

## Characteristics of VRM in Oceanic Basalts\*

W. Lowrie<sup>1</sup> and D.V. Kent<sup>2</sup>

<sup>1</sup> Institut für Geophysik, ETH Hönggerberg, 8093 Zürich, Switzerland

<sup>2</sup> Lamont-Doherty Geological Observatory, Palisades, New York 10964, USA

**Abstract.** Laboratory experiments, each lasting several weeks, have been conducted to establish the characteristics of viscous remanent magnetization (VRM) in oceanic basalts from many sites of the Deep Sea Drilling Program (DSDP). VRM is most pronounced in low-coercivity basalts whose natural remanences (NRM) have low median destructive fields, less than 100 Oe. A simple logarithmic acquisition law is rarely obeyed, but two or three distinct stages are instead observed, in each of which a logarithmic dependence of VRM intensity on acquisition time may be assumed. This observation leads to a simple interpretational model for the nature of VRM in DSDP basalts, but also implies that extrapolation of laboratory observations to geological times is not meaningful. Instead, the ratio of laboratory VRM (acquired in a 1 Oe field during 1000 h) to NRM is used as a minimum indicator of the potential seriousness of VRM. Experiments show that VRM acquired in the presence of NRM is more serious than VRM acquired in alternating field (AF) demagnetized samples. As most published VRM data in DSDP basalts were obtained after AF demagnetization, these are regarded also as minimum estimates of the significance of VRM acquired by oceanic basalts in situ. The consequences of the common occurrence of such an unstable component of magnetization in the oceanic basalt layer are considered in relation to the nature and distribution of oceanic magnetic quiet zones. The Cretaceous, and possibly the Jurassic, magnetic quiet zones are considered adequately explained by constant paleomagnetic field polarity. However, if VRM is a substantial and widespread magnetization component in the oceanic crust, it may not always be appropriate to interpret oceanic magnetic anomalies (or their absence) as an exact record of paleomagnetic field behavior. Remagnetization of the oceanic crust by VRM acquisition may be a viable alternative explanation of the origin of the marginal magnetic quiet zones.

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\* Institut für Geophysik, ETH Zürich, Contribution No. 200 Lamont-Doherty Geological Observatory, Contribution No. 2635

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## Introduction

Sea floor spreading studies are based upon interpretation of marine magnetic anomalies which are thought to derive chiefly from magnetization contrasts in Layer 2 of the oceanic crust. The principal sources are usually ascribed to the extrusive basalts in the uppermost 500 m (Layer 2A) (Talwani et al., 1971; Atwater and Mudie, 1973) although it is probable that a substantial part of the signal has sources deeper in Layer 2 (Harrison, 1976; Lowrie, 1974, 1977) and perhaps even in Layer 3 (Cande and Kent, 1976). The Koenigsberger ratios of most oceanic basalts whose magnetic properties have been studied are generally greater than unity; that is the remanent magnetizations dominate the magnetizations that can be induced by the present magnetic field. This condition fulfills one of the requirements of the Vine and Matthews (1963) hypothesis, that the oceanic magnetic anomalies result from remanent magnetization contrasts.

The rocks additionally must pass the usual paleomagnetic requirement that they have high magnetic stability in order to preserve original remanent magnetization directions over geologically long periods of time. The remanences of many investigated oceanic basalts are in fact stable in the sense that they show only minor intensity or directional variation when measured repeatedly over laboratory experimental times, and also are resistive to alternating field (AF) demagnetization.

Not all oceanic basalts display this high stability. Whereas the median destructive fields of stable basalts commonly lie within the range 100–1000 Oe, a large proportion of the samples that have been investigated have median destructive fields lower than 100 Oe (Lowrie, 1974). These unstable basalts show a pronounced tendency during laboratory investigation to remagnetize in the presence of a constant magnetic field by acquisition of viscous remanent magnetization (VRM). If this can happen in the laboratory it can happen also to the basalt in situ. For this reason it has been proposed that a possible explanation for some oceanic magnetic quiet (or smooth) zones lies in the remagnetization of the oceanic crust in these areas by acquisition of VRM (Lowrie, 1973).

In light of the possible importance of VRM as a component of magnetization of the oceanic crust it is desirable to establish the characteristics of this remanence in oceanic basalts, and to understand what limitations are placed on the VRM mechanism as a possible explanation of magnetic quiet zones.

## VRM Characteristics in Oceanic Basalts

Since it was first suggested that VRM might be an important magnetization component of the oceanic crust in some areas (Lowrie, 1973), many studies of VRM acquisition have been carried out on oceanic basalts recovered on

the different legs of the Deep Sea Drilling Project (DSDP). The main interest in VRM has been to estimate its seriousness and most of the experiments carried out have been similar in type. A select number of samples are left at room temperature in a constant magnetic field of intensity usually in the range 0.5 Oe to 1 Oe, and the measurement of remanent magnetization is repeated at intervals over a period of generally 500 to 2000 h.

### *Simple Logarithmic Acquisition of VRM*

The properties of the natural remanent magnetization (NRM) of the basalts, including their stability, have usually been of primary interest, and, as a result, most VRM experiments on DSDP basalts have been initiated after AF demagnetization has virtually eliminated the original NRM in the samples. Whether the VRM is acquired by multidomain or by very fine, near-superparamagnetic grains, the expected growth is logarithmic with time. Over intervals of time ( $t$ ) lasting several minutes to several tens of hours, the VRM grows according to a law of the form

$$J(t) - J(0) = S \log t$$

where  $S$ , the magnetic viscosity coefficient, depends on the magnetic field and ambient temperature for a given sample.  $J(0)$  and  $J(t)$  are the initial remanence and that after time  $t$ , respectively.

There is usually a fairly large amount of scatter in VRM acquisition data. This may be due to uncontrolled temperature effects; a variation of a few degrees can influence  $S$  by several percent. Moreover, the VRM is an extremely unstable magnetization and it is possible that removing the sample from the acquisition field to make a measurement can affect the remanence.

