# 39. PALEOMAGNETISM OF BASALT SAMPLES FROM LEG 29[1]

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ABSTRACT

Remanent magnetic properties were measured in basalt from Sites 279 (Hole 279A) 280 (Hole 280A), 282 and 283. Unusually low intensities of remanence were measured in Hole 280A specimens. At Sites 279 (Hole 279A) and 283 the remanent magnetization was less important than the induced magnetization. Thermomagnetic analysis indicated that the basalt was of deuteric oxidation class I, with titanomagnetite or titanomaghemite as the magnetic mineral. The Site 282 basalt was drilled in a quiet zone; viscous remanent magnetization (VRM) experiments showed that this quiet zone cannot be caused by VRM of the oceanic crust. However, very unstable magnetic properties of Site 283 basalt allowed it to acquire VRM very readily.

## INTRODUCTION

Specimens of basalt were obtained from each of the sites 279 (Hole 279A), 280 (Hole 280A), 282, and 283 of Leg 29. The site locations and basalt descriptions are given in Table 1. The basalt was mostly fine-grained and had been altered to some degree. The basalt from Sites 279 (Hole 279A), 283, and 282 was identified as pillow basalt. The Site 282 basalt is of particular interest because it was believed to represent quiet zone in the oceanic crust; they were separated into five groups according to minor lithologic differences.

Five meters of intrusive basalt were recovered at Site 280 (Hole 280A). There were three layers of basalt, which were 2.0, 0.5, and 1.1 meters thick, respectively, and were separated by detrital sediments. The site summary (Chapter 7, this volume) suggests that these represent "either three separate but subparallel basalt intrusives, or more likely represent three tongues at the margin of a single intrusive mass." Samples were collected from each layer and from the baked clay separating the upper two layers.

Paleomagnetic specimens were cut in the form of right circular cylinders 2.54 cm (1 in.) in diameter and 2.54 cm (1 in.) in height to preserve as accurately as possible the known upward vertical direction. A small slice of each specimen was reserved for thermomagnetic analysis to identify the magnetic mineralogy.

## REMANENT MAGNETIC PROPERTIES

Remanent magnetizations were measured with a 5-Hz spinner magnetometer; susceptibilities were measured with an a.c. bridge. The intensities of the natural remanent magnetization (NRM) and susceptibility ($k$) are plotted on Figure 1. Straight lines indicate constant values of the ratio $Q'_n$ = (NRM)/$k$. The individual specimen values of NRM and $k$ are also given in Table 2. Using these values, the Königsberger ratios ($Q_n$) were calculated: $Q_n$ = (remanent magnetization)/ (induced magnetization) = (NRM)/($k \times H$), in which $H$ represents the intensity of the inducing field. For these computations the intensities of the 1965.0 International Reference Field at the sites were used.

The remanent magnetic properties of DSDP and other dredged and drilled oceanic basalt from all studies through 1973 have been summarized by Lowrie (in press). A very wide range of values for NRM, $k$, and $Q_n$ has been observed, generally between sites, but in some cases within the same site. In DSDP basalt the mean values of 26 sites were NRM = $2.1 \times 10^{-3}$G, $k = 6.3 \times 10^{-4}$G/oe, and $Q_n$ = 7.9.

A considerable range of both NRM and $k$ was found in the Leg 29 basalt (Figure 1, Table 2). NRM intensities at Sites 279, 282, and 283 were fairly close to average; but at Site 280 the NRM intensities were exceptionally low. The susceptibilities vaired considerably from the average; at Sites 279 and 283 the susceptibilities were higher than average, and at Sites 280 and 282 they were much lower than average in many specimens. These variations reflect significant variations in the concentration and grain size of the magnetic mineral and differences in its composition. At Site 280 the altered basalt below the baked clay had a remanent intensity close to that of the clay and much lower than the already low values in the rest of the hole.

