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National Aeronautics and Space Administration
Lunar Sample Analysis Program

MAGNETIC STUDIES FOR LUNAR SAMPLES

Final Technical Progress Report

by

David W. Strangway

Massachusetts Institute of Technology

January, 1969

Principal Investigator - David W. Strangway

Prepared under Contract No. NAS 9-7973

by

Massachusetts Institute of Technology

Cambridge, Mass., 02139

for

National Aeronautics and Space Administration

Manned Spacecraft Center

Lunar Receiving Laboratory

Houston, Texas

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Introduction

This report is presented in the form of a series of preprints or short papers on various aspect of the magnetic properties of volcanic samples. An attempt has been made, as will be seen in the report, to prepare for the returned lunar samples and in particular to attempt to determine the strength of any ancient magnetic field that may once have existed and can be found preserved in the rocks. In order to achieve this end, several different problems have been examined during this study. These problems are summarized here and followed by more detailed discussions.

1. Determination of paleointensity from a group of basaltic rocks from central Colorado. In this area a series of normal and reversely magnetized flows were found separated by a group of flows with an intermediate direction of magnetization. It is believed that these flows represent a transition in the earth's magnetic field polarization and that the intensity during the transition is quite weak. Studies of the intensity showed that these rocks which are about 24 my. old, were magnetized in fields ranging from about 1.5 oe to .05 oe or over a dynamic range of 30. This indicates quite clearly that even if there has been a lunar field of only about 1% that of the earth's it would be possible to clearly determine the strength. In fact if the mechanism of acquisition of remanence is linear, instrumental sensitivity would permit us to determine the field even if it was only .01% of the earth's field when the magnetic field was acquired.

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rock types from the Mogollon plateau in New Mexico. A large area of southwestern New Mexico has many of the characteristics of a volcano - tectonic depression and is being studied in detail at the University of New Mexico as a possible lunar analogue. In this area is exposed a large variety of volcanic rock types ranging from acidic to basic. The present study shows that it is possible to use different rock types for the determination of paleointensity. Due to the different assemblages of magnetic minerals found in the rocks, the approach used for various rock types is different.

3. An attempt was also made to study the paleointensity in a series of Silurian or Devonian volcanics from northeastern Massachusetts in which some metamorphism was known to have taken place. These volcanics were overlain by a volcanic conglomerate derived from them and a fold was present and it was found that they had been remagnetized since the volcanics were formed. Consequently, information on the paleointensity could not be derived. This effect is believed to be due to thermal metamorphism.

A Tertiary Magnetic Transition in Colorado

D.W. Strangway[✩], E.E. Larson[✩✩] and D. York[✩]

Abstract

A sequence of 26 volcanic flows from central Colorado have revealed a magnetic transition zone with directions of magnetization intermediate between the older normally magnetized flows and the younger reversely magnetized flows. Nine of the flows have an intermediate direction of magnetization which varies only slightly from flow to flow. This indicates that this sequence of flows came out in rapid succession before the field, caught in the process of reversing, had a chance to change much. Potassium-argon dating gives an age of 24.5 my. for this transition or lower Miocene age. The strength of the magnetic field during the transition was also studied. The field strength varied from a high of 1.3 oe after the transition, to a low of .047 oe during the transition or over a range of about 30. There is a clear indication that the field reduced considerably in strength before any direction changes appeared indicating that the field collapses rather than flipping over during a reversal.