Another source of scatter is the effect of stress on the magnetization. A high speed spinner magnetometer of the Princeton Applied Research (PAR) type exerts quite high stresses on the sample: at a distance of 1 cm from the axis of rotation the centrifugal force is equivalent to 9 g at 15 Hz ( $g$ =force of mean gravity), and to 440 g at 105 Hz. The first reported observation of VRM in DSDP basalts consisted of a dramatic decay of remanent intensity during the measurement of NRM with a 105 Hz PAR spinner in Leg 15 basalts from the Caribbean Sea (Lowrie and Opdyke, 1973). The sensitivity to stress of VRM in oceanic basalts was emphasized by Peirce et al. (1974) who recorded an abnormal change in VRM on lightly tapping a sample. It is therefore to be expected that in such unstable samples the DSDP drilling process itself may have a strong effect on the magnetization that is first recorded and analyzed as NRM.

Because of the data scatter, and also because data are gathered at rather infrequent intervals, a straight line is often fitted through all the points on a semi-logarithmic plot so as to determine an average value of  $S$  for the period of observation (Peirce et al., 1974). This value of  $S$  has been used to extrapolate to much longer times, specifically to 700,000 years, the present duration of the Brunhes period of normal geomagnetic polarity, in order to estimate the VRM that could be acquired in that interval (Lowrie, 1973; Tarasiewicz et

al., 1976). This method makes the assumption that the VRM acquisition is a single-phase process and that observations made within laboratory experiments can be simply extrapolated to geologic periods. This assumption is usually unwarranted but the seriousness of VRM in many samples can often be demonstrated without it.

### *Multi-Stage VRM Acquisition and Decay*

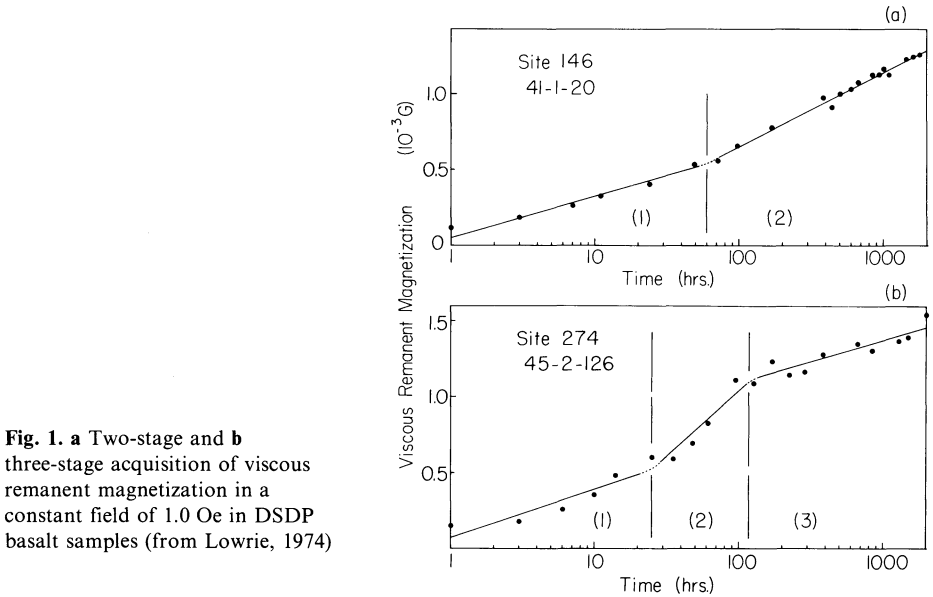
VRM observations in which closely spaced data have been acquired over a long period of time indicate that in most DSDP basalts a multi-stage acquisition process is involved. It is frequently possible to observe more than one of these stages during an acquisition experiment in 1 Oe lasting 2000 h or less. In Leg 28 basalts, the semi-logarithmic plot was clearly non-linear (Lowrie and Hayes, 1975). We have fitted many data sets with higher order polynomials up to 5th order but this has proved to be a rather fruitless exercise as it leads one into the temptation of overinterpreting the acquisition curves. The data are frequently well-satisfied by dividing them into three separate sections (Fig. 1 b), to each of which a straight line is fitted. The slopes of the straight line segments have been calculated for a number of such experiments and it is found that the slopes of segments 1 and 3 are approximately equal (Lowrie, 1974, Table 4).

A three-stage process is often not observed during the period of a normal laboratory experiment, but in most cases a 2-stage VRM acquisition curve is observed (Fig. 1a), with the slope in the second segment about two to three times that in the first (Fig. 2). It is possible that the same situation exists here as in the three-stage case; if the experiment could be continued for a sufficient length of time the third stage might be observed. The logarithmic nature of the acquisition process limits the deductions that can be made to those observable within a practical length of time, and the possibility of additional stages at longer times can not be excluded. Although the process can be speeded up by using higher fields or temperatures, additional assumptions have to be made that the results are still applicable under the ambient conditions in the oceanic crust.

