Anomalous Remanent Magnetization of Basalt

GEOLOGICAL SURVEY BULLETIN 1083-E

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By ALLAN COX

EXPERIMENTAL AND THEORETICAL GEOPHYSICS

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A study of causes of anomalous magnetization with analysis of field and experimental data to show that lightning probably produced anomalous magnetization in basalts in Idaho

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ABSTRACT

Anomalous remanent magnetization in igneous rocks, defined as remanent magnetization obliquely oriented with respect to the field in which the rocks cooled, is often characterized by varying intensity and direction throughout a magnetized body. Cells of anomalous magnetization are defined as regions within which there exists a correlation between the remanent magnetization observed at any two points. For basalts of Pliocene and Pleistocene age from Idaho, cells of anomalous magnetization commonly have dimensions on the order of 25 feet.

A detailed study of one occurence of anomalous magnetization indicates that the magnetization is isothermal and that it is due to the intense magnetic field accompanying a lightning discharge with a peak current of 22,000 amperes. Lightning is probably the most common cause of anomalous magnetization in the lava flows of Idaho. Most cells of anomalous magnetization due to lightning probably have dimensions on the order of 20–100 feet. Viscous magnetization causes a much smaller anomalous magnetization in these rocks.

Thermoremanent magnetization is relatively stable, but both types of anomalous magnetization can be selectively destroyed using alternating magnetic fields.

INTRODUCTION

This research was aided by grants from the American Petroleum Institute and the Institute of Geophysics of the University of California and was directed by John Verhoogen and members of the staff of the University of California. Most of the material used here is from a thesis submitted in partial fulfillment of the requirements of the Ph. D. degree at the University of California, Berkeley. Fieldwork was done in collaboration with Harold Malde, U.S. Geological Survey, and James Berkland assisted in the field. To all the individuals and institutions here named, grateful acknowledgment is made.

The natural remanent magnetization of a rock may consist of several components corresponding to different events occurring during the rock's history, and the significance of the magnetization for applications such as reconstruction of the earth's magnetic field in the past can be fully assessed only after appropriate analysis. This paper describes the laboratory analysis of three components of natural remanent magnetization found in a lava flow.

THERMOREMANENT MAGNETIZATION

Most rocks containing randomly oriented ferromagnetic particles acquire, when they are cooled from their Curie temperatures in the laboratory, a TRM (thermoremanent magnetization) parallel to the magnetic field in which they cooled. Of the hundreds of rock units studied in various laboratories, 10 at the most have been described which acquire a thermoremanent magnetization exactly opposed to the applied field. These include several volcanic rocks (Kawai and others, 1956; Uyeda, 1958) and a single metamorphic rock sample (Balsley and Buddington, 1954). A TRM obliquely oriented with respect to the field in which igneous rocks have cooled in the laboratory has never been reported.

Theoretically, a TRM parallel to the applied field is generally expected for rocks containing randomly oriented ferromagnetic particles (Néel, 1955). Also, theoretically, several special mechanisms can give rise to a remanent magnetization exactly opposed to the magnetic fields in which rocks have cooled (Néel, 1955; Uyeda, 1958). However, there is no theoretical basis for anticipating a remanent magnetization obliquely oriented with respect to the magnetic field in which igneous rocks have cooled unless the magnetic mineral grains were not randomly oriented or unless the remanent magnetization was not entirely thermoremanent.

Much of the naturally occurring remanent magnetization in igneous rocks is consistent with the above laboratory observations and theoretical conclusions about TRM. The earth's field changes slowly enough so that it is essentially constant in direction during the time of cooling of many small igneous bodies such as lava flows, thin dikes, and sills. Frequently, samples collected throughout such bodies have a uniform direction of magnetization (some excellent examples are shown in Graham, 1953, and in Graham and Hales, 1957). Moreover the observed direction of magnetization of a number of historic lava flows is parallel to the known direction of the earth's magnetic field at the time the flow cooled (Chevallier, 1925). No remanent magnetization of historic lava flows has been reported that is not parallel with the observed field.

ANOMALOUS REMANENT MAGNETIZATION

DEFINITION AND CHARACTERISTICS

In contrast to these experiments and field observations, many groups of samples from igneous bodies that have cooled rapidly have remanent magnetization widely scattered in direction (Graham, 1953; Muehlberger and Baldwin, 1958). Remanent magnetization that is not parallel to the field in which rocks have cooled is herein termed "anomalous magnetization."

Within a cooling igneous body the fields due to the magnetized parts of the body are usually much less intense than the earth's field, and the total field in most cases does not change in direction more than several degrees throughout the body. In terms of the above definition, widely scattered directions of magnetization are examples of anomalous magnetization, and in view of the evidence reviewed in the first section, it is very improbable that the anomalous magnetization is thermoremanent.

POSSIBLE CAUSES

MECHANICAL EFFECTS AND CRYSTALLIZATION MAGNETIZATION

Bruckshaw and Robertson (1949) have suggested that ferromagnetic mineral grains may first acquire a TRM parallel to the earth's magnetic field and then be rotated by fluid motions in the partially molten magma at temperatures lower than the Curie temperatures of the minerals. Anomalous magnetization caused in this way should have a rather uniform intensity and resemble TRM in all magnetic properties except in not being parallel to the original applied field.

Change in magnetization due to the effect of stress has been suggested as another possible cause of anomalous magnetization (Graham, 1956; Graham and others, 1957, 1959). Little is known about the magnetic properties of anomalous magnetization due to such magnetostrictive effects. Petrova (1959) has suggested that rocks may acquire an anomalous magnetization in seismically active regions presumably because of elastic waves, and that this magnetization would have properties approaching those of ideal or anhysteretic magnetization. Crystallization (or chemical) magnetization, acquired during the growth of ferromagnetic minerals at low temperatures in the earth's magnetic field, has been suggested as another possible cause of anomalous magnetization (Doell, 1956; Cox, 1957). Crystallization magnetization produced in the laboratory has many of the magnetic characteristics of TRM (Nagata and Kobayashi, 1958; Haigh, 1958).

ISOTHERMAL REMANENT MAGNETIZATION

Rocks acquire an IRM (isothermal remanent magnetization) when they are subjected, at constant temperature, to strong magnetic fields of short duration. IRM has magnetic properties vastly different from those of TRM or crystallization magnetization. It is destroyed or its direction changed in a field stronger than that which originally caused the IRM, whereas TRM and crystallization magnetization developed in weak magnetic fields are only slightly affected by comparatively strong fields. Two possible sources of magnetic fields which might cause anomalous IRM in rocks have been suggested, one being the intense electric current in lightning discharges (Nagata, 1953; Thellier and Rimbert, 1954, 1955; Schmucker, 1957; Matsuzaki and others, 1954), and the other being possible electric currents arising during the cooling of magmas (Hawes, 1952).

VISCOUS MAGNETIZATION

A rock placed for a short period of time in a magnetic field as weak as the earth's will acquire little or no IRM, but over a long period of time it will acquire a magnetization that is proportional to the logarithm of the time and that increases with increasing values of the weak field. This magnetization is termed viscous and has been suggested as a possible cause of anomalous magnetization (Thellier and Rimbert, 1954; Brynjólfsson, 1957; Cox, 1957; Creer, 1958; As and Zijderveld, 1958).

SAMPLING AND MEASUREMENT

The anomalous magnetization described in this report was observed during a systematic study of the remanent magnetization of basalts of Pliocene and Pleistocene age in the Snake River Plain in Idaho. Oriented samples were obtained by drilling 1-inch-diameter cores with a portable water-cooled diamond drill. Cores were up to 5 inches in length and their orientation was measured while still attached to the basalt body; orientation errors rarely exceeded 3°. The cores were cut into specimens 1 inch long, and the remanent magnetization of these specimens was measured with the motor-driven spinner magnetometer at the University of California. Tests of internal consistency of results as well as comparisons with measurements made at other institutions indicate that measurements of direction of magnetization are accurate within 1½°, and of intensity within 3 percent.

FIELD OBSERVATIONS

The following generalizations emerged while collecting and measuring over 400 oriented samples from this region.