At Site 282 the Königsberger ratio was quite high (averaging 11.4), which has been frequently observed in oceanic basalt. At Site 279 the mean value was much lower, but was significantly larger than unity. At sites 280 and 283 the mean value was much less than unity; clearly in the basalt from these holes the remanent magnetization is of secondary importance to the induced magnetization. At Site 279 the remanence is dominant, but induced magnetic effects could seriously perturb any associated magnetic anomalies.

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TABLE 1
Latitude and Longitude of Leg 29 Sites from Which Samples Were Studied and Brief Descriptions of Samples

| Location | NRM[a] ($10^{-4}$G) | Description of Samples |
|---|---|---|
| **Hole 279A** | | |
| 51.3°S, 162.6°E | 26.6 | Vesicular, porphyritic to fine-grained, dark gray basalt |
| **Hole 280A** | | |
| 48.9°S, 147.2°E | | Three intrusive layers and one baked clay |
| (1) 23-2, 23-118 cm | 0.31 | Holocrystalline, fine-grained, greenish-black basalt |
| (clay) 23-3, 14 | 0.025 | Consolidated, light brown baked clay, with thin calcite veins |
| (2) 23-3, 63 | 0.030 | Fine-grained, greenish-black basalt cut by close spaced veins of calcite; slightly altered |
| (3) 23-4, 69-108 cm | 0.17 | Fine-grained, greenish-black basalt cut by thick (3-8 mm) veins of calcite; some thicker veins contain pyrite |
| **Site 282** | | |
| 42.2°S, 143.5°E | | Pillow basalts |
| (1) 18-2, 17-81 cm | 4.5 | Light greenish-brown, altered basalt |
| (2) 18-3, 45-145 cm | 17.9 | Fine-grained, dark greenish-gray basalt with some thin calcite veins |
| (3) 19-1, 110; 20-1, 130 | 8.2 | Very fine-grained, olive-black basalt with thin calcite vein |
| (4) 20-2, 33 to 20-3, 57 | 8.4 | Very fine-grained, greenish-gray, slightly altered basalt |
| (5) 20-3, 113 | 8.1 | Fine-grained, olive-green basalt with thick (~5 mm) calcite veins |
| **Site 283** | | |
| 43.9°S, 154.2°E | 6.9 | Pillow basalts; fine-grained, dark gray altered basalt with thick calcite veins |

Note: Numbers in parentheses indicate lithological differences.
[a]Intensity of natural remanent magnetization at the site.

On the basis of these data it would be unwise to interpret magnetic anomalies at Sites 279, 280, and 283 on the basis of the conventional remanently magnetized block model without giving consideration to the induced magnetizations. Only at Site 282 was the Königsberger ratio high enough to warrant neglecting induced effects. Paradoxically, Site 282 was located in a quiet zone of low anomaly amplitudes in which the linear pattern of anomalies could not be correlated.

## Stability and Inclination of Remanent Magnetization

All specimens were progressively demagnetized in alternating magnetic fields to isolate the stable direction of magnetization. Vector diagrams are given in Figure 2 illustrating the stability versus this treatment of representative specimens from each site. Variations of the north (N) and east (E) components define the declination variation. The mean declination is meaningless in these samples, which lacked azimuthal orientation. The vertical (V) and horizontal (H) components define the magnetic inclination which has validity since the samples were oriented with respect to vertical.

Stable inclinations for each sample are listed in Table 2. From each demagnetization curve, the field required to erase 50% of the original remanence was determined. Individual values of this median destructive field (MDF) are also listed in Table 2. Geometric mean values of MDF and arithmetic mean site inclinations are listed in Table 3, in which the site inclinations of the 1965.0 International Reference Field and the present axial dipole field are shown for comparison. Occasional accidentally inverted samples at Site 282 have been corrected in the preparation of Table 3.