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Introduction

Reversals in the earth's field are known to have been very common in geologic time, but the detailed pattern of reversals has been difficult to work out. In recent years, many workers have contributed to elaborating the detailed reversal history back as far as 4 my. During this time the field has reversed itself many times and the pattern shown in figure 1 has emerged. This work has been summarized by Dalrymple et al (1967) and by Dalrymple and Doell (1968). The extension of this work back into Pliocene times has proven to be quite difficult due to the uncertainties in the age determination. As pointed out by Dalrymple et al (1967), well-defined stratigraphic sequences of rocks will be needed to recover the nature of the reversals in Pliocene and Miocene times. One such sequence including a transition zone was reported previously from Steens mountain, Oregon by Baksi et al (1967) and Goldstein et al (1969) who found a sequence from reversed at the bottom to intermediate in the middle and normal at the top with an age of 15.1 ± 0.3 my. Heinrichs (1967) reported an age of 6.9 ± 0.2 my. for an intermediate group of rocks in Nevada. Kawai and Hirooka (1966) reported a widespread series of intermediate directions from Japanese rocks. They found these to lie between 13.1 and 14.3 my. with a mean age of about 13.7 my. Grommé (1965) reported on a series of rocks with intermediate ages at about 22 - 24 my. Other isolated points in figure 1 in the range 22 - 32 my. are taken from current studies in New Mexico and Arizona. This information is summarized in figure 1. The present paper describes a transition zone found in central Colorado dated at 24.5 my. and is similar to studies by Momose (1963) and Van Zijl et al (1962).

Geology

In central Colorado, piles of young volcanic rocks are found at high elevations. These are shown on the geologic map of Colorado as late Tertiary or Quaternary in age. The location sampled is about 2 miles north and slightly east of State Bridge in Eagle County on Yarmony Mountain. (see fig. 2). The series of flows overlies steeply dipping Permian red beds unconformably and has a slight dip (7°SW, strike N30W). The data reported on in this paper are from a sequence of 26 basaltic flows. At a few places the flows are interbedded with sands and gravels indicating that stream deposition was taking place concurrently with the formation of the flows and that the flows were not equally spaced in time.

Paleomagnetic Data

The magnetic data were measured in the laboratory using a spinner magnetometer and the results analyzed by the standard Fisher statistics. All samples were subjected to A.C. demagnetization at 200 oe and it is these results which are presented (Table 1). Figure 3 shows the way in which the inclination and declination vary flow by flow. The lowest group of flows (Nos. 1 - 12) are all normal in direction. The heavy lines in figure 3 represent the declination and inclination to be expected if the directions corresponded to the present rotation pole. It is seen that the inclination should give a mean value of 59° and it comes very close to this, while the declination is slightly west of north. In general, however, the direction is close to the present field direction.

The next group of flows (13 - 18 and 1-8 - 1-6) falls in an intermediate category with a mean inclination of 70° and a declination of 210°. Although nine distinct flows are present there is no tendency for there to be a gradational pattern in the directions such as has been found in other transition zone studies e.g. Watkins (1965), Goldstein et al (1969) . This is taken as an indication that the flows involved came out in a very short time interval, since reversals are believed to take place rapidly in a few thousand years. The final groups of flows (1-1 to 1-5) are found to be nearly reversely magnetized. The expected values for a true reversal and a field along the rotation axis is given by the heavy lines. The inclination is seen to be somewhat small and the declination is also too small. Either the field did not reverse itself exactly or else the original field direction was not reached in this group of flows, even by sampling to the highest level found in the sequence.

Covered intervals in which gravels and sandstones were formed are shown in figure 3 as gaps along the ordinate. It is not known how much time is represented by this sequence of flows but it is likely that the flows are not uniformly spaced in time and in fact considerable time gaps could be present. Samples from the base of the reversed zone were dated at 24.9 my. giving a lower Miocene age for this transition and from the uppermost flows the dates are about 22 my.

The corresponding computations for the mean pole positions of the various groups are given in Table 1 and plotted in figure 4. Pole positions 4 and 5 correspond to the lowest normal polarity sequence and give positions reasonably close to the present rotation pole. Pole No. 3 is the transition pole and this is found to lie near the present equator. Nine individual flows are represented in this group and it is quite clear that even this many flows is inadequate to provide a representative mean pole position for the Miocene period. Finally, poles 1 and 2 are from the upper reversed sequence. They deviate from the present pole position, indicating that the magnetic field has not recovered to its true reversed orientation. In this group of 26 flows, 14 show unusual directions of magnetization. Even averaging over this many flows would not have given a representative Miocene pole position. Less evidence than this has been used to postulate drift and rotation of continental size blocks.

