 oe for a weak field VRM acquired for 32 months) to 2 for low mdf values (20 oe for a similar VRM). For submarine basalts, it can be seen in Table 1 that no evident relationship appears between the mdf and the $\Delta\sigma_i/\Delta\sigma_r$, ratio. This may indicate that the magnetic viscosity of submarine basalts is not only a thermally activated viscosity, but results also from a diffusion aftereffect process.

CONCLUSIONS

1. The VIM carried by submarine basalts is notably larger than the corresponding VRM measured just after the removal of the field. For the samples studied here the mean ratio of the intensities is equal to five, the extreme values being 2 and 20.

2. The growth of the VIM with time is important. The VIM for t = 0.7 m.y. extrapolated from the measurements carried out when t increases from 5 sec to 20 min, is about four times larger than the VIM for t = 20 min (extreme values: 1.2 and 11). For about one quarter of the 20 samples studied, the VIM carried in situ is probably comparable in intensity to the natural remanent magnetization.

3. Because of the systematic effect of the VIM, we calculate that the global magnetization carried in situ by normally magnetized blocks must be statistically twice larger—or so—than the magnetization carried by the blocks with reverse NRM.

4. For most of the samples, the VRM is notably smaller than the stable NRM. Moreover the VRM is not difficult to erase by AF treatment. AF cleaning seems therefore an efficient method to get reliable paleomagnetic results from most of these rocks.

TABLE 2
Magnetic Measurements for Determination of the Viscosity Index

Sample (Interval in cm)	Weight (g)	σ_{NRM}	σ_{VRM}	V(%)
Hole 332A				
21-1, 131-134	39.0	66.5	6.41	9.6
29-1, 74-77	42.6	63.2	5.05	8.0
33-2, 92-95	46.3	608	18.2	2.8
37-1, 116-119	43.9	155	2.39	1.5
Hole 332B				
2-2, 86-89	57.9	58.0	1.38	2.6
2-6, 129-132	52.4	79.9	5.92	7.4
3-4, 10-15	53.9	24.1	9.09	37.8
9-2, 104-106	44.7	145	5.15	3.5
14-2, 81-83	43.3	28.4	5.54	19.5
22-1, 57-60	37.9	295	1.32	0.4
25-4, 47-49	42.7	60.2	5.62	9.3
27-2, 4-6	15.5	100	5.10	5.1
28-2, 23-26	45.2	111	3.32	3.0
33-1, 62-65	45.6	33.2	5.70	17.2
35-1, 4-7	14.4	10.0	6.25	62.5
35-1, 46-49	16.4	40.7	6.11	15.0
35-1, 104-107	14.9	25.6	5.02	19.6
35-1, 136-139	14.4	53.5	7.65	14.3
35-2, 29-32	34.9	24.9	6.15	24.7
35-2, 33-36	16.6	72.1	9.66	13.4
35-2, 91-94	16.2	48.0	6.19	12.9
35-3, 28-31	18.3	180	5.94	3.3
35-3, 81-84	12.0	176	1.23	0.7
36-1, 104-106	17.4	136	2.86	2.1
36-2, 3-12	17.7	104	0.42	0.4
36-2, 113-115	12.6	151	0.45	0.3
36-2, 153-161	22.4	146	5.84	4.0
36-3, 143-145	17.5	134	0.27	0.2
36-5, 40-42	46.9	73.9	1.49	2.0
36-6, 66-68	16.5	118	1.77	1.5
37-1, 126-128	18.3	109	3.82	3.5
37-2, 43-45	21.2	192	2.30	1.2
37-2, 102-105	13.9	517	8.79	1.7
43-2, 94-96	40.4	177	0.90	0.5
44-1, 75-77	32.6	99.1	9.36	9.4
44-4, 24-26	16.1	200	3.60	1.8
Site 335				
5-2, 36-38	47.4	124	2.53	2.0
9-2, 74-76	52.4	74.2	1.24	1.7
10-5, 101-103	48.5	139	0.82	0.6
12-3, 115-117	46.4	194	1.94	1.0

Note: The specific magnetizations σ are given in 10^{-5} emu/g. ν is the viscosity index (defined in the text).

