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 \textit{in situ}. Usually, it is assumed that the induced magnetization is given by $\chi H$ where $\chi$ 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 theoretical purposes (Néel, 1951).

The change with time or “trainage” 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 $k = \Delta\sigma_2/\Delta\sigma_1$ where $\Delta\sigma_1$ and $\Delta\sigma_2$ 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 “trainage” (increase or decrease) deviates from a logarithmic function. For volcanic rocks, all the parameters characterizing the “trainage” 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).

VISCOS INDUCED MAGNETIZATION (VIM)

We see from Table 1 that:

1) The various parameters can be quite different from sample to sample;
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 $k_t$ parameter being lower than 1, except for Sample 332B-44-4, 24-26 cm, the extrapolated value of $\sigma_i$ 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 $\sigma_i$ for $t = 0.7$ m.y. is generally several times greater than $\sigma_i$ for $t = 5$ sec, the maximum difference corresponding to a factor of 20.

5) The geometric mean for the $\sigma_{NRM}/\sigma_{ex}^{\text{extr}}$ 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 NRM + VMI 0.7 m.y.) carried in situ by these basalts is statistically twice—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 ($k \approx 1$, 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.,
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 (Figure 2 and Table 2).

However the median destructive field (mdf, Table 1) is always smaller than the mdf for the NRM of non viscous 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 \( \frac{\Delta \sigma_r}{\Delta \sigma_i} \) 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 \( \frac{\Delta \sigma_r}{\Delta \sigma_i} \) 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.
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 titanomagnetites (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.

REFERENCES

Biquand, D. and Prévot, M., 1970. Sur la surprenante résistance à la destruction par champs magnétiques alter-