Paleointensity

The procedure for determining paleointensity has been described previously (Strangway et al, 1968). To summarize briefly, it consists of selecting samples which are likely to show minimum changes in the magnetic minerals on heating. This is done either by observing polished sections and selecting samples that show a high-degree of auto-oxidation or by measuring an A.C. decay curve. In general, if the magnetization decreases slowly so that at 200 oe the intensity is at least half of the original intensity, the samples are suitable for heating. The samples are then heated to 600°C, 700°C and 800°C in turn and the remanence acquired after cooling in the earth's field measured. The A.C. decay curve is measured after each cooling in steps up to 800 oe. The paleointensity is then determined by matching the 500 and 800 oe portions of the decay curves of the NRM and the remanence acquired by cooling from 600°C in a known field. The heatings to 700°C and 800°C are used to test the suitability of the sample. Oxidized samples do not change significantly between 600°C and 800°C while unoxidized samples invariably acquire increasing remanence values due to the development of small particles. Suitable samples then are characterized by only small changes in the remanence acquired on cooling from 600°C, 700°C and 800°C and only decreases are permitted since this involves the oxidation of magnetite to hematite but not the development of lamellae.

In the present study, eleven samples were tested for paleointensity. Of these only one showed a rapid decrease in the remanence on A.C. demagnetization and at 200 oe had a value of remanence less than half of the initial NRM. All the other samples appeared suitable for the paleointensity determinations and 10 determinations have been made and are reported here. The data from a representative sample is presented in figure 5 to illustrate the procedure. Checks of the ratios at both 500 and 800 oe demagnetizing fields are shown in Table II giving an idea of the general level of agreement in ratios obtained at these demagnetizing fields. Differences are encountered in a few samples but these are not generally large. The paleofield values given in Table II are also plotted in figure 6 as a function of flow number in the sequence. Since it is flow number that ⇉ is involved it is clear that the vertical scale does not represent time except in the sense that the top of the scale is young and the bottom is older.

The peak value of the field is about 1.3 oe in the youngest flows, a value of almost 3 times the present field. The transition units have much lower fields with values as low as 0.047 oe. This indicates that the field during the reversal dropped by a factor of about 30 from the maximum recorded in this suite of rocks. In the normal rocks at the bottom, the field decreases from 0.46 oe close to the bottom, steadily to the transition zone values of around 0.05 oe. The implication is that the field started to decrease before there was much change in direction. This, together with the large change in amplitude, suggests that the field collapsed and then rebuilt in the opposite direction. This is in agreement with the conclusions drawn by Smith (1967) and others about the nature of the reversal process.

Grand Mesa

A second set of flows from the Grand Mesa area of western Colorado were also sampled. Six flows were present forming the crest of the mesa and these were found to be normally magnetized. No transition zone was found and the age is uncertain although they are probably related to the flows from Yarmony Mtn. The data from these samples is given in Table III and the pole position shown in figure 7. This pole position almost coincides with the present rotation pole and it is interesting to speculate that they might be somewhat younger than the Yarmony Mtn. flows.

Conclusions

This paper has presented the results of a detailed study of a transition zone of age 24 my. from central Colorado. Several flows were found with intermediate directions of magnetization. Since there was little change in this direction, it is probable that this group of flows were extruded in a short time. The intensity of the field ranged from a maximum of 1.3 oe to a minimum of 0.047 oe or over a range of almost 30 in its strength.

Acknowledgements

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References

Baksi, A.D., D. York and N.D. Watkins, 1967, Age of the Steens Mountain geomagnetic polarity transition, J.G.R., 72, 6299-6308.

Dalrymple, G.B., A. Cox, R.R. Doell and C.S. Gromme, 1967, Pliocene geomagnetic polarity epochs, Earth and Planetary Science Letters, 2, 163-173.

Dalrymple, G.B. and R.R. Doell, 1968, Comment on paper by M. Ozima, M. Kono, I. Kaneoka, H. Kinoshita, Kazuo Kobayashi, T. Nagata, E. Larson and D. Strangway, J.G.R., 73, 1502-1503.