5. There is some evidence that the magnetic viscosity of these submarine basalts is not only a thermally activated viscosity but results also from a diffusion after effect process. The diffusion processes may be easier in titanomaghemites (because of imperfections in the crystal structure) than in fresh, nonoxidized titanomagnetites. This hypothesis would explain the increase in magnetic viscosity as the submarine basalts become older and their titanomagnetites more maghemitized.

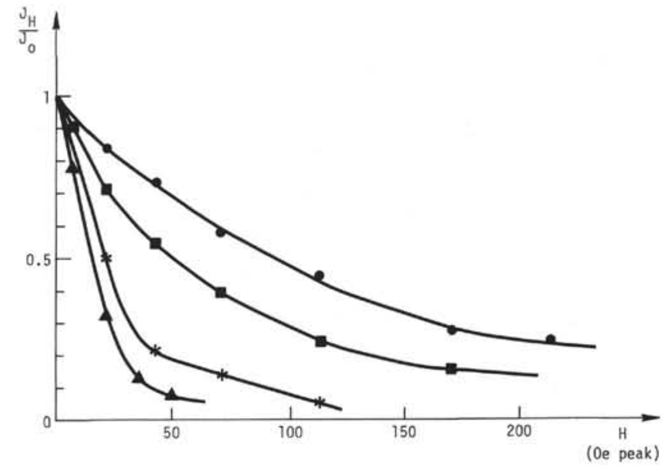

Figure 2. *Alternating field demagnetization curves for VRMs obtained in a 3-oe field applied for 1 month. Circles: Sample 332B-36-2, 3-12 cm; squares: sample 332B-37-2, 102-105 cm; asterisks: Sample 332B-35-1, 136-139 cm; triangles: Sample 332B-35-2, 29-32 cm.*

REFERENCES

Biquand, D. and Prévot, M., 1970. Sur la surprenante résistance à la destruction par champs magnétiques alternatifs de l'aimantation rémanente visqueuse acquise par certaines roches sédimentaires au cours d'un séjour, même bref, dans le champ magnétique terrestre: C.R.Aca. Sci. Paris, v. 270, p. 362-365.

Lecaille, A., Prévot, M., Tanguy, J-C., and Francheteau, J., 1974. Intensité d'aimantation de basaltes dragués dans le rift médio-atlantique vers 36°50'N) C.R.Acad. Sci. Paris. v. 279, p. 617-620.

Lowrie, W., Løvlie, R., and Opdyke, N.D., 1973. Magnetic properties of Deep Sea Drilling Project basalts from the North Pacific Ocean: J. Geophys. Res., v. 78, p. 7647-7660.

Néel, L., 1949. Théorie du traînage magnétique des ferromagnétiques en grains fins avec application aux terres cuites: Ann. Géophys., v. 5, p. 99-136.

________, 1951. Le traînage magnétique: J. Phys. Radium, v. 12, p. 339-351.

Plessard, C., 1971. Modification des propriétés magnétiques, en particulier du traînage, après réchauffement d'une roche préalablement stablisée thermiquement: C.R. Acad. Sci. Paris, v. 273, p. 97-100.

Pozzi, J-P. and Thellier, E., 1963. Perfectionnements récents apportés aux magnétomètres de très haute sensibilité utilisés an minéralogie magnétique: C.R. Acad. Sci. Paris, v. 257, p. 1037-1041.

Prévot, M., 1975. Magnétisme et minéralogie magnétique de roches néogènes et quaternaires: Thèse, Paris.

Prévot, M. and Grommé, S., 1975. Intensity of magnetization of subaerial and submarine basalts and its possible change with time: Geophys. J. R. Astron. Soc., v. 40, p. 207-224.

Thellier, E., 1967. A "big sample spinner magnetometer". *In* Methods in paleomagnetism; Amsterdam (Elsevier), p. 150-154.

Thellier, E. and Thellier, O., 1944. Recherches géomagnétiques sur des coulées volcaniques d'Auvergne: Ann. Géophys., v. 1, p. 37-52.