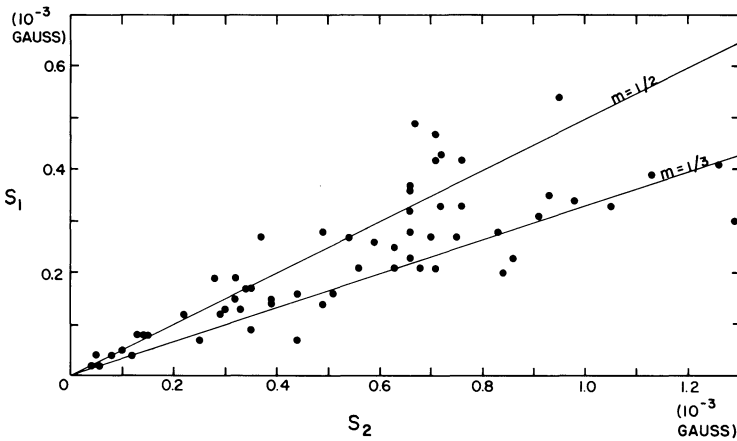
In contrast to the acquisition of VRM in a constant field, viscous relaxation behaviour is also displayed by oceanic basalts under zero-field conditions. Samples which have been given a VRM in a 1.0 Oe field over a period of 1000 h were placed in a zero-field space created by Helmholtz coils. Their magnetizations, observed over several hundred hours (Fig. 3), decayed in a manner also involving several stages. Too few experiments have been carried out and data are too sparsely distributed to establish whether the slopes of the different parts of the VRM decay curves are correlated with the corresponding slopes of the VRM acquisition curves. On theoretical grounds it is expected that the viscosity coefficient for VRM decay is the same as that for VRM acquisition starting from the AF demagnetized state (Dunlop, 1973).

### *Comparison of VRM and NRM*

It is evident from the above that, even if a simple semi-logarithmic relationship is observed in the course of a laboratory VRM experiment extrapolation to



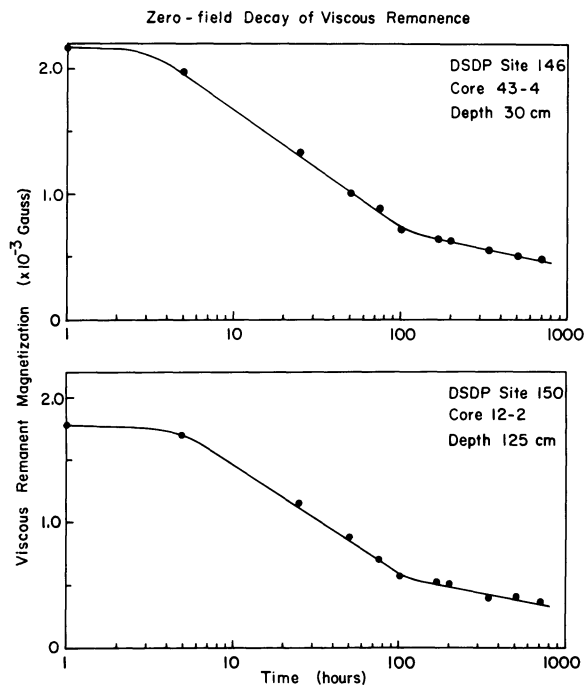
**Fig. 1.** a Two-stage and b three-stage acquisition of viscous remanent magnetization in a constant field of 1.0 Oe in DSDP basalt samples (from Lowrie, 1974)



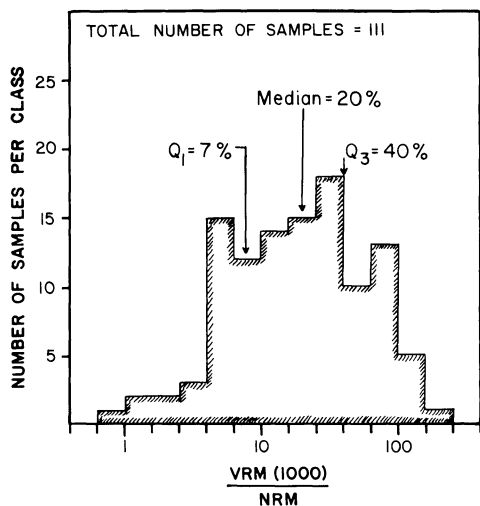
**Fig. 2.** Comparison of VRM acquisition coefficients in 60 DSDP basalt samples.  $S_1$  and  $S_2$  are the slopes of the straight lines in stages 1 and 2, respectively, in Figure 1. Lines (solid) of constant ratio ( $S_1/S_2$ ) are shown for reference

geological periods of time is highly uncertain. Thus predictions of the amount of VRM that may be acquired since the beginning of the Brunhes are entirely speculative.

Frequently, however, DSDP basalts are so susceptible to VRM acquisition that the NRM intensity is exceeded within the duration of a laboratory experiment. For example, basalts from site 319A of Leg 34 acquired VRM intensities equivalent to their NRM in times of only 9 to 490 h in a 1 Oe field (Lowrie and Kent, 1976).

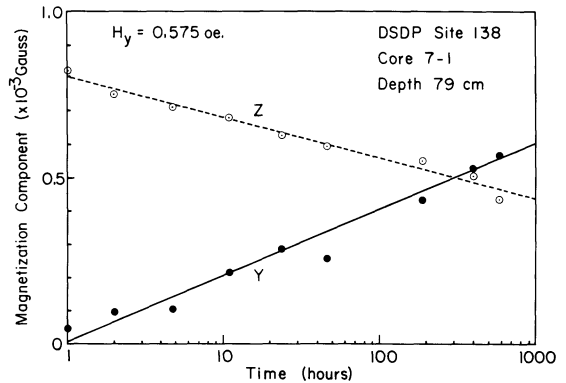


**Fig. 3.** Zero-field decay of VRM acquired in a 1.0 Oe field over a period of 1000 h in two DSDP basalt samples



**Fig. 4.** Histogram of the ratio VRM(1000)/NRM in 111 DSDP basalt samples. VRM(1000) was acquired after AF demagnetization of NRM in most cases in a constant field of 1 Oe over 1000 h. The values of the first quartile ( $Q_1$ ), median, and third quartile ( $Q_3$ ) of the distribution are indicated

An effective method of comparing the VRM acquisition in a sample to its NRM intensity is to use a standard field for a standard length of time. Most observers of VRM have continued their observations for at least 1000 h. Fields used have been in the range 0.5 to 1.0 Oe, in which the viscosity coefficient presumably varies linearly with applied field. It is, however, unsafe to correct