Median destructive fields of DSDP samples have been found to lie commonly in the 200-400 oe range, although many instances of unstable remanences with MDF less than 100 oe have been found (Lowrie, in press). At Site 280, in spite of the low intensity, the remanence was quite stable with MDF averaging 257 oe. The MDF at

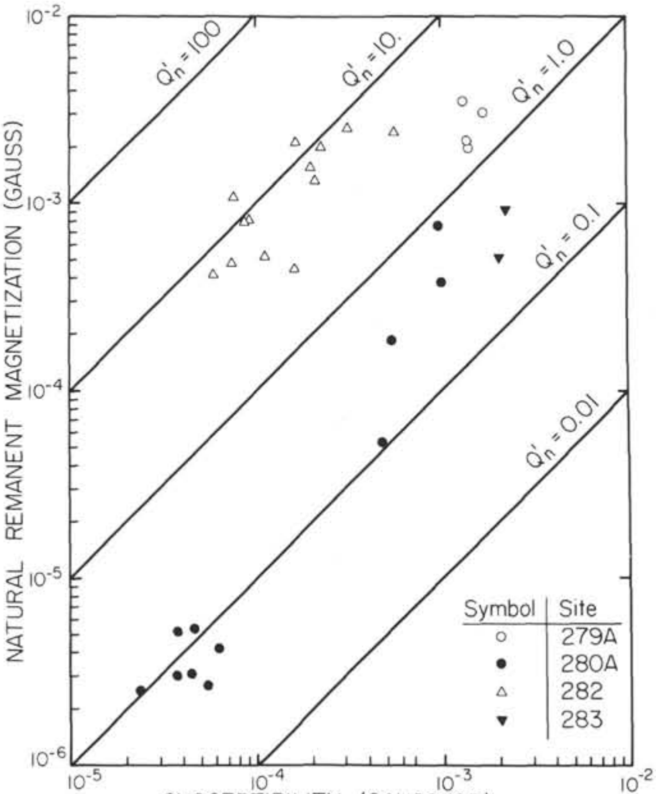


Figure 1. *Natural remanent magnetization (NRM) intensities and susceptibilities* (k) *of all Leg 29 basalt specimens measured. The straight diagonal lines represent constant values of the ratio* $Q'_n = (NRM)/k$.

Site 282 was also satisfactorily high, averaging 263 oe. However, at Sites 279 and 283 the MDF values were very low, averaging only 84 and 50 oe, respectively.

The samples from Sites 279 and 283 were normally magnetized; the more stable Sites 280 and 282 were reversely magnetized for Southern Hemisphere sites. The mean site inclinations at Sites 279, 280, and 282 were close to the absolute value of the axial dipole field (ADF) inclinations for the sites. At first glance this would imply that the basalt was magnetized at magnetic latitudes close to the present site latitudes. However, this may be fortuitous; it has been found that the inclinations of DSDP basalt magnetizations do not agree closely with expected inclinations except in a statistical sense (Lowrie, in press). The inclination of the Site 283 basalt, from which only two small samples were obtained, was very low.

These sites were drilled in a region whose past tectonic history has been very complex and is little understood at present. For this reason no attempt has been made to perform plate reconstructions in this study in order to compare the observed inclinations with those expected from such modeling.

The direction of magnetization of the baked clay from Site 280 was very similar to those of the basalt samples above and below it in the hole. This indicates that the clay was thermally remagnetized when the basalt was intruded.

Further information about the originality of the remanent directions was obtained from thermomagnetic analysis and consideration of secondary magnetizations.

## THERMOMAGNETIC ANALYSIS

The magnetic mineralogy of the basalt was investigated by thermomagnetic analysis. Small chips from specimens from each site were ground to a powder and heated in the presence of a strong magnetic field (2-4 koe) in a Curie balance of the vertical motion type. Zero-field observations were made regularly to compensate for weight loss of the specimen. A typical, computer-processed thermomagnetic curve showing the variation of strong field magnetization as a function of temperature is shown in Figure 3. Temperature calibration was accurate to within 5°C; magnetization measurements were uncalibrated. The Curie temperatures were determined from each curve using a simple construction method (Grommé et al., 1969). The Curie temperatures from the heating and cooling portions of the curves are listed in Table 4, which also shows the ratio of the initial magnetization ($J_i$) to the final magnetization ($J_f$) for each curve.