1. The amount of anomalous magnetization, as shown by the amount of scatter in direction of magnetization in a number of samples from the same volcanic unit, is not a property of individual formations or lava flows, but rather of individual outcrops.
2. Fresh outcrops, such as those recently exposed in roadcuts or quarries, usually show the least amount of scatter in the direction of magnetization.
3. Many specimens with anomalous direction of magnetization have an abnormally high intensity of magnetization.
4. Many anomalous zones are so strongly magnetized that they can be easily located in the field with simple detecting equipment such as a compass.
5. The dimensions of cells of anomalous magnetization are estimated to be on the order of several tens of feet on the basis of the following observations. If one of two specimens collected several inches apart is anomalously magnetized, the other almost invariably is also; their direction and intensity of magnetization are usually about the same. For specimens collected several feet apart, if one is anomalously magnetized the other usually is also, although both direction and intensity of magnetization may vary considerably. However, for two samples collected several tens of feet apart, one sample is very commonly anomalously magnetized, and one is not. A sampling interval of 25 to 50 feet generally insures that there will be no correlation between the magnetization of adjacent samples—that is, the samples will not be from the same cell of anomalous magnetization.

DEMAGNETIZATION

APPLICATIONS OF PARTIAL DEMAGNETIZATION

Partial demagnetization is of interest in the study of rock magnetism because of two important applications. Since it is the mean direction of remanent magnetization of a body which is often of greatest interest in paleomagnetic studies and in interpreting aeromagnetic maps, techniques which reduce the amount of scatter in direction of magnetization without altering the mean direction of the TRM are of considerable practical value. Such techniques

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often make it possible to determine the mean direction of magnetization with high precision with comparatively few samples. Of much greater theoretical interest is the application of partial demagnetization for analyzing the different components of remanent magnetization that may be present in a rock.

TECHNIQUES

THERMAL DEMAGNETIZATION

Doell (1956) showed that the direction of magnetization of sediments becomes less scattered when the sediments are heated to 100° C and cooled in field-free space. A similar procedure has proved useful with lava flows (Cox, 1957). As samples from an outcrop or flow are successively heated to higher temperatures and then cooled in field-free space, the scatter in direction of magnetization usually decreases until an optimum temperature is reached, beyond which the scatter increases again. This optimum temperature, which usually occurs from a few tens to a few hundreds of degrees below the Curie temperature of the magnetic constituents of the rock, depends largely on experimental conditions, and especially on the extent to which a field-free region has been achieved.

ALTERNATING-FIELD DEMAGNETIZATION

REVIEW OF TECHNIQUES

Thermal demagnetization cannot be used on all rocks because chemical and phase changes in the ferromagnetic constituents frequently occur at comparatively low temperatures, destroying the TRM along with the anomalous magnetization. Demagnetization in an alternating magnetic field does not have this disadvantage, and it often strikingly reduces scatter in direction of magnetization (Brynjolfsson, 1957; Hood [1]; Creer, 1958; As and Zijderveld, 1958). A common technique is to increase the current in a coil surrounding the sample until the alternating field reaches a peak value of several hundred oersteds, and then slowly decrease the field to zero. The orientation of the sample with respect to the axis of the coil is then changed and the process repeated.

Several precautions are necessary. If even a weak, constant magnetic field is present, the sample will acquire a stable anhysteretic magnetization parallel to the constant field as a result of the demagnetization process (Thellier and Rimbert, 1954). Another difficulty

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[1] Hood, P. J., 1958, Paleomagnetic studies of some Precambrian rocks in Ontario: Unpublished Ph. D. thesis, Univ. of Toronto, Canada, 200 p.

is that if the alternating current passing through the coil has an asymmetrical wave form, as it frequently does, the sample will acquire a remanent magnetization directed along the axis of the coil. One solution to this problem is to filter out the even harmonics of the line frequency (As and Zijderveld, 1958). An alternative solution is to spin the sample in the magnetic field; the field then appears symmetrical, though not generally sinusoidal, with respect to the reference axes fixed in the sample. An advantage of this second approach is that it is not necessary to conduct the experiment in field-free space. Brynjólfsson (1957) used this general method, rotating his specimens in an alternating field about two perpendicular axes, one of which was parallel to the direction of magnetization.

RANDOM ORIENTATION

The demagnetization technique used in the present investigation was to slowly decrease an alternating magnetic field ($\tilde{H}$) as the specimen was given an orientation that changed by simultaneous rotation about two axes both perpendicular to the axis of the alternating field. (This procedure was first used by J. R. Balsley, of the Geological Survey. The apparatus used in the present investigation was designed in conjunction with R. R. Doell, and details of its construction will appear in another report.) This technique has the advantage that the peak demagnetizing field effectively passes through the specimen in all directions, whereas, if the specimen is demagnetized along 3 orthogonal axes, some directions in the specimen are 55° removed from the direction of the applied field and the field intensity is only 57 percent of the peak applied field. If the specimen is spun about three orthogonal axes, there are directions along which the maximum field component is only 82 percent of the applied field. This is important because an alternating field demagnetizes most effectively when it is parallel to the remanent magnetization (Thellier and Rimbert, 1955).

EXAMPLES

Figures 45 through 48 show the effect of alternating-field demagnetization on sets of samples with varying amounts of scatter in their initial direction of magnetization. (Schmidt equal-area projections were used throughout this study.) The average spacing between samples is 25 feet for lava flow CC 1 and 20 feet for flow KH 1.

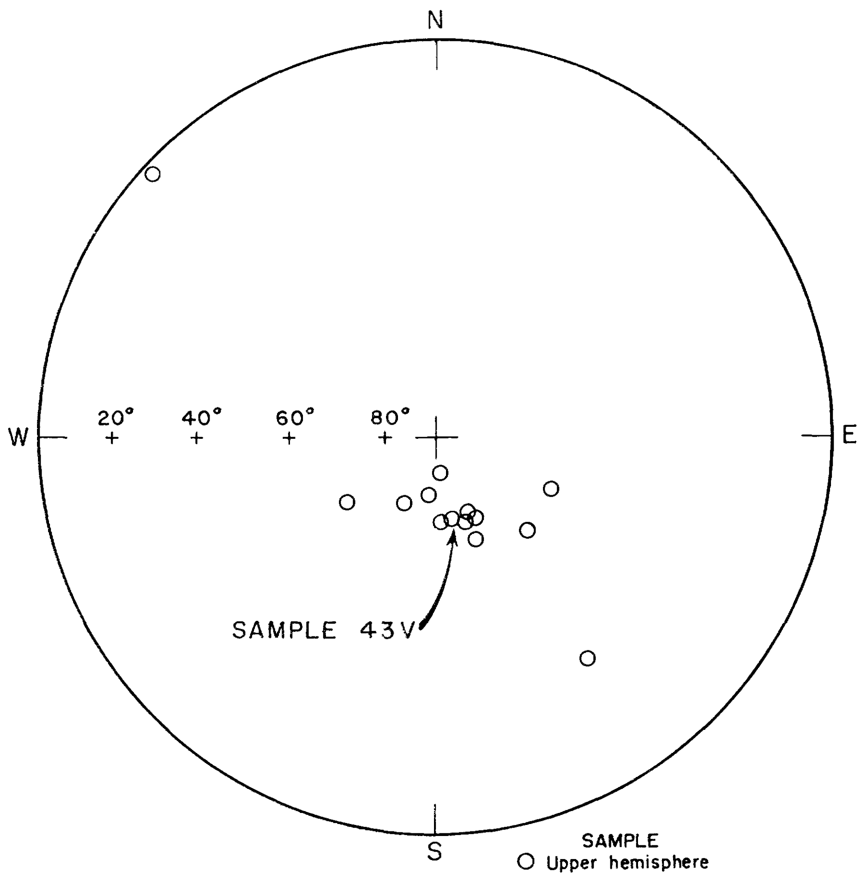

FIGURE 45.—Original direction of magnetization of 14 oriented samples from basalt flow CC 1.