**Fig. 5.** Acquisition of VRM in the presence of NRM in a DSDP basalt sample. Sample was aligned so the magnetic field ( $H=0.575$  Oe) was parallel to  $Y$ -axis and the NRM lay in the  $X$ - $Z$  plane

for this field variation (for the same reasons that acquisition curves cannot be extrapolated) and data from authors who have not used a 1.0 Oe field (Peirce et al., 1974; Tarasiewicz et al., 1976) are incorporated without correction in compiling a histogram of VRM (1000)/NRM values for 111 basalt samples representing 30 DSDP sites (Fig. 4). The median value of the distribution is 20%. The distribution is probably not truly representative of all DSDP basalts since VRM investigations are usually carried out deliberately on those basalts which display unstable characteristics during measurement of NRM properties. Nevertheless the histogram indicates that in  $1/4$  of the samples studied the VRM acquired in a few weeks in the laboratory exceeded 40% of the original NRM intensity. Moreover, these 30 sites represent 40% of all DSDP sites up to Leg 41 for which basalt magnetic properties have been published. Their ages range from a few million years (site 332B) to 150 million years (site 100).

*VRM Acquisition in the Presence of NRM*

The VRM data described above were acquired after the NRM properties of the basalts had been studied and after the NRM had been effectively eliminated (or reduced to a very low value) by AF demagnetization. The conditions prepared for acquisition of VRM are, therefore, artificial when compared to the conditions in nature, where VRM is not acquired from a demagnetized state but in the presence of an NRM component (presumed to be TRM). It is questionable if deductions on the importance of VRM made on the basis of laboratory acquisition in demagnetized basalts are directly applicable to VRM acquisition in the oceanic crust. Laboratory experiments indicate, however, that VRM in nature is likely to be even more serious than indicated by the above laboratory data.

An undemagnetized basalt sample was oriented so that its NRM direction was exactly perpendicular to the geomagnetic field in the laboratory. The sample axes were defined so that the  $Y$ -axis was parallel to the field direction and the NRM lay in the  $Z$ - $X$  plane. The acquisition of VRM over a period of 500 h was practically logarithmic and was accompanied by a corresponding

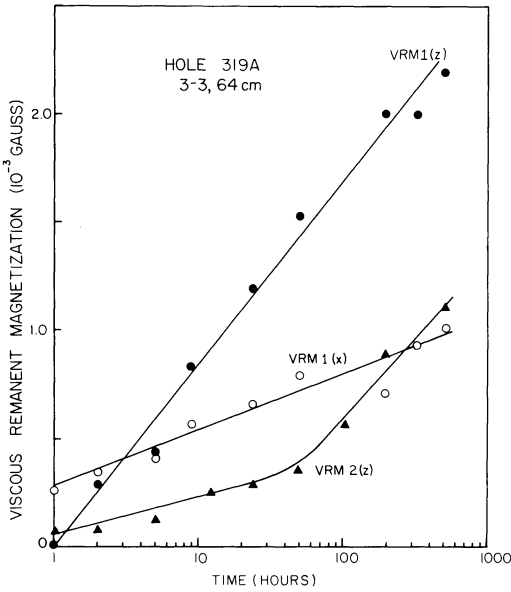


Fig. 6. Acquisition of VRM in presence of NRM (VRM 1) and after AF demagnetization (VRM 2) in a DSDP basalt sample

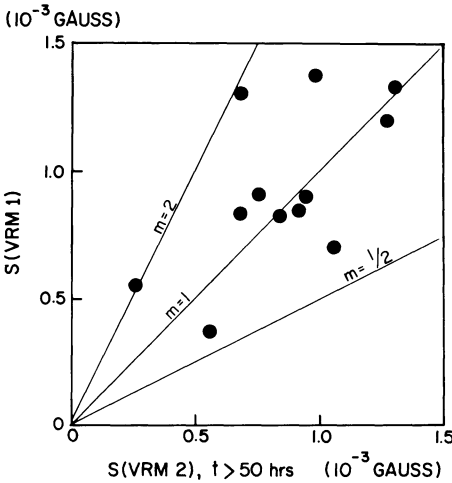


Fig. 7. Comparison of the viscosity coefficient characterizing VRM growth in the presence of NRM ( $S(\text{VRM } 1)$ ) and the viscosity coefficient for the second segment of VRM growth after AF demagnetization ( $S(\text{VRM } 2), t > 50 \text{ h}$ ) in DSDP Leg 34 basalt samples. Lines (solid) of constant ratio are shown for reference

decay of the Z-component (Fig. 5). The X-component was much stronger than the Y or Z-components; variation in this component could not be distinguished from the error of measurement. Possibly part of the growth of VRM along the Y-axis is enhanced by the decay of NRM along the Z-axis as the unstable (soft) component rearranges itself. In this case the VRM acquisition was not multistage.

In VRM experiments on basalts from DSDP Leg 34 (Fig. 6) Lowrie and Kent (1976) also reported simple logarithmic growth of VRM prior to AF demagnetization (VRM1(z)). This was again accompanied by a change in the remanence component normal to the VRM. After AF demagnetization the