The thermomagnetic curves were typical of oceanic basalt of deuteric oxidation class I (Wilson and Watkins, 1967), in which the initial magnetic mineral was either titanomagnetite or its oxidized form, titanomaghemite. On the initial heating, the strong field magnetization decreases to a low value at a Curie temperature between 200°C and 400°C. Above 400°C, the mineral undergoes rapid separation into two phases, one of which is titanium-rich (hemo-ilmenite or ilmenohematite), and the other is titanium-poor and close to magnetite in composition. On cooling from above 600°C, the magnetization increases rapidly at the Curie temperature of the magnetite phase; at room temperature the final magnetization is stronger than that of the original mineral, and the ratio ($J_i/J_f$) is usually less than 1.

It has been suggested (Lowrie, in press) that thermomagnetic curves performed in air can, under certain conditions, reveal the presence of maghemitization. The observed value of ($J_i/J_f$) is then lower than expected on the basis of the Curie temperature. This test is not unambiguous. For example, whereas low values indicate maghemitization, values close to or greater than the expected value do not necessarily indicate absence of maghemitization. In this study (Table 4) most of the observed ratios were higher than expected. In only one of the Site 282 specimens was there a low value. This indicates the presence of titanomaghemite in at least some of the Site 282 specimens. It could not be determined from these results whether the magnetic mineral in the remainder of the specimens was titanomagnetite or titanomaghemite.

TABLE 2
Remanent Magnetic Properties of Individual Specimens, All of Which Were Basalt Except 280A-23-3, 14 cm Which Was a Baked Clay

| Specimen | NRM ($10^{-4}$G) | Suscept-ibility ($10^{-4}$ G/oe) | Königs-berger Ratio | Stable Inclin-ation | Demag-netizing Field (oe) | Median Destructive Field (oe) |
|---|---|---|---|---|---|---|
| **Hole 279A** | | | | | | |
| 12-1-133 | 30.6 | 17.2 | 2.77 | -59.7 | 75 | 40 |
| 13-1-56 | 20.0 | 14.6 | 2.13 | -70.6 | 75 | 152 |
| 13-1-138 | 22.9 | 14.7 | 2.41 | -68.0 | 75 | 86 |
| 13-2-85 | 35.5 | 13.0 | 4.26 | -65.7 | 75 | 95 |
| **Hole 280A** | | | | | | |
| 23-2-23(a) | 7.72 | 9.65 | 1.23 | 65.8 | 150 | 90 |
| 23-2-23(b) | 3.82 | 10.3 | 0.570 | 66.1 | 150 | 95 |
| 23-2-84 | 0.052 | 0.374 | 0.214 | 73.8 | 150 | 156 |
| 23-2-118(a) | 0.042 | 0.627 | 0.103 | 60.4 | 350 | 390 |
| 23-2-118(b) | 0.054 | 0.464 | 0.149 | 60.3 | 300 | 430 |
| 23-3-14 | 0.025 | 0.231 | 0.165 | 68.5 | 100 | 495 |
| 23-3-63 | 0.030 | 0.370 | 0.123 | 65.6 | 500 | 527 |
| 23-4-69(a) | 0.031 | 0.443 | 0.105 | 69.7 | 300 | 557 |
| 23-4-69(b) | 0.027 | 0.548 | 0.075 | 68.1 | 500 | 430 |
| 23-4-108(a) | 1.84 | 5.43 | 0.519 | 70.5 | 150 | 132 |
| 23-4-108(b) | 0.532 | 4.79 | 0.170 | 76.8 | 150 | 173 |
| **Site 282** | | | | | | |
| 18-2-81 | 4.52 | 1.68 | 4.27 | 68.5 | 75 | 191 |
| 18-3-45 | 24.4 | 5.53 | 7.01 | 65.9 | 150 | 158 |
| 18-3-145 | 13.1 | 2.12 | 9.79 | -65.5 | 150 | 190 |
| 19-1-143 | 21.6 | 1.64 | 21.0 | 75.3 | 150 | 351 |
| 20-1-93(a) | 10.7 | 0.765 | 22.2 | 62.5 | 150 | 517 |
| 20-1-93(b) | 8.13 | 0.919 | 14.0 | 68.2 | 150 | 356 |
| 20-1-130(a) | 4.17 | 0.589 | 11.2 | -61.2 | 150 | 341 |
| 20-1-130(b) | 4.86 | 0.746 | 10.3 | -69.6 | 75 | 393 |
| 20-2-94 | 15.7 | 2.00 | 12.5 | 72.7 | 75 | 274 |
| 20-3-10 | 25.2 | 3.13 | 12.8 | 67.3 | 150 | 196 |
| 20-3-55(a) | 20.7 | 2.25 | 14.6 | 52.0 | 150 | 242 |
| 20-3-55(b) | 5.19 | 1.13 | 7.27 | 52.1 | 150 | 162 |
| 20-3-113 | 8.08 | 0.877 | 14.6 | 64.3 | 300 | 280 |
| **Site 283** | | | | | | |
| 18-1-97 | 5.26 | 20.2 | 0.415 | -40.2 | 150 | 30 |
| 18-1-109 | 9.13 | 22.4 | 0.650 | -29.1 | 150 | 82 |