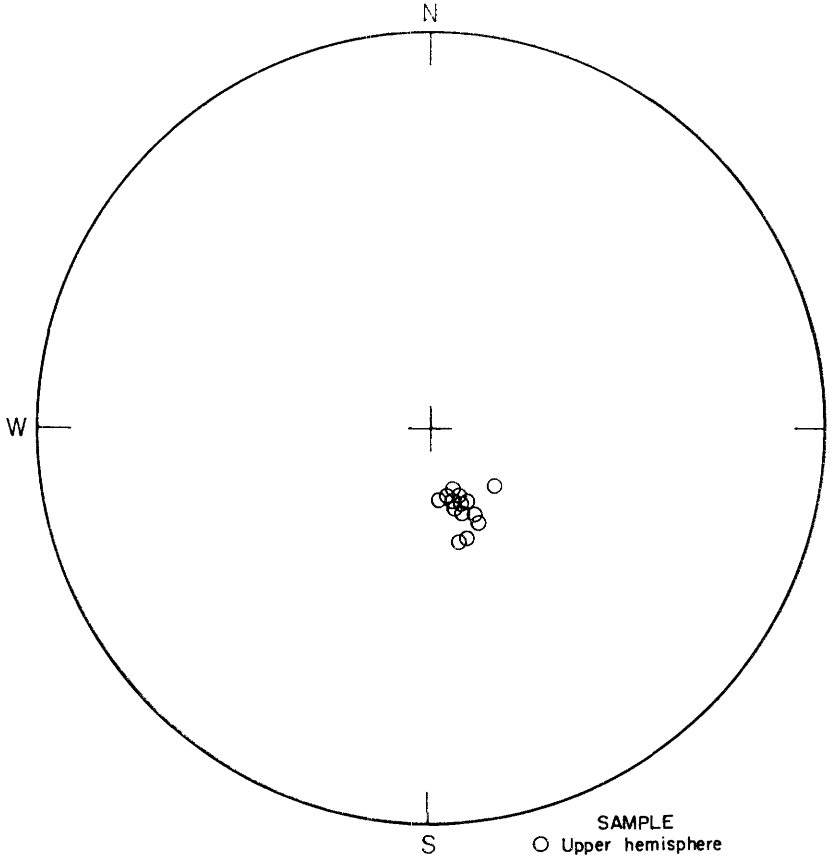

FIGURE 46.—Direction of magnetization of 14 samples from flow CC 1 after partial demagnetization in a 200-oersted-peak alternating magnetic field.

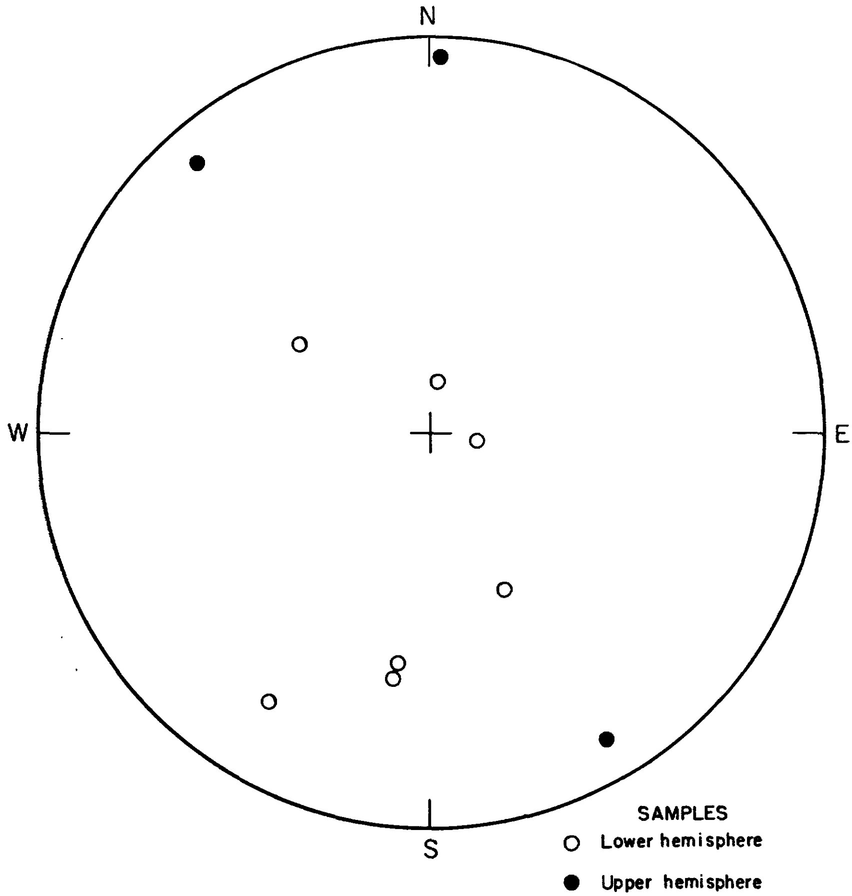

FIGURE 47.—Original direction of magnetization of 10 oriented samples from basalt flow KH 1.

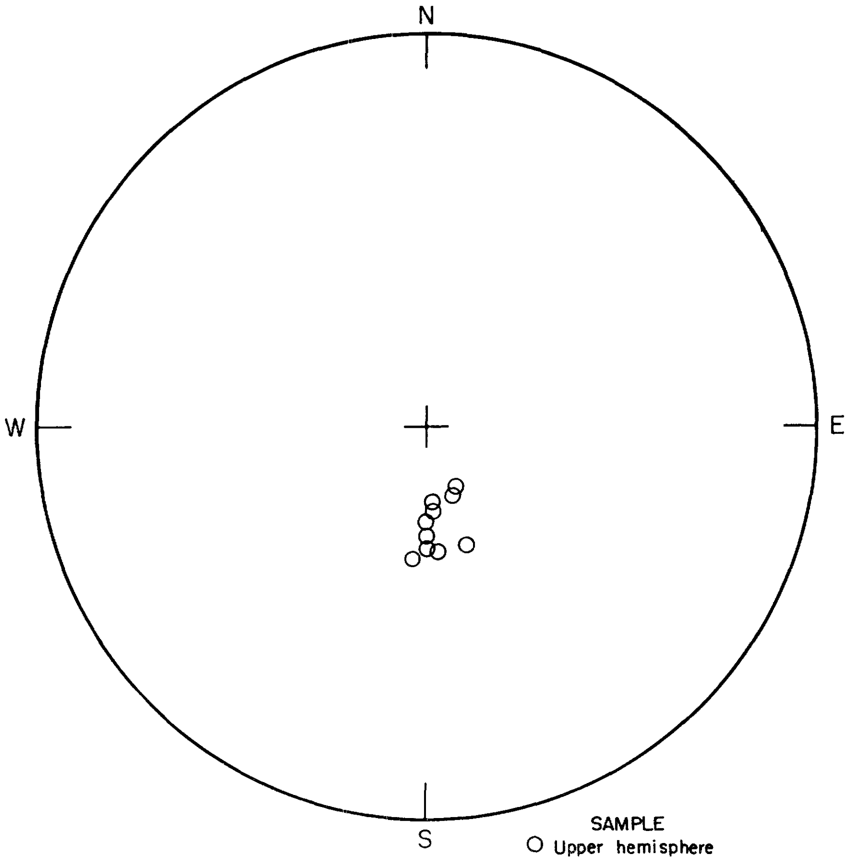

FIGURE 48.—Direction of magnetization of the 10 samples from flow KH 1 after partial demagnetization in a 300-oersted-peak alternating field.

The effect of demagnetization on the intensity of magnetization of two specimens from the same lava flow is shown in figure 49. For each point on the curves, the specimen was placed in an alternating magnetic field (with peak intensity as indicated by the abscissa) and demagnetized. The intensity of the remanent magnetization remaining after the alternating field had been reduced to zero is plotted as the ordinate. Sample 43V is from a part of the flow which does not seem to be anomalously magnetized; its direction of magnetization was originally along the mean direction of magnetization of the flow (fig. 45), and its intensity of magnetization is about average. Sample 54C is from a highly anomalous zone in the same flow; this zone is adjacent to the part of the flow from which the samples in figures 45 and 46 were collected.