**Table 1.**

Site	Sample	NRM ( $10^{-3}$ Gauss)	VRM ( $10^{-3}$ Gauss)	VRM/NRM (%)
100	11-1-20	16.0	1.83	11
	11-1-100	23.7	1.51	6
	11-1-125	6.18	2.49	40
105	42-2-5	3.53	0.68	19
	42-2-38	1.07	1.34	124
	42-2-71	3.09	1.18	38
	42-2-105	3.21	0.98	31
	42-2-121	1.43	1.55	108
	42-2-147	3.27	0.91	28
146	41-1-20	2.65	1.13	43
	41-2-2	1.21	1.13	93
	42-2-70	2.81	1.75	62
	42-3-148	2.78	1.72	62
	43-2-123	5.93	1.39	23
	43-3-73	3.79	1.75	46
	43-4-130	4.98	1.76	35
	150	11-2-65	3.92	1.39
12-1-132	6.64	1.40	21	
12-2-125	4.69	1.46	31	
151	14-1-118	5.84	0.56	10
	15-1-148	1.96	0.39	20
152	23-1-112	2.38	0.75	31
	24-1-68	1.68	0.58	35
	24-2-75	8.32	0.57	7
153	19-1-118	8.81	1.53	17
	20-1-147	5.88	1.39	24
	20-2-82	3.52	1.55	44
274	44-1-cc	2.74	1.32	48
	44-3-cc	2.22	1.78	84
	45-1-cc	12.3	0.94	8
	45-2-2	12.2	1.37	11
367	38-2-76	5.36	0.014 (3.39)	0.3 (63)
	38-3-2	3.84	0.25 (3.65)	7 (96)
	38-3-129	2.59	0.022 (2.83)	0.8 (109)
	39-2-35	2.78	0.26 (1.47)	9 (53)
	39-2-122	1.39	0.040 (2.10)	3 (66)
	40-1-87	4.06	0.20 (2.71)	5 (67)

entire character of the VRM acquisition curve changed (VRM2(z)); two distinct segments were now discernible and there were no changes in the orthogonal directions. When plotted against each other the slope of the steeper second segment and the slope of the single stage VRM acquisition prior to demagnetization (Fig. 7) are scattered but are positively and significantly correlated ( $r=0.614$ ) and do not differ by more than a factor of 2.

The character of VRM acquisition observed before and after AF demagnetization differed also in experiments conducted for 500 h on basalts from site 367

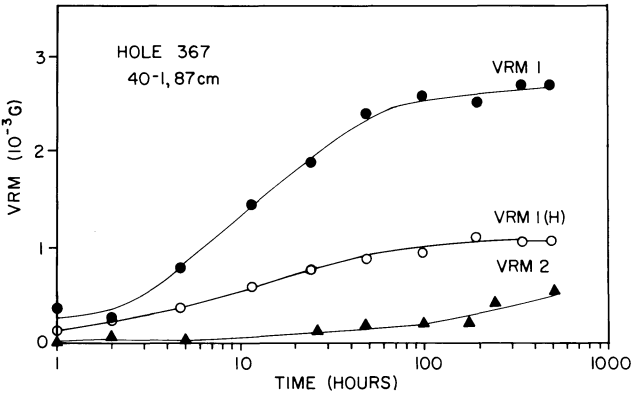


Fig. 8. Acquisition of VRM in presence of NRM (VRM 1) and after AF demagnetization (VRM 2) in a DSDP basalt sample from a site in the Jurassic Quiet Zone in the eastern North Atlantic. VRM 1 (H) represents the change in remanence in the plane perpendicular to the applied field of 1 Oe

(Kent and Tsai, 1977). Before demagnetization the VRM acquired in this short period amounted to a large fraction (53% to 109%) of the initial NRM intensity (Table 1). In this case also the growth of VRM is accompanied by a change in the component normal to the acquisition field, which shows a 3 stage relaxation exactly matching the VRM acquisition. In contrast, the VRM observed after AF demagnetization was much less pronounced. Whereas prior to AF demagnetization 3-stage acquisition was exhibited, this was not observed after demagnetization, although the slope of the logarithmic plot appears to increase after 100 h (Fig. 8). The marked difference in VRM acquisition as a function of the initial remanence state was similar to that noted in Leg 34 basalts (Fig. 6, and Lowrie and Kent, 1976).

From these few data it cannot be established if the same physical process is involved in both cases (i.e. before and after AF demagnetization). It appears that the AF demagnetization stabilized the short activation-time component that participated previously in the VRM acquisition. The important paleomagnetic observation is that the rate of VRM acquisition in the presence of NRM is at least equivalent to the most rapid acquisition from the AF demagnetized state. Since the laboratory VRM acquisition experiments made in the presence of NRM are likely to be more representative of the viscous behavior exhibited by the basalts in situ, we feel that a significant portion of the NRM of these site 367 and Leg 34 basalts can be attributed to recently acquired viscous components.

#### *Summary of VRM Acquisition Experiments*

The experimentally established characteristics of VRM in oceanic basalts may be summarized as follows:

1. The tendency of DSDP basalt to acquire VRM varies approximately

inversely with the median destructive field and is especially high in basalts with MDF less than 100 Oe (Kent and Lowrie, 1977).

2. A long term simple logarithmic law is rarely obeyed during acquisition of VRM in oceanic basalts. Two or three stages are usually observed, in each of which a simple logarithmic relationship can be assumed.

3. For this reason it is not meaningful to try to extrapolate quantitatively from the results of laboratory VRM experiments in an attempt to account for the NRM intensity of the basalts. Instead we prefer to consider the VRM acquired during the course of a laboratory experiment as a minimum indicator of the seriousness of VRM in situ. If a large fraction of NRM can be accounted for by VRM acquisition during a period of only a few weeks it is reasonable to assume that an equivalent or larger fraction of the remanence of the basalt in situ must be viscous.

4. Contrary to expectation, the VRM acquired under laboratory conditions in the presence of NRM is apparently more serious than that acquired in the demagnetized basalts. Since the overwhelming majority of published VRM results (Lowrie, 1974; Peirce et al., 1974; Tarasiewicz et al., 1976) have been obtained after demagnetization, most of these data must be interpreted as minimum estimates of the significance of VRM acquired by DSDP basalts in situ (that is, in the presence of NRM).

## Origin of VRM in Oceanic Basalts

### *Magnetic Domain State*

The remanent magnetic properties of oceanic basalts are due to fine grains of titanomagnetite or titanomaghemite with titanium compositional parameters in the range  $x=0.4$  to  $x=0.6$ . Formulae that allow computation of the critical grain size for transitions between the different magnetic domain states are summarized and their limitations discussed, by Stacey and Banerjee (1974). Although they probably are qualitatively correct, they are rather inexact quantitatively because of simplifying assumptions that are involved.