It is not entirely clear what effect oxidation has on the primary magnetic properties of oceanic basalt. The maghemitization causes a decrease in the remanent intensity, but does not significantly alter the direction of magnetization (Marshall and Cox, 1972). Secondary chemical magnetization of a stable character appears not to have serious effects.

## VISCOUS REMANENT MAGNETIZATION

Unstable secondary magnetization has been observed in a variety of oceanic basalt samples. During storage tests in constant and zero fields in the laboratory, development of secondary viscous remanent magnetization (VRM) has been studied (Lowrie, 1973, in press; Lowrie et al., 1973). The VRM grows logarithmically with time. It could have a serious effect on oceanic magnetic anomalies, if a region of the oceanic crust possessed the capability of developing a significant VRM. For example, the oceanic crust would slowly remagnetize in the direction of the ambient geomagnetic field after each magnetic field reversal, and magnetization contrasts with adjacent crustal blocks would be reduced with consequent deterioration of associated magnetic anomaly patterns. It has been suggested (Lowrie, 1973) that this might be an explanation for some types of magnetic quiet zones. Site 282 was drilled into a quiet zone, and the basalt from this site afforded a direct test of the VRM hypothesis.

Basalt specimens from each of the four sites were left in a constant field of 1.0 oe for almost 3 months. The remanence was repeatedly measured at intervals spaced approximately logarithmically, and a plot of the growing VRM was obtained (Figure 4). The slope of the best-fitting line gives an estimate of the rate at which VRM is acquired and is referred to as the magnetic viscosity coefficient. The ratio of the VRM after 1000 hr ($VRM_{1000}$) to the NRM intensity gives an indication of the relative importance of VRM in the specimen. A