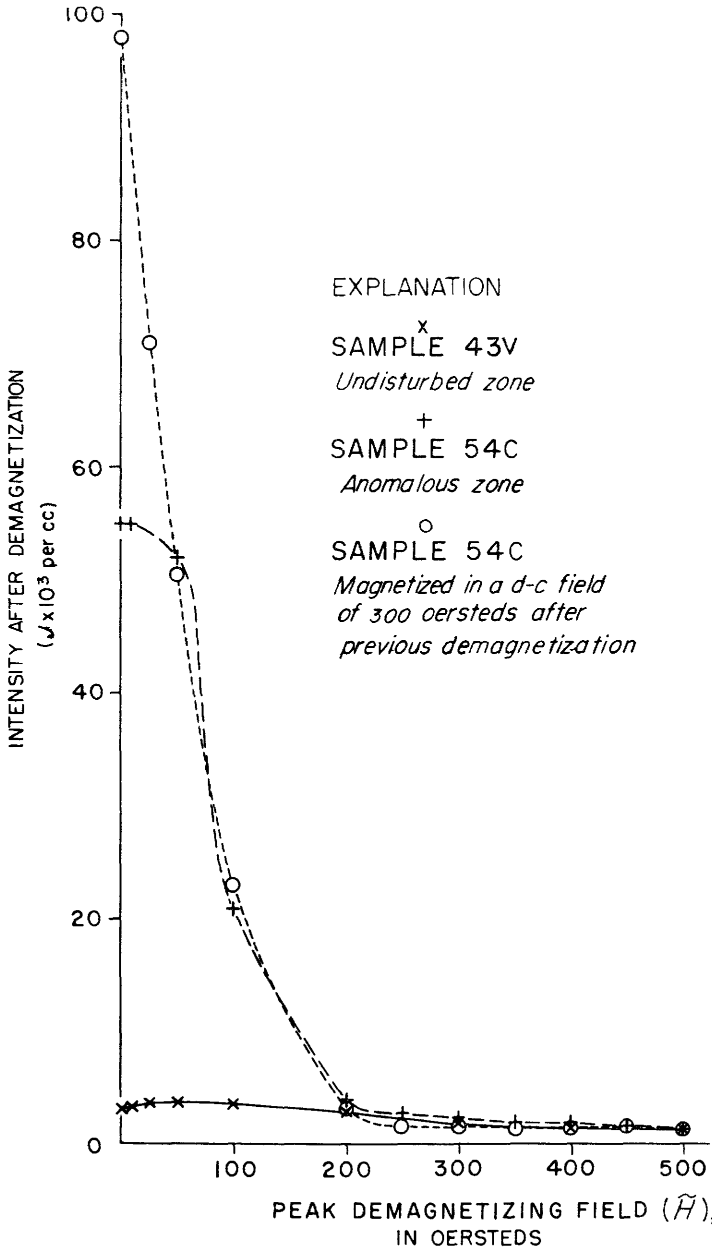

FIGURE 49.—Demagnetization curves showing intensity of remanent magnetization versus peak demagnetizing field for 2 samples from flow CC 1. (Sample 54C is not one of the samples shown in figures 45 and 46.)

The demagnetization characteristics exhibited by these specimens are rather typical. The remanent magnetization of the specimen from the anomalous zone is large, but it is rather easily destroyed in an alternating field. The remanent magnetization of the sample from the undisturbed zone is comparatively small, but it is very stable in an alternating field. For comparative purposes the sample from the disturbed zone was, after demagnetization, remagnetized in a d-c field of 300 oersteds and again demagnetized.

The direction of magnetization of the sample from the anomalously magnetized zone after each step of the demagnetization process is plotted in figure 50. Comparison of figures 49 and 50 reveals that the direction of magnetization of the sample from the anomalous zone approaches the mean direction of magnetization of the flow as the anomalous magnetization becomes relatively small.

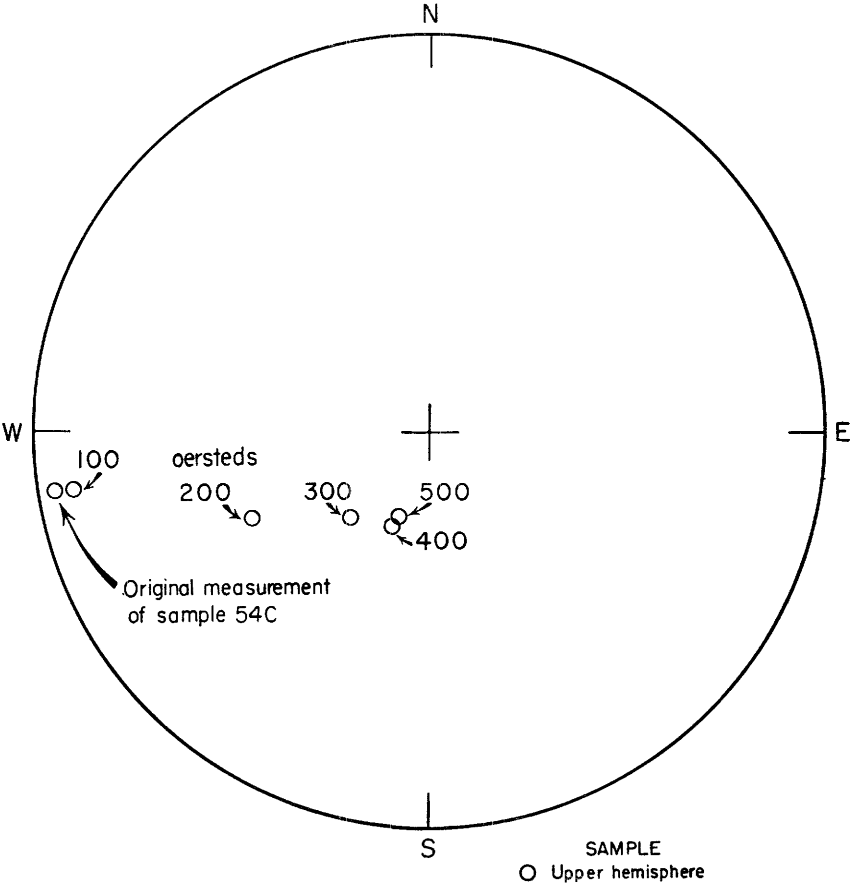

FIGURE 50.—Direction of magnetization of sample 54C after demagnetization in alternating magnetic fields with various peak intensities.

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The above experimental results point to the existence of remanent magnetization of two types in rocks from the anomalously magnetized zone: an anomalous magnetization that is comparatively easily removed in an alternating field, and a coexisting stable component of magnetization having the same direction and about the same intensity, after demagnetization, as that found in parts of the flow which are not anomalously magnetized.

OPTIMUM VALUE OF THE DEMAGNETIZING FIELD

Generally when several specimens from the same outcrop are demagnetized in successively stronger fields, the scatter in their direction of magnetization progressively decreases. However, beyond some optimum value of the demagnetizing field, ranging between 200 and 500 oersteds in the present study, the directions of magnetization begin to diverge again. Ideal, complete demagnetization would be achieved if each ferromagnetic domain were given a random orientation. The net residual magnetization J of the sample would then be randomly oriented and would have an intensity statistically determined by the number of domains, their volume, and the saturation magnetization of the ferromagnetic mineral. An approximate calculation indicates that the J for basalt containing 2 percent magnetite would be less than 10^{-6} emu per cc (electromotive units per cubic centimeter)—a much smaller quantity than that indicated in the present experiments. The probable cause of the divergence of directions of magnetization on increasing the peak demagnetizing field beyond the optimum value is that the demagnetization process was imperfect. The current in the demagnetizing coils decreased from its peak value to zero in about 200 steps in the apparatus used. Although some smoothing was achieved by placing a bank of capacitors in parallel with the coils to form a resonant circuit, the irregularities in decreasing the peak field current are probably the principle cause of the random component J remaining after demagnetization. As the peak value of the demagnetizing field is increased an amount $\Delta\tilde{H}$ in successive experiments, J also increases an amount ΔJ. The optimum value of the demagnetizing field is reached when the value of ΔJ, corresponding to an increase $\Delta\tilde{H}$ in the demagnetizing field, becomes larger than the associated reduction in the anomalous component of magnetization. It is desirable, therefore, that the remanent magnetization imparted to the rock as a result of the demagnetization process be as small as possible, since it limits the range of applicability and usefulness of the process.