For the compositional range found in oceanic basalts the transition from superparamagnetism to single domain behavior occurs at grain sizes of 0.04–0.07  $\mu\text{m}$ ; the thickness of a domain wall is 0.1–0.2  $\mu\text{m}$ , and the critical upper grain size for single domain behavior is 0.2–0.6  $\mu\text{m}$ . Pseudo-single domain behavior is displayed until grain sizes of 20–40  $\mu\text{m}$ , above which multidomain behavior is found.

The only direct optical evidence of magnetic domain states in titanomagnetites was obtained by the Bitter technique on a titanomagnetite with compositional parameter  $x=0.65$  by Soffel (1971). He observed that particles up to several microns in size contained only two domains, and by extrapolating the plotted relation between number of domains and particle size, he inferred a critical maximum diameter of about 1  $\mu\text{m}$  for single domains.

Commonly oceanic basalts belong to deuteritic oxidation class 1 according to the scheme of Wilson and Watkins (1967), but occasionally classes 2, 3

or 4 have been reported (Ade-Hall et al., 1976). Systematic measurement of magnetic grain sizes and correlation with stable or unstable remanent magnetic properties unfortunately have not been made. Most DSDP basalts investigated have contained grains from a few microns in size down to the limit of optical resolution, while some have occasionally contained grains coarse enough to permit optical classification of the deuteric oxidation state. Very coarse grains up to 100  $\mu\text{m}$  in size were observed in DSDP basalts from size 57 in the North Pacific Ocean (Lowrie et al., 1973) while electron microscope investigation of oceanic basalts dredged from the North mid-Atlantic ridge revealed grain sizes finer than 0.1  $\mu\text{m}$  (Evans and Wayman, 1972).

Although VRM has been observed in a wide range of basalt grain sizes, it is most serious in comparison to NRM in coarse-grained basalts and dolerites. It therefore seems reasonable to associate stable remanence in oceanic basalts with single domain grains, and viscous behavior with pseudo-single-domain (PSD) and multidomain (MD) grain sizes.

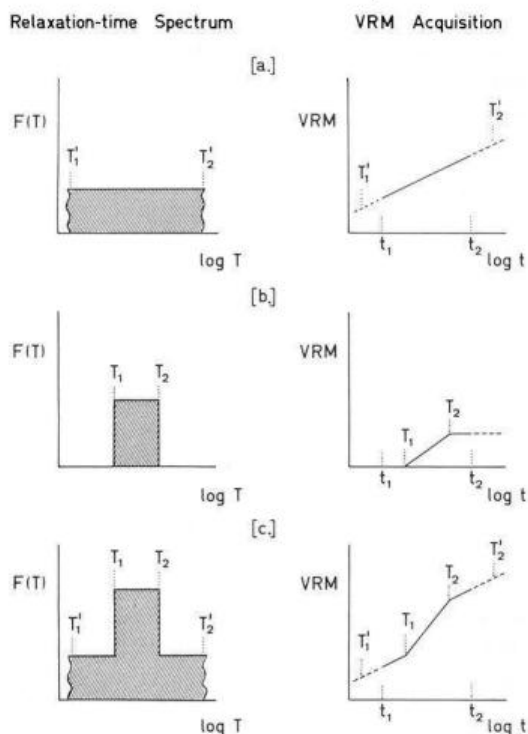
This conclusion is supported by the properties of NRM in a number of DSDP sites (Lowrie, 1974, 1977). Königsberger ratios ( $Q_n$ ) are high in basalts with stable NRM, and even in unstable basalts rarely are much lower than unity. Viscous remanent magnetization is often observed in basalts with low median destructive fields and  $Q_n$  values around unity; sometimes a strong NRM intensity is compensated by correspondingly large susceptibility. The NRM contains a low-coercivity fraction usually accompanied by a small hard component which is hard to isolate in the presence of the larger soft component. The soft component of NRM and the sample susceptibility are possibly multidomain effects, while the hardest part of NRM arises from PSD moments. Support for this rather generalized statement also comes from the VRM characteristics.

### *Theory of VRM in Oceanic Basalts*

The current status of the theory of VRM in SD, PSD and MD materials has been reviewed and discussed critically by Dunlop (1973). The following phenomenological interpretation of our VRM observations is based on his article, which should be consulted for details and a stricter analysis.

Without specifying the domain state or nature of the magnetization a phenomenological model may be set up in which a relaxation time ( $T$ ) is associated with each magnetic moment. If the spectrum of  $\log T$  is open ended and uniform (Fig. 9a), a simple logarithmic VRM acquisition law will be obeyed for all experimental times. For this situation it would be possible to extrapolate the results from experimental times to geological periods. Dunlop (1973) has shown that a uniform  $\log T$  distribution can result from a wide range of grain sizes and coercivities.

Non-uniformity of the  $\log T$  distribution gives rise to non-logarithmic acquisition of VRM. In particular, if the  $\log T$  spectrum is bounded by relaxation times  $T_1$  and  $T_2$ , both of which lie within the period of experimental observation, a VRM acquisition curve similar to that shown in Fig. 9b results. For observation times  $t \ll T_1$  and  $t \gg T_2$  there is no activation; for  $T_1 < t < T_2$  a logarithmic



**Fig. 9 a-c.** Illustration of VRM acquisition curves in materials with three different distributions of magnetization relaxation times  $T$ . **a** VRM grows logarithmically when the distribution of  $\log T$  is uniform over a wide range, **b** VRM grows logarithmically over a certain time range, representing the limits of a discrete range of relaxation times. **c** Three-stage VRM growth results from the combination of effects **a** and **b**

mic growth of VRM is observed. In fact the onset and termination of VRM growth due to activation of this discrete range of relaxation times need not coincide with  $T_1$  or  $T_2$ , and the acquisition curve will have tails.