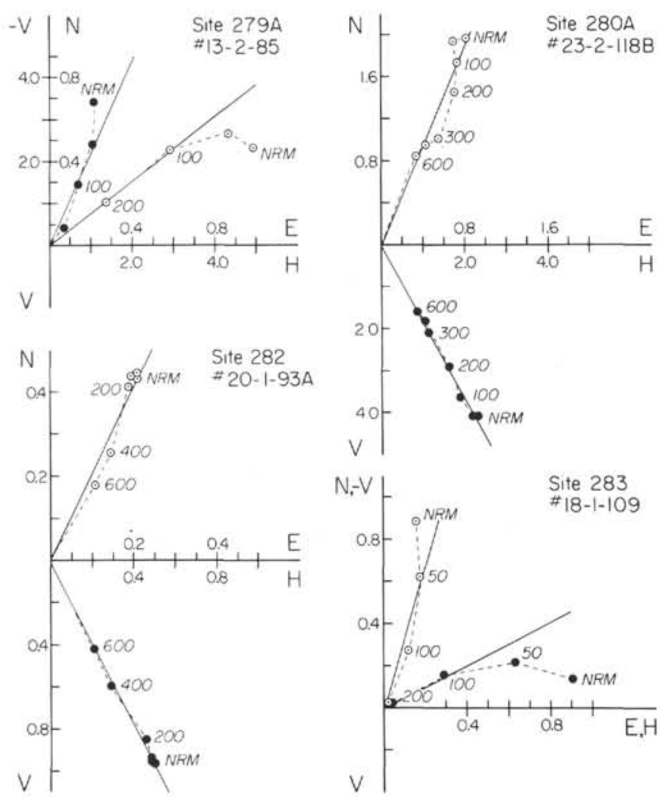


Figure 2. *Vector diagrams illustrating the stability against alternating-field demagnetization of representative specimens from each site. The horizontal (H) and vertical (V) components of magnetization define the inclination (solid circles), while the north (N) and east (E) components define the declination (open circles), which is arbitrary. All intensities are in units of $10^{-3}$G, except for Site 280 (Hole 280A) where the units are $10^{-6}$G. Numbers on each curve represent the peak field at each stage of demagnetization.*

small ratio, as is found in basalt from stable areas where good magnetic anomaly patterns exist, indicates that VRM is not a serious secondary magnetization. In some basalt, particularly that with a low MDF value, the VRM can exceed the NRM after only a few weeks of growth (Lowrie, in press).

The results showed that: (1) in some of the basalt, particularly from Sites 279, 280, and 283, a VRM, equivalent to very high percentages of the NRM (and in one case almost double the NRM), could be acquired. In Site 282 basalt, however, only a relatively small percentage of the NRM was developed as VRM in the laboratory experiments.

This result argues against the hypothesis of VRM as an explanation of the quiet zone in which Site 282 was drilled. It does not, however, exclude VRM as an explanation of some other quiet zones for which there may be several valid mechanisms. For example, between anomaly 32 and the Keithley sequence, the quiet zone is apparently due to a long period of normal geomagnetic polarity during the Cretaceous.

## CONCLUSIONS

The remanent magnetic properties of Leg 29 oceanic basalt differed in several ways from those of typical oceanic tholeiitic crust. At Site 280 exceptionally low intensities were found, perhaps resulting from alteration or the fact that the basalt was intrusive. No attempt was made to reconstruct local plate motions that would explain the remanent inclinations of the basalt. These did not differ much from the axial dipole values and suggest that the crust was formed at a paleomagnetic latitude similar to its present one, although this may not be a valid conclusion.

The magnetic mineralogy was identified from thermomagnetic analysis to be either titanomagnetite or titanomaghemite, and the irreversible thermomagnetic curves indicated that the basalt was in deuteric oxidation class I. Viscous remanent magnetization studies showed that VRM was readily acquired in the Site 279, 280, and 283 specimens, but was less intense at Site 282. The magnetic properties of the Site 282 quiet zone basalt were in many respects very similar to those found in oceanic basalts from regions with good associated magnetic anomalies. This argues against the origin of this quiet zone being due to VRM of the oceanic crust.