LABORATORY ANALYSIS OF REMANENT MAGNETIZATION

The nature of the remanent magnetization of a rock sample is best regarded as an unknown to be found by laboratory analysis. Demagnetization experiments of the type described above are especially useful in determining the origin of the various types of remanent magnetization. In interpreting the results of these demagnetization experiments, the usual ferromagnetic hysteresis curves and associated parameters, such as coercive force, are of limited usefulness. On demagnetization, rocks behave as if they consisted of many constituents, each with its own hysteresis cycle. All these constituents may not be separate mineralogical phases but they may correspond, for example, to magnetization associated with different barriers to domain wall movement. If the amount of each constituent and the parameters of its hysteresis cycle were known, the overall hysteresis cycle for the rock could be derived. However, it is not possible to solve the inverse problem of determining the distribution of constituents with different coercive forces from the overall hysteresis cycle for the rock. Moreover, even if the hysteresis cycle for each of the magnetic constituents were known, it would still be necessary, in order to specify the magnetic state of the rock, to specify which constituents were systematically magnetized in preferred directions, and which were randomly magnetized. Such information is very useful in analyzing the origin of the remanent magnetization of rocks, since the different processes causing remanent magnetization impart preferred orientation to constituents with different ranges of coercive force.

DEMAGNETIZATION SPECTRUM

DEFINITION

An experimentally determinable function which combines a description of the "coercive force spectrum" (Graham, 1953) with a description of the preferred orientation of the various constituents of magnetization is as follows. We take (Brynjolfsson, 1957) the negative derivative of the alternating-field demagnetization function with respect to the demagnetizing field; that is, $-\mathrm{d}J/\mathrm{d}\tilde{H}$ of the curves shown in figure 49. The area under the demagnetization spectrum curve between the two values of the demagnetizing field, H_1 and H_2, corresponds to the constituent of the original magnetization that was stable with respect to a demagnetizing field H_1, but was destroyed (made random) by a demagnetizing field H_2. This constituent of the magnetization is here designated $J_{\tilde{H}_2}^{\tilde{H}_1}$, and this representation of the magnetic state of the rock is termed the "demagnetization spectrum."

INTERPRETATION

Some examples of demagnetization spectra are shown in figure 51, where the curves correspond to those in figure 49.

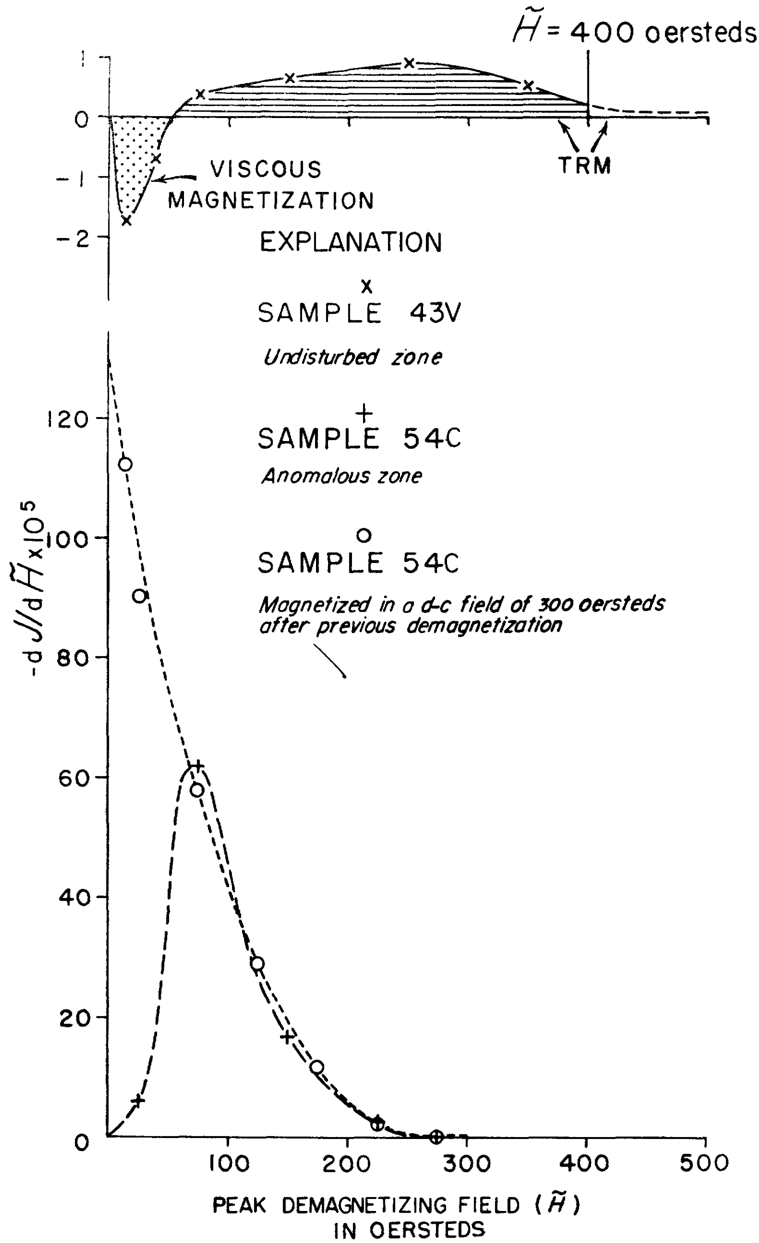

FIGURE 51.—Demagnetization spectra of samples shown in figure 49.

These curves are typical of samples from anomalously magnetized zones and undisturbed regions. By comparison with laboratory experiments by other workers on components of remanent magnetization of known origin, it is possible to recognize the following three components of magnetization in these rocks.

THERMOREMANENT MAGNETIZATION

Sample 43V from the undisturbed zone has a remanent magnetization which is approximately reversed with respect to the present earth's field and which is very stable with respect to demagnetizing fields. The constituent $\tilde{J}^{400}_{\infty}$ (unshaded area under the curve in fig. 51) contributes 40 percent of the remanent magnetization (total area under the curve in fig. 51) of sample 43V. Thus, the demagnetization spectrum is seen to approach zero very slowly in large demagnetizing fields.

TRM as the origin of this stable component of magnetization is suggested by experiments by other workers. Many investigators have found that a TRM produced in the laboratory is remarkably stable in large demagnetizing fields (Nagata, 1953; Thellier and Rimbert, 1955). Rimbert (1956a) has found that an appreciable TRM remains after demagnetization in a field of 900 oersteds, with little change between 500 and 900 oersteds. Crystallization magnetization is also very stable (Nagata and Kobayashi, 1958) and cannot, on the basis of these demagnetization experiments, be eliminated as a possible source of the stable magnetization. However, a much more probable source is a TRM acquired when the lava flow cooled.

VISCOUS MAGNETIZATION

In addition to this stable TRM with a direction opposite to the present direction of the earth's field, sample 43V has a comparatively unstable component of magnetization parallel to the present field. The existence of this magnetization is inferred from the observation that on demagnetization up to 50 oersteds, the remanent magnetization increased in intensity while remaining constant in direction. This component of magnetization may be described approximately as the constituent $\tilde{J}^{0}_{50}$ (dotted area in fig. 51). The boundary between the two components of magnetization is probably not as sharp as this representation suggests. Experiments by other workers indicate that part of the TRM acquired in weak d-c fields is removed in alternating fields of 50 oersteds (Nagata and others, 1954), and a small part of the unstable component of magnetization is probably also present after demagnetization in fields several times larger than 50 oersteds. Fifty oersteds is simply the point at which the slopes of the demagnetization curves of the two components with opposing directions of magnetization are equal.