We envisage the 3-stage VRM acquisition curves in AF demagnetized DSDP basalts to be represented by the sum of these two effects; a discrete range of relaxation times is superposed on a broader background (Fig. 9c). In view of the known magnetic mineralogy of oceanic basalts, the background VRM growth is probably due to multidomain grains, on which is superposed a discrete fraction possibly representing SD or PSD grains. The coexistence of two disparate grain size generations among titanomagnetites in the same basalt sample is supported by observation. Ade-Hall et al. (1976) describe massive basalts containing anhedral grains up to 100  $\mu\text{m}$  in size and skeletal grains from 10  $\mu\text{m}$  down to the limit of visibility.

Creer et al. (1970) and Petherbridge (1977) heated Rauher Kulm basalt samples at 400° C to produce a 'daughter' magnetic mineralogical phase whose interaction with the 'mother' phase led to partial self-reversal, and also to a change in the character of viscous magnetization acquisition. Heated (two-phase) samples showed 2-stage acquisition (as in Fig. 1a) whereas natural unheated samples did not.

Production of a 'daughter' phase in the laboratory by heating can be achieved in nature at lower temperatures over longer time intervals. Abundant optical evidence has been reported of oceanic basalts containing otherwise homogeneous

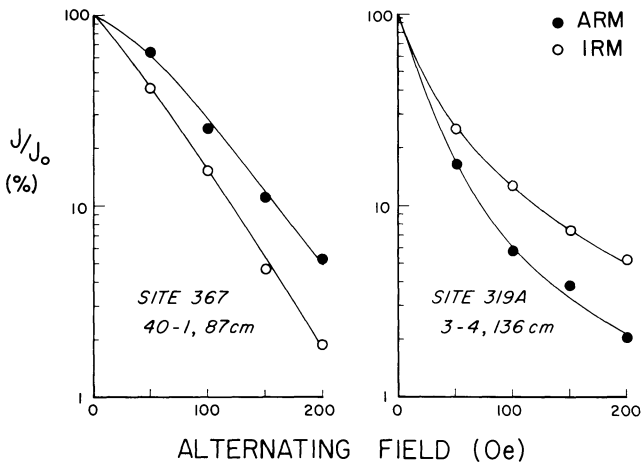
titanomagnetites that displayed the characteristic whitening of maghemitization along internal cracks and on grain rims (see, for example, Ade-Hall et al., 1976). Strong-field thermomagnetic curves occasionally also show an initial increase of induced magnetization on heating (see, for example, Lowrie et al., 1973, Fig. 2), possibly indicating partial self-reversal.

Petherbridge (1977) attributed viscous behaviour of the 'daughter' mineralogical phase to ultra-fine, unstable grains whose sizes were intermediate between the ranges for superparamagnetism and stable SD magnetization. However, the viscosity coefficient for this SD-type VRM ought to be more than an order of magnitude greater than that for MD-type (Dunlop, 1973), whereas the observed ratio of viscosity coefficients in stages 1 and 2 is only around 2 or 3 (Fig. 2). We attribute stage 2 rather to a PSD fraction.

Some of the experimental evidence suggests that a single stage VRM growth observed before AF demagnetization changes to multi-stage acquisition after AF demagnetization (Fig. 6) with the original viscosity coefficient matched by the viscosity coefficient in stage 2 (Fig. 7). This implies that AF demagnetization resulted in partial stabilization of the spectrum of relaxation times, preventing their participation in further VRM growth. For this model the AF demagnetized state is taken to be equivalent to an anhysteretic remanent magnetization (ARM) acquired in a constant field of zero intensity. ARM can possess quite high stability, and we envision this to be imparted to a fraction of the magnetization spectrum that originally participated in the VRM process. However, we can offer no exact mechanism by which this took place or by which it can be quantitatively explained. In the hole 367 basalts 3-stage VRM acquisition was greatly altered by AF demagnetization, to the extent that the magnetic viscosity was almost entirely stabilized (Fig. 8).

### *Discussion*

Dunlop and Hale (1976) report strong VRM in DSDP Leg 37 basalts that contain stoichiometric titanomagnetites and weaker, more variable VRM in basalts with cation-deficient oxidized titanomagnetites and attribute the difference primarily to a difference in effective magnetic grain size. However, from our investigations of VRM in a large number of geographically distributed DSDP sites we do not observe a simple relationship between extent of VRM, grain size and degree of maghemitization. Strong VRM has been observed in fresh coarse-grained basalts elsewhere, for example at site 57 (Lowrie, 1973) and at site 319A (Lowrie and Kent, 1976), in apparent agreement with Dunlop and Hale's findings, but strong VRM has been observed as well in some fine-grained, altered basalts. For example, basalts from site 367 have elevated Curie temperatures near to 400° C that suggest cation-deficient oxidized titanomagnetites and give a fine-grained pattern in the test according to Johnson et al. (1975) of dominant magnetic domain state (Kent and Tsai, 1977; Fig. 10a). These properties are in contrast to the coarse-grained basalts from site 319A which have low Curie temperatures conforming to near stoichiometric titanomagnetites (Lowrie and Kent, 1975) and which give a coarse-grained indication in a test of domain state (Fig. 10b). However, both the site 367 and site 319A



**Fig. 10.** Comparison of stability against AF demagnetization of anhysteretic (*ARM*) and isothermal (*IRM*) remanent magnetizations in two DSDP basalt samples. The sample from site 367 gives a single-domain indication while the sample from site 319A gives a multidomain indication. However, both samples have viscous remanent magnetic properties

basalts were able to acquire large VRM components in laboratory experiments (compare Figs. 6 and 8; Table 1). We conclude from this that while it is possible that strong VRM may be a characteristic of fresh coarse-grained oceanic basalts, it does not necessarily appear to be confined to them.