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TABLE 3
Geometric Mean Values of Natural Remanent Magnetization (NRM) Intensity, Susceptibility ($k$), Königsberger Ratio ($Q_n$), and Median Destructive Field (MDF) For Each Site

| NRM ($10^{-4}$G) | $k$ ($10^{-4}$G/oe) | $Q_n$ | MDF (oe) | Magnetization Inclination Observed | 1965.0 IRF | ADF |
|---|---|---|---|---|---|---|
| **Hole 279A** | | | | | | |
| 26.6 | 14.8 | 2.79 | 84 | -66.0 | -75.9 | -68.2 |
| **Hole 280A** | | | | | | |
| 0.163 | 1.17 | 0.209 | 257 | 67.8 | -76.8 | -66.4 |
| **Site 282** | | | | | | |
| 10.5 | 1.46 | 11.4 | 263 | 65.0 | -72.1 | -61.1 |
| **Site 283** | | | | | | |
| 6.93 | 21.3 | 0.519 | 50 | -34.7 | -72.0 | -62.5 |

Note: The arithmetic mean values of the observed stable inclinations of remanent magnetization are shown for comparison with the inclinations of the 1965.0 International Reference Field (IRF) and the present axial dipole field (ADF).

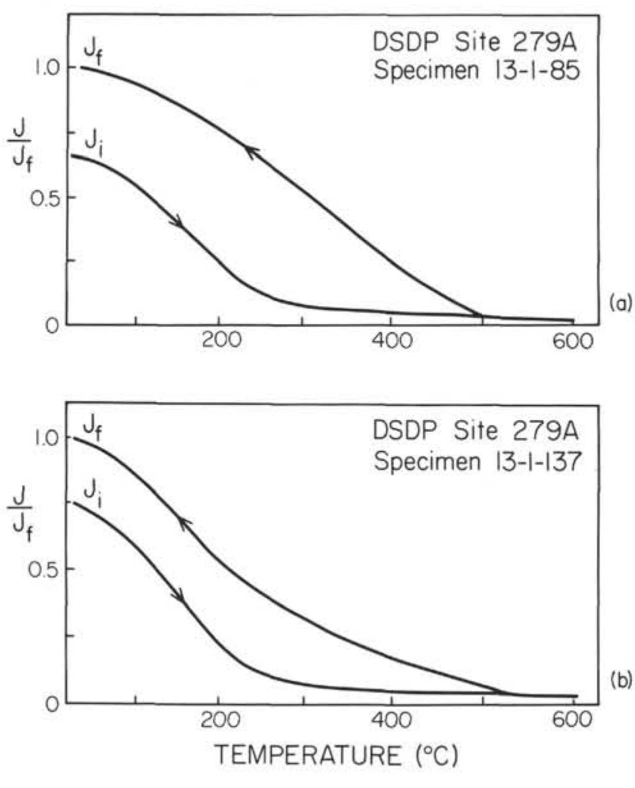


Figure 3. *Typical computer-processed thermomagnetic curve for Leg 29 oceanic basalt.* $J_i$ *and* $J_f$ *are the room temperature strong field magnetizations of the initial and final magnetic minerals, respectively. Arrows on the curve indicate the sense of the magnetization change.*