A similar unstable component has been observed in samples of basalt from Iceland and has been attributed to viscous magnetization. The close similarity of the demagnetization curves of sample 43V and the Icelandic basalts suggests that both unstable components have the same origin. Moreover, comparison with the demagnetization characteristics of viscous magnetization produced in the laboratory (Rimbert, 1956b, 1959) also suggests that this magnetization is viscous. Rimbert viscously magnetized samples of basalt from the the Auvergne by placing them in constant magnetic fields $\overline{H}$ for varying lengths of time t. The alternating magnetic field $\tilde{H}_d$ necessary to completely destroy the viscous magnetization was found to vary logarithmically with $\overline{H}$ and t, as shown by the experimentally derived formula

$$\tilde{H}_d = -100 + 75 \log \overline{H} + 10(2 + \log \overline{H}) \log t$$

where t is in seconds, $\overline{H}$ in oersteds, and $\tilde{H}_d$ in effective oersteds (Rimbert, 1959). For comparison with the experiments on sample 43V, Rimbert's results may be extrapolated to estimate the alternating field that would be necessary to completely demagnetize the Auvergne basalts if they were placed in a constant field of 0.57 oersted, the present field intensity in Idaho, for ½ million years, the approximate age of sample 43V. By substituting these values in Rimbert's formula, $\tilde{H}_d = 113$ effective oersteds. The corresponding alternating field intensity at which the unstable component of sample 43V was completely removed cannot be determined exactly because the TRM was also being removed, but figures 49 and 51 suggest a value between 75 and 200 peak oersteds, or 53 and 141 effective oersteds. This order of magnitude agreement with the experiments of Rimbert on different basalts, together with the fact that the unstable magnetization is parallel to the present field, indicate that the unstable component is probably of viscous origin.

ISOTHERMAL REMANENT MAGNETIZATION

The magnetization of the sample (54C) from the disturbed zone is much larger, and most of it resides in constituents which are easily demagnetized. Except for the extreme lower part of the demagnetization spectrum (J_{75}^{0}), the original demagnetization spectrum of the sample from the anomalous zone resembles the spectrum of the IRM acquired by sample 54C in a d-c magnetic field of 300 oersteds. This indicates that the anomalous remanent magnetization may be isothermal.

DETAILED STUDY OF AN ANOMALOUS ZONE

SAMPLING GRID

In order to obtain additional information about the possible origin of anomalous magnetization, the morphology of one anomalously magnetized part of a lava flow was investigated in detail. Ten oriented cores, from which 42 specimens 1 inch long were cut, were drilled perpendicularly to a planar, nearly vertical cliff face in a zone where anomalous magnetization was suggested by large deflections of a compass needle. The sampling grid is shown in figure 52.

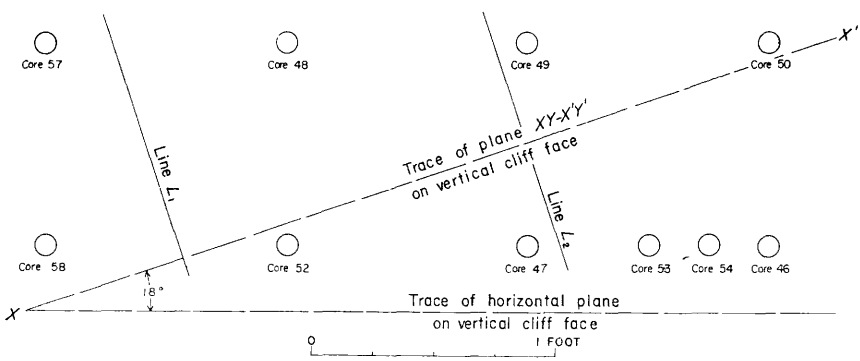

FIGURE 52.—The sampling grid on the vertical cliff face in the anomalously magnetized zone.

DIRECTION OF MAGNETIZATION

The direction of magnetization of each of these 42 specimens is plotted in figure 53 on an equal-area projection. The plane of the projection is perpendicular to the cliff face and dips 18° from the horizontal in the direction of strike of the cliff face. As seen in figure 53, the direction of magnetization of each of the 42 specimens tends to lie in this plane.

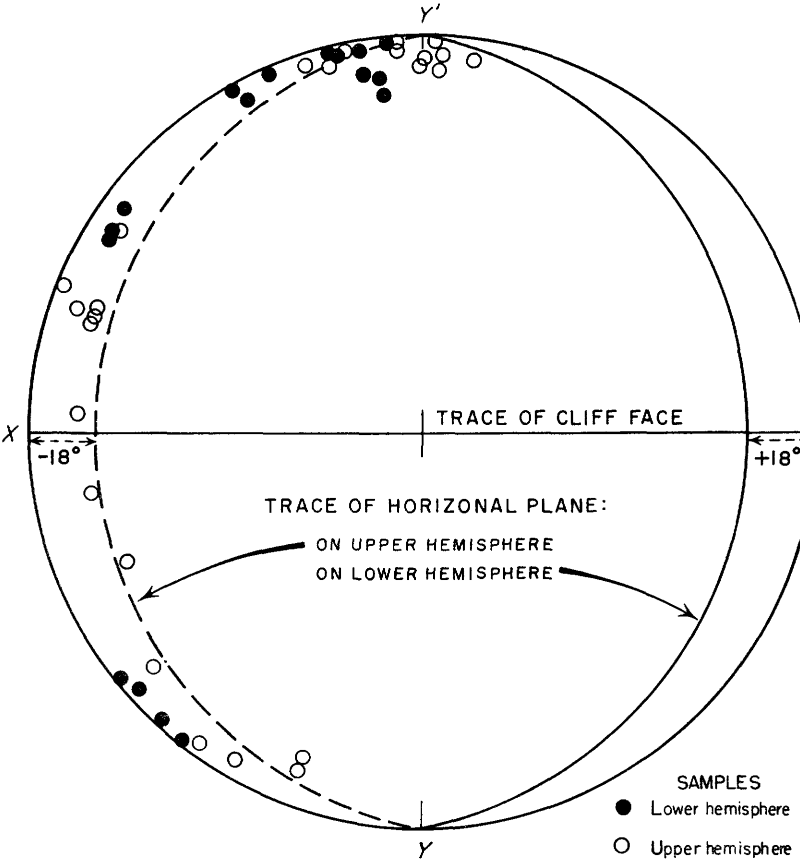

FIGURE 53.—Direction of magnetization of 42 segments cut from 10 cores. Directions tend to lie in plane of projection, which dips 18° from the horizontal. Line Y–Y' is perpendicular to the cliff face and line X–X' lies both in the cliff face and in the plane of the projection.

Because the magnetization of the specimens is nearly coplanar, both the direction and intensity of the magnetization can be plotted as a function of position in a plane parallel to the plane of magnetization. (As the plane of projection in figure 53 is the plane of magnetization, the directions can be measured directly from that figure.) In figure 54 an outline of each specimen is projected onto the plane $XYX'Y'$

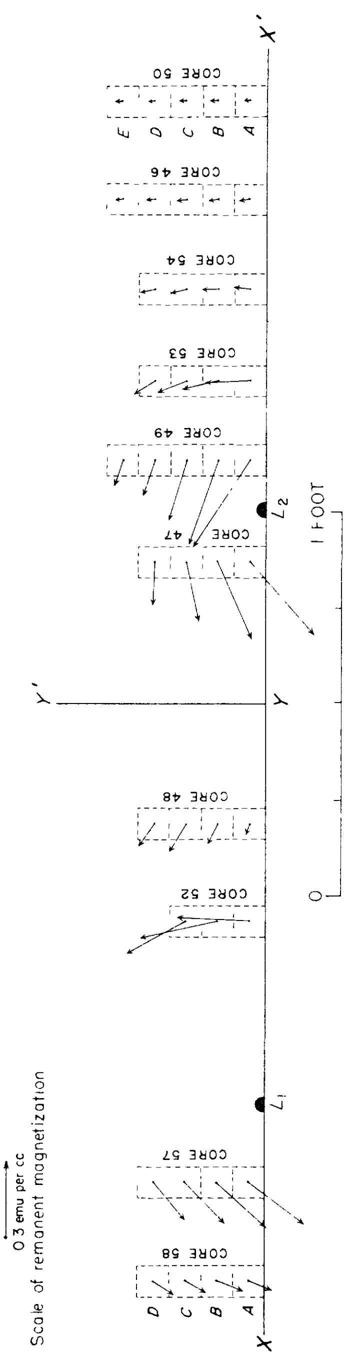

FIGURE 54.—Intensity and direction of magnetization of the 42 specimens projected onto plane $XYX'Y'$, which is perpendicular to the cliff, dips 18°, and is parallel to the plane of projection of figure 53.

which is perpendicular to the face of the cliff, dips 18° from the horizontal, and is parallel to the plane in which the directions of magnetization tend to lie. The direction and intensity of magnetization of each specimen is shown by a vector originating at the center of the projection of the specimen.