Gromme, S., 1965, Anomalous and reversed paleomagnetic field direction from the Miocene Lovejoy basalt, northern California, J. Geomag. and Geoel., 17, 445-457.

Goldstein, M.A., E.E. Larson and D.W. Strangway, 1969, Paleomagnetism of a Miocene transition zone, Earth and Planetary Science Letters, in press.

Heinrichs, D.F., 1967, Paleomagnetism of the Plio-Pleistocene Lousetown Formation, Virginia City, Nevada, J.G.R., 72, 3277, 3294.

Kawai, N. and K. Hirooka, 1966, (abstract only) Anomalous direction of NRM in Miocene volcanic rocks in Japan, proc. of U.S.-Japan scientific cooperation meeting held in Kyoto in Oct. 1966.

Momose, K., 1963, Studies on the variation of the Earth's field during Pliocene time, Bull. Equake. Res. Inst., 41, 487.

Smith, P.J., 1967, The intensity of the ancient geomagnetic field: a review and analysis. Geophysical Journal, 12, 321-362.

Strangway, D.W., B.E. McMahon and E.E. Larson, 1968, Magnetic paleointensity of a recent basalt from Flagstaff, Arizona, J.G.R., 73. 7031- 7037

Van Zijl, J.S., K.W.T. Graham and A.L. Hales, 1962, The paleomagnetism of the Stormberg lavas I and II, Geophysical Journal, 7, 23 and 169.

Watkins, N.D., 1965, Frequency of extrusion of some Miocene lavas in Oregon during an apparent transition of the polarity of the geomagnetic field, Nature, 206, 4986, 801-803.

TABLE I

Summary of palecmagnetic data

NRM

	Samples	D	I	k	α_{95}	Long.	Lat.	δM	δP
1-1, 1-2	4	303	61	99.1	9.3	174	48	14	11
1-3, 1-4, 1-5	7	306	44	10.9	19.1	197	43	24	15
(1-6, 1-7, 1-8, ((13-18	16	196	56	5.9	16.6	120	-13	24	17
6-12	14	337	54	22.1	8.6	207	71	12	8
1-5	9	337	66	23.2	10.9	162	71	18	15

After ACD at 200 oe

	Samples	D	I	k	α_{95}	Long.	Lat.	δM	δP
1-1, 1-2	(1) 5	319	51	24.2	15.9	197	56	21	14
1-3, 1-4, 1-5	(2) 7	302	45	18.0	14.6	194	41	18	12
(1-6, 1-7, 1-8, ((13-18	(3) 16	210	70	62.0	4.7	124	8	8	7
6-12	(4) 14	335	57	26.8	7.8	197	70	11	8
1-5	(5) 9	346	60	33.1	9.1	187	79	14	10

TABLE II

Paleointensity Data

Sample No.	Ratio of NTM/TRM after demag.at 500 oe	Ratio of NRM/TRM after demag.at 800 oe	Paleofield oe
1-1-1	1.9	2.5	1.3
1-2-1	2.1	2.2	1.3
1-3-1	1.1	1.3	.73
1-5-1	1.2(?)	1.3	.76
1-6-1	.11	.11	.067
18A	.11	.11	.067
14A	.26	.26	.16
12A	.044	.077	.047
5A	.38	.38	.23
2A	.75	.75	.46