The potential seriousness of VRM in oceanic basalts is therefore difficult to predict. The relatively few studies of VRM and the bias of these studies towards those basalts which display unstable characteristics (i.e., low median destructive fields) during measurement of NRM properties do not enable us to categorically state the extent of VRM in the magnetization of the oceanic crust. However, it is possible that VRM is more prevalent in oceanic basalts than is indicated by these VRM studies. The average median destructive field (MDF) of DSDP basalts from 51 sites averaged only 120 Oe (Lowrie, 1977). In basalts with MDF less than 100 Oe VRM can account for a large fraction of the NRM. Moreover, VRM can be important, at least theoretically, even in basalts with high MDF. This is because VRM is a thermally activated process and under certain conditions may not be strongly related to coercivity (Pullaiah, et al., 1977).

A fundamental assumption in the Vine and Matthews (1963) hypothesis is that the remanent magnetization of the ocean crust is preserved from the time of crustal formation at the sea floor spreading axis. If the oceanic basalts recovered by the Deep Sea Drilling Project are considered representative of the source of marine magnetic anomalies, the occurrence of strong VRM of recent origin in many of these rocks suggests that this assumption is not uniformly applicable and it may not always be appropriate to interpret marine magnetic anomalies (or their absence) as a precise record of paleomagnetic field behavior.

We note that the acquisition of a secondary magnetization in oceanic basalts does not necessarily result in reduced anomaly amplitudes. For example, if

a secondary (or an induced) magnetization component is acquired in a uniform direction and in equal amounts by adjacent source blocks with opposite remanent polarities, the magnetization contrast is unaltered and hence the magnitude (and the shape) of the magnetic anomaly does not change provided the original remanent magnetization is not affected. All other factors the same, a decrease in the amplitude of marine magnetic anomalies will only result from a reduction in the original basalt remanent magnetization that carries the record of field reversals.

Our data indicate that VRM acquisition is accompanied by erosion of another component of NRM (Fig. 5, 6 and 8). It is not certain what the "NRM" in this case represents. The large soft component of most basalts studied for VRM purposes obscures unambiguous identification of the original remanence. In many cases AF demagnetization of unstable DSDP basalts beyond only 100 Oe results in scattered directions, and a stable inclination is difficult or impossible to isolate. Although a thermoremanence must have been acquired during initial cooling of the basalts, subsequent modification by VRM, by chemical alteration, by the stresses of sampling, and by other secondary processes, are very likely. For example, the dramatic effect on the remanence observed after lightly tapping an unstable DSDP basalt (Peirce et al., 1974), emphasizes the possibility that drilling with a magnetic drill collar and core barrel can induce a secondary remanent magnetization (Ade-Hall and Johnson, 1976). The apparent decay of NRM during VRM acquisition may merely represent relocation of a secondary unstable component acquired just prior to the laboratory investigation.

It is also possible, however, that the original TRM of unstable basalts has been at least partly lost. If the original TRM is carried by grains whose magnetization relaxation times at ambient sea-floor temperatures are shorter than a few hundred thousand years, a part of the original TRM will be eroded and participate in a VRM acquisition process. Magnetization contrasts between adjacent, oppositely magnetized crustal blocks will consequently be reduced and the associated magnetic anomalies will be reduced in amplitude or absent.

Of interest in this context are marine magnetic quiet zones, regions in which magnetic anomalies are either poorly developed or not lineated. The interpretation of the Cretaceous quiet zone as representing sea-floor spreading during an interval of predominantly normal geomagnetic polarity is supported by independent paleomagnetic data (e.g., Helsley and Steiner, 1968; Lowrie and Alvarez, 1977). In contrast, the available land paleomagnetic record does not independently require an interval of constant geomagnetic polarity for the interval of time corresponding to the Jurassic quiet zones (Irving and Pullaiah, 1973) and apparently conflicting interpretations of paleomagnetic field behavior during this interval have been given (i.e., dominantly normal polarity: Larson and Pitman (1972), Larson and Hilde (1975); dominantly reversed polarity: Steiner and Helsley (1975); rapidly reversing field polarity: Cande et al. (1977). It is possible that a single explanation does not suffice for the Jurassic quiet zone. However, the fact that the Jurassic quiet zone boundary appears to cut across magnetic lineations in the eastern North Atlantic (Hayes and Rabinowitz, 1975) indicates that it is not an isochron, but is a feature of variation in the rock



magnetic properties of the oceanic crust. This, in addition to the unstable magnetic properties of the only DSDP basalts recovered from the Jurassic quiet zone (Site 100 and perhaps Site 105 in western, Site 367 in eastern, North Atlantic) and the current lack of independent paleomagnetic data suggest that viscous remagnetization of the crust may contribute to the observed smooth magnetic field over the Jurassic quiet zones.

Magnetic quiet zones are also found adjacent to the margin of certain continents, such as southern Australia (Weissel and Hayes, 1972). Irving (1970) pointed out that a local geological cause is probably responsible for marginal quiet zones and suggested the probable difference in conditions for submarine basalt formation at the time of initial rifting compared to later steady sea-floor spreading. An example at present is to be seen in the Red Sea; although a well-defined axial anomaly exists, oceanic magnetic anomaly amplitudes in the adjacent areas are subdued (Girdler, 1969). Irving assumed that conditions at initial rifting would favor development of coarse grain sizes in basalts, and expected these to have low NRM intensities and stabilities. The concurrence of high VRM in coarse-grained DSDP basalts observed by Dunlop and Hale (1976) and in this study indicates that viscous remagnetization may be an important process in the production of marginal quiet zones.

Lineated magnetic anomalies are not always absent in magnetic quiet zones although their amplitudes are greatly reduced. There is frequently good correlation between topography and positive anomalies, but reversely magnetized zones have also been interpreted as in the Jurassic quiet zone in the eastern North Atlantic (Barrett and Keen, 1976). These observations indicate that the quiet zone crust is acting as a poor recorder of reversals, and are compatible with the VRM model hypothesized above.

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