The directions of magnetization of the specimens tend to be tangential to circles with centers at L_1 and L_2 of figure 54. This geometry is approximately that of the magnetic field surrounding two line currents of infinite length perpendicular to the plane $XYX'Y'$ and passing through L_1 and L_2. These hypothetical line currents would, therefore, lie in the face of the cliff.

REVIEW OF TECHNIQUES FOR INFERRING D-C FIELDS FROM IRM

In order to test the hypothesis that the observed anomalous magnetization is IRM acquired in the magnetic field surrounding two line currents, it is necessary to have some method by which the intensity of the original magnetic field can be inferred from the remanent magnetization. Pockels (1898) placed bars of basalt around lightning rods and measured their remanent magnetization after the rods had been struck by lightning, and he also measured the magnetization of basalt, in natural situations, that was believed to have been struck by lightning. In order to estimate the current in the lightning bolts, he assumed that the remanent magnetization was proportional to the peak magnetic field producing it.

A similar approach is used in the surge crest ammeter designed to measure the current carried by power lines and towers during lightning discharge. It was found experimentally that the amount of IRM acquired by pieces of cobalt steel in magnetic fields is proportional to the peak intensity of the fields (Foust and Kuehni, 1932).

In the present study it was found that the assumption that remanent magnetization is proportional to the magnetic field is invalid because specimens approximately equidistant from the locus of the hypothetical line current have different intensities of remanent magnetization. In addition, the intensity of remanent magnetization of samples from the anomalous zone has probably been reduced by viscous demagnetization—the effect of thermal agitation acting over an interval of time on remanent magnetization not parallel to the earth's magnetic field. As described earlier, viscous magnetization seems to have occurred in the undisturbed zone, and theoretical considerations (Néel, 1955) indicate that a much larger viscous effect is to be expected in more strongly magnetized rocks; thus, viscous demagnetization has probably reduced the intensity of remanent magnetization of samples from the anomalous zone. Modification of the original IRM by viscous demagnetization is suggested by the difference between the demagnetization spectra of the sample from the anomalous zone as originally demagnetized, and as demagnetized after remagnetization in a d-c field (fig. 51). Correlating the remanent magnetization observed in an anomalously magnetized zone with the field necesssary to produce an equal IRM in the unmagnetized rock in the laboratory would result in an underestimate of the original magnetic field.

USE OF DEMAGNETIZATION CURVES TO ESTIMATE MAGNETIC FIELDS

Consistent results between specimens equidistant from the inferred locus of a line current are obtained if the upper (high alternating field) parts of the demagnetization curves or of the demagnetization spectra are compared. The upper parts of the demagnetization curves of samples from the anomalous zone are parallel to the curves for specimens that have been magnetized in various d-c fields in the laboratory, and it is thus possible to construct a set of standard demagnetization curves for the remanent magnetization acquired in d-c fields of various intensities.

For the lava flow in which the anomalous zone occurs, the demagnetization curves for samples from different parts of the flow are nearly identical in the upper parts of the curves, eliminating the need of constructing a different set of standard curves for each specimen. A single set of standard curves may thus be used to estimate original field intensities from the demagnetization curves of samples from the anomalous zone, and the decrease of the inferred magnetic field with the distance from the inferred line current may be used to test the hypothesis that the anomalous magnetization was due to the magnetic fields surrounding the line currents.

The standard demagnetization curves in figure 55 are based on demagnetization experiments with 4 samples spanning a total distance of 300 feet. All samples are from the flow in which the anomalous zone occurs, but only one is from the anomalous zone. The experimental points on the demagnetization curve for the remanent magnetization acquired by these 4 samples in a 300–oersted d-c field are shown. The upper (high alternating field) parts of the curves are quite similar and most of the upper parts of the demagnetization curves of specimens from the anomalous zone are parallel to these standard curves. The example shown in figure 49, in which the demagnetization curve for sample 54C after remagnetization in a field of 300 oersteds corresponds closely with the standard curve for 300 oersteds, illustrates a somewhat better than average fit.

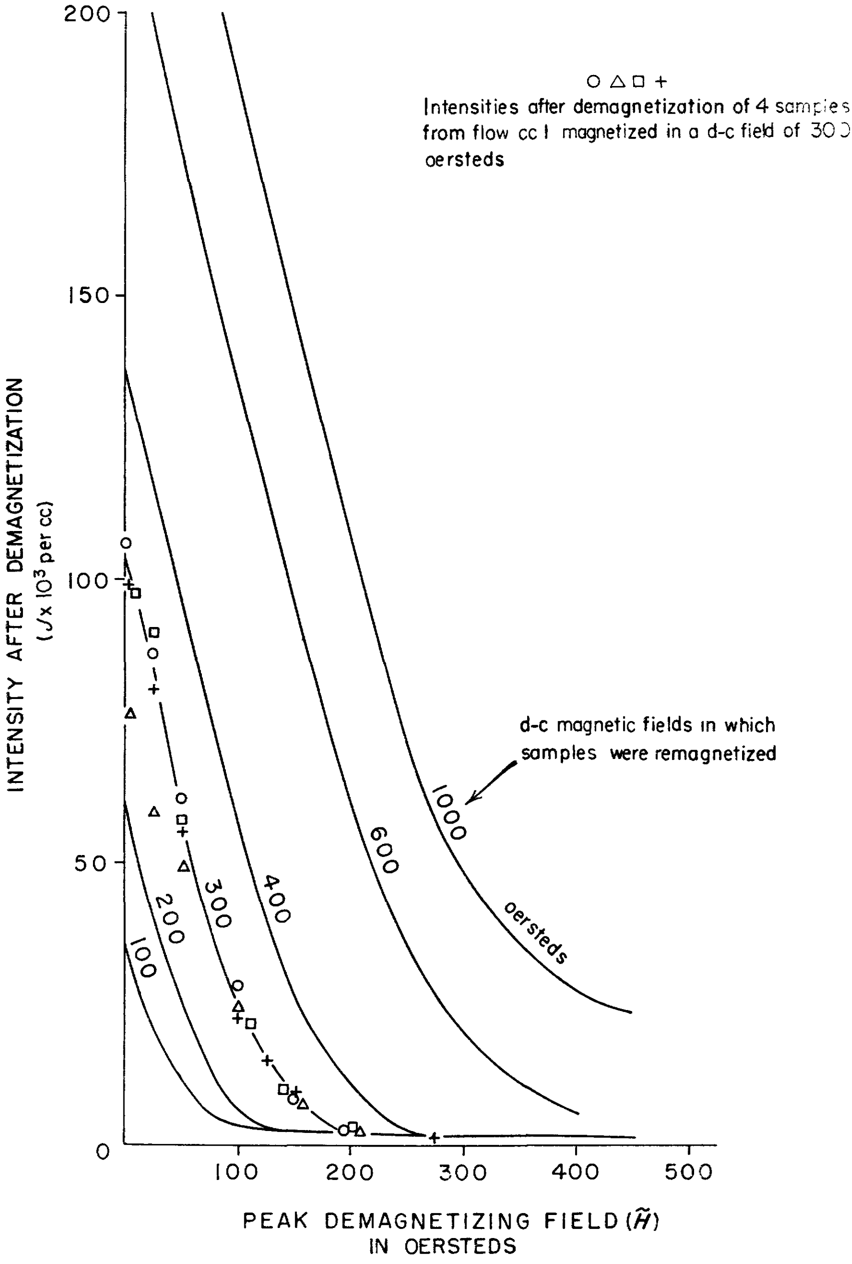

FIGURE 55.—Standard demagnetization curves for the IRM acquired in various d-c magnetic fields. Curves are based on demagnetization experiments on 4 samples from flow CC 1; data for these samples for the 300-oersted curve are plotted.

COMPARISON OF INFERRED D-C FIELDS WITH LINE-CURRENT MODEL

In order to test the hypothesis that the magnetization in the anomalous zone is due to the magnetic fields surrounding line currents, complete demagnetization curves were found for seven specimens that had been collected at different distances from L_2 and at different depths from the surface of the cliff (specimens 47A, 47C, 49A, 49C, 53C, 54C, 46C, fig. 54). The d-c magnetic fields inferred from these demagnetization curves are plotted in figure 56 as a function of the distance of the specimens from L_2. The two curves in this figure are the theoretical magnetic-field intensities which would

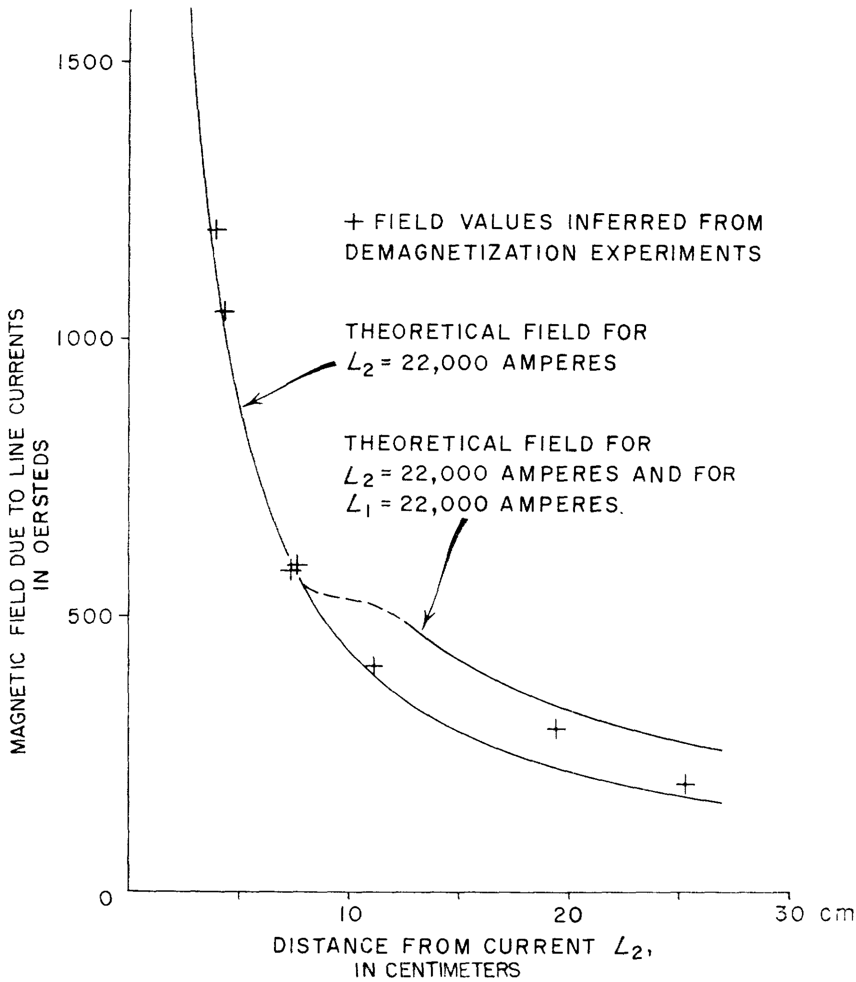

FIGURE 56.—Peak intensity of magnetic field as a function of distance from L_2 as inferred from demagnetization curves and for a theoretical line-current model.

exist at the various specimen sites if a line current of infinite length and 22,000–amp intensity flowed in the plane of the cliff through the point L_2 (fig. 52), or if 2 such line currents each of 22,000–amp intensity flowed through points L_2 and L_1. The current of 22,000 amp is a rough estimate based on additional demagnetization experiments on a single specimen from core 58. Which of these two alternatives is appropriate depends upon whether the currents flowed simultaneously or sequentially. There is insufficient experimental control to permit a choice between these two possibilities on the basis of the data in figure 56, but the pattern of magnetization in cores between L_1 and L_2, especially in core 48, strongly suggests that approximately equal currents flowed simultaneously in L_1 and L_2. The sense of the current flow for both L_1 and L_2 is that of a positive charge flowing upward.

DEPTH OF PENETRATION OF CURRENT AND HEATING EFFECTS

The location of the cores does not permit a precise determination of the depth of penetration of the current. However, the fit of points to the theoretical curve in figure 56 is closer than if the current had flowed through a considerable volume of the rock, or in a wide sheet along the surface of the cliff. Heating of any of the specimens to temperatures as high as 540°C, the Curie temperature of the basalt, is ruled out by the nature of the magnetization; if this temperature had been reached, the remanent magnetization produced by the magnetic field of the line current would have been destroyed and the rock would, on cooling, have acquired a TRM parallel to the earth's field. The surface of the cliff at the locus of the inferred line currents is not fused or discolored; conduction may have been in a narrow, ionized region as it is in lightning discharges.

COMPARISON WITH KNOWN CURRENTS IN LIGHTNING DISCHARGES

Lightning discharges seem the most likely source of currents of tens of thousands of amperes. Schonland (1953) reports that the current in lightning discharges ranges from several thousand to 250,000 amp, with an average value of 20,000 amp. The currents generally rise to a peak value in about 2 microseconds and fall to half their peak value in about 24 microseconds, with considerable variation in both of these quantities. About 90 percent of all lightning discharges transport a negative charge from the cloud to the ground (Lewis, 1950), which corresponds to the sense of the current both for L_2 and L_1.

CONCLUSION ABOUT THE SOURCE OF ANOMALOUS MAGNETIZATION

The anomalous magnetization in the anomalous zone is due to the large magnetic field accompanying lightning discharges with a peak current on the order of 22,000 amp. The following observations support this conclusion. (a) The directions of magnetization are parallel to the directions of the magnetic field which would accompany two line currents lying in the face of the cliff. (b) The high-field parts of the demagnetization curves of the samples from the anomalous zone are parallel to the curves of an IRM acquired in d-c magnetic fields. (c) The field values inferred from the demagnetization curves are inversely proportional to the distance from the locus of the line currents inferred from the directions of magnetization as theoretically expected. (d) The inferred peak intensity of the line currents (about 22,000 amp) is well within the known range of lightning discharges. (e) The sense of the current flow is the same as that observed in 90 percent of all lightning discharges.

DIMENSIONS OF CELLS OF ANOMALOUS MAGNETIZATION

In order to estimate the dimensions of the cells of anomalous magnetization caused by lightning, it is first necessary to estimate the minimum field required to cause a lasting remanent magnetization. When the field causing an IRM is removed, the magnetization begins to decay due to the effects of viscous demagnetization—that is, to the effect of thermal agitation acting over an interval of time—and the desired minimum field value depends to some extent upon the interval of time under consideration. For the rocks studied here, the demagnetization spectra shown in figure 51 suggest 25 oersteds as a reasonable estimate of the lower limit of the field necessary to produce a lasting remanent magnetization. Using this value, a line current of 250,000 amp would produce a tube of anomalous magnetization 130 feet in diameter, and a 20,000-amp current, a tube 10 feet in diameter. The length of such tubes of anomalous magnetization is probably highly variable. For lightning striking on wet ground the tubes are probably short, whereas for lightning striking at the top of a high cliff they probably extend the height of the cliff. Most current distributory systems are probably much more complicated than the two parallel line currents described in this study. The cells of anomalous magnetization of most lightning bolts thus probably have dimensions of several tens of feet, with an upper limit of several hundred feet.

SUMMARY

Three components of magnetization with different magnetic properties were present in a single lava flow: stable thermoremanent magnetization acquired when the flow cooled, viscous magnetization acquired over a long period of time in the weak field of the earth, and isothermal remanent magnetization acquired in the magnetic field of lightning bolts. In dozens of lava flows studied in this region, the relative importance of lightning as a source of anomalous magnetization is indicated by several lines of investigation. Many sets of samples from exposed outcrops have a magnetization that varies widely in intensity and direction, whereas samples from quarries have magnetization characteristics that are tightly grouped. Demagnetization curves of the samples with considerable magnetic scatter usually closely resemble those for the samples from the anomalous zone described here; moreover, the dimensions of the cells of anomalous magnetization in lava flows are within the range expected from typical currents in lightning bolts.

The intensity of viscous magnetization was usually about half the intensity of the TRM or less. However, the direction of the combined viscous and TRM components was usually within 10° to 15° of the direction of the TRM, because the viscous and TRM components in these samples are in almost exactly opposite directions. The effect of viscous magnetization is often masked by IRM due to lightning, which commonly has an intensity of 10 to 100 times that of TRM.

The TRM of these lava flows is very stable in alternating magnetic fields, but the viscous magnetization and IRM are easily destroyed.

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