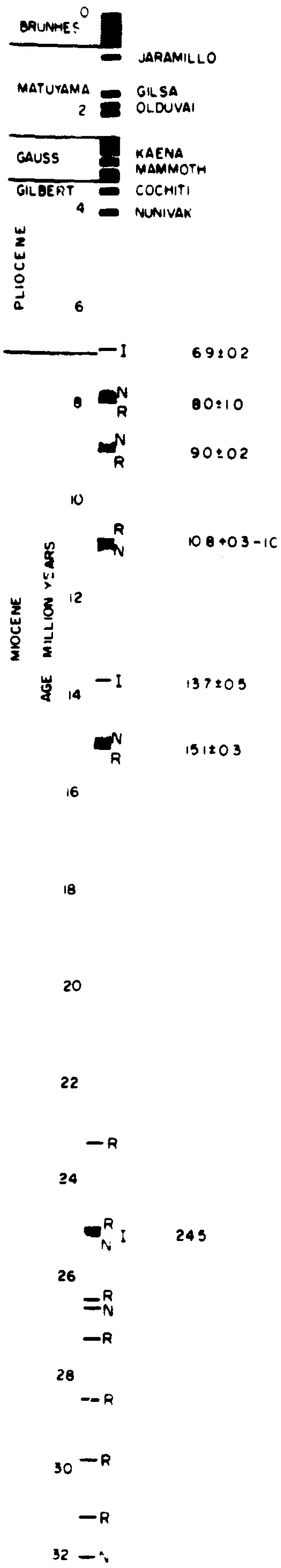
TABLE III

Summary of paleomagnetic data
Grand Mesa
(6 flows)

	Samples	D	I	R	α_{95}	Long.	Lat.	δM	δP
NRM	10	10	58	28.3	9.2	17°	83°	14	10
After AF Demag.at 200 oe	10	2	58	38.2	7.9	30°	89°	12	9

Figure Captions

1. Chart showing known reversals in the past 32 million years.
2. Location map in central Colorado.
3. Graph showing inclination and declination through the sequence of flows - heavy lines represent true normal and reversed directions.
4. Mean pole positions from the five groups of flows at Yarmony Mountain. + - present mean dipole axis.
5. Graph showing procedure for determining paleointensity.
6. Graph of intensity variation through the transition zone.
7. Mean pole position for the Grand Mesa flows. + - mean dipole axis.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PLIOCENE
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I
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8.0±1.0
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9.0±0.2
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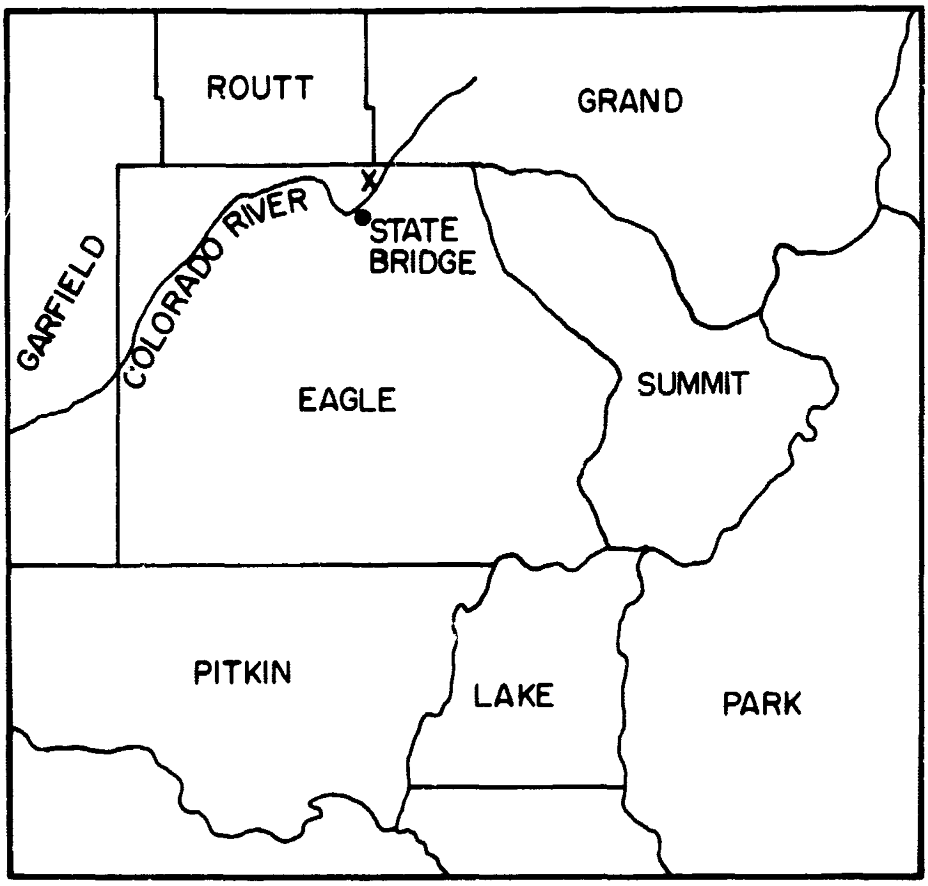
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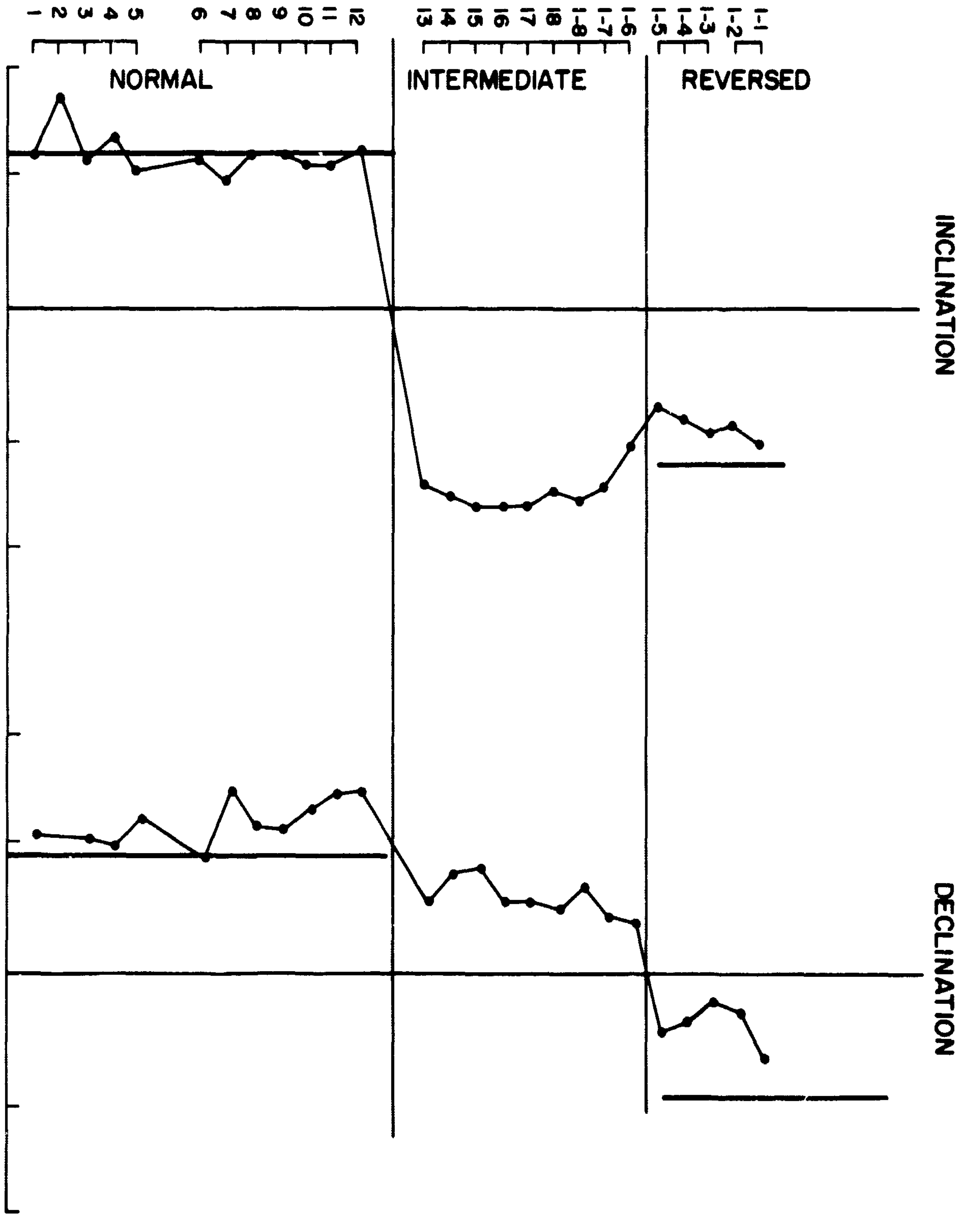
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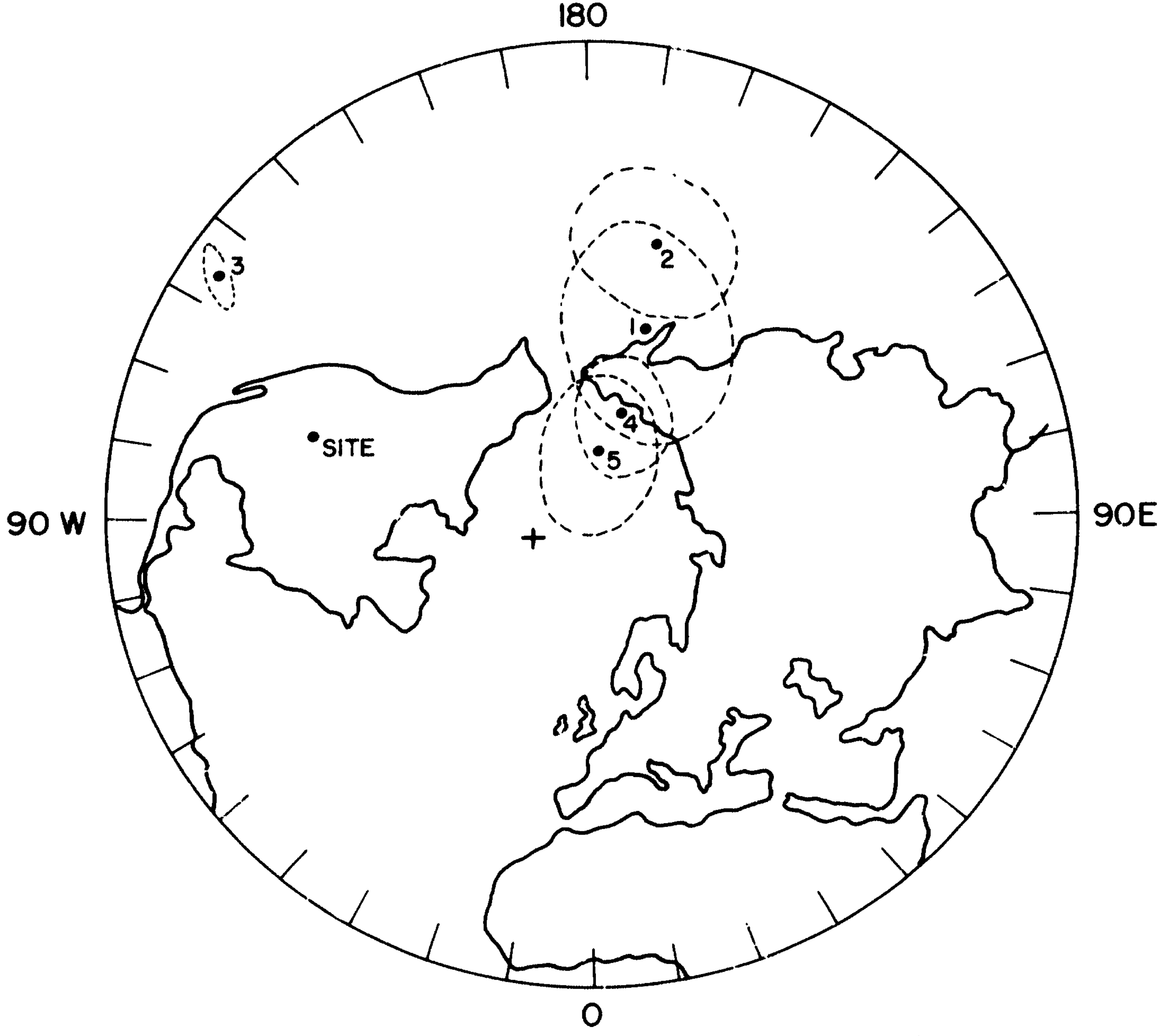
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