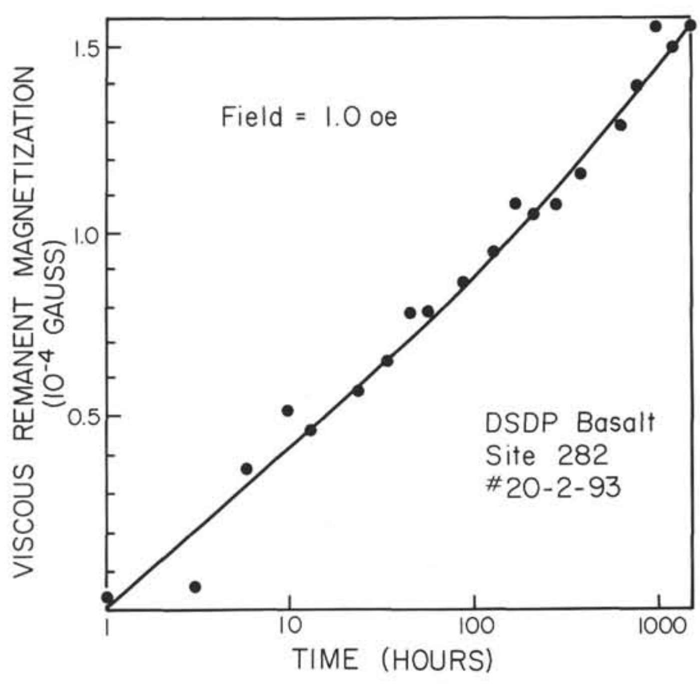


Figure 4. *Acquisition of VRM in a basalt specimen from Site 282. The magnetic viscosity coefficient, S, is the slope of the line.*

TABLE 4
Thermomagnetic Data Obtained in Fields of 2000-3800 oe
in Specimens From Each Site

| Specimen | Curie Temperatures (°C) $\theta_1$ | $\theta_2$ | Magnetization Ratios ($J_i/J_f$) Observed | Expected |
|---|---|---|---|---|
| **Hole 279A** | | | | |
| 13-1-85(a) | 256 | 505 | 0.646 | 0.426 |
| 13-1-85(b) | 259 | 521 | 0.590 | 0.431 |
| 13-1-137 | 234 | 535 | 0.765 | 0.388 |
| **Hole 280** | | | | |
| 23-2-22 | 413 | 550 | 0.868 | 0.695 |
| 23-2-83 | 410 | 545 | 0.886 | 0.690 |
| **Site 282** | | | | |
| 20-1-92 | 310 | 561 | 0.161 | 0.518 |
| 20-3-54 | 308 | 534 | 0.840 | 0.515 |
| **Site 283** | | | | |
| 18-1-96 | 392 | 508 | 0.976 | 0.659 |

Note: $\theta_1$ is the Curie temperature of the initial magnetic mineral, $\theta_2$ is that obtained from the cooling half of each thermomagnetic curve, and $J_i/J_f$ is the ratio of the initial magnetization ($J_i$) to the final magnetization ($J_f$) at room temperature.

TABLE 5
Viscous Remanent Magnetization (VRM) in a 1-oe Field
in Selected Specimens From Each Site

| Specimen | NRM ($10^{-4}$G) | $k$ ($10^{-4}$ G/oe) | MDF (oe) | $S$ ($10^{-4}$G) | $VRM_{1000}$ ($10^{-4}$G) | $\left\{\frac{VRM_{1000}}{NRM}\right\}$ (%) |
|---|---|---|---|---|---|---|
| **Hole 279A** | | | | | | |
| 13-1-85 | 20.0 | 14.6 | 152 | 6.10 | 16.9 | 84 |
| 13-1-137 | 22.9 | 14.7 | 86 | 4.95 | 17.3 | 76 |
| **Hole 280A** | | | | | | |
| 23-2-22 | 7.72 | 9.65 | 90 | 1.79 | 6.75 | 87 |
| **Site 282** | | | | | | |
| 18-2-80 | 4.52 | 1.68 | 191 | 0.15 | 0.48 | 11 |
| 18-3-144 | 13.1 | 2.12 | 190 | 0.72 | 1.91 | 15 |
| 19-1-142 | 21.6 | 1.64 | 351 | 0.54 | 1.15 | 5.3 |
| 20-2-93 | 15.7 | 2.00 | 274 | 0.53 | 1.47 | 9.4 |
| **Site 283** | | | | | | |
| 18-1-96 | 5.26 | 20.2 | 30 | 3.78 | 10.0 | 191 |
| 18-1-108 | 9.13 | 22.4 | 82 | 2.21 | 7.65 | 84 |

Note: NRM, $k$, and MDF are the original remanent properties of the specimens. $S$ is the magnetic viscosity coefficient and $VRM_{1000}$ is the intensity of VRM acquired in 1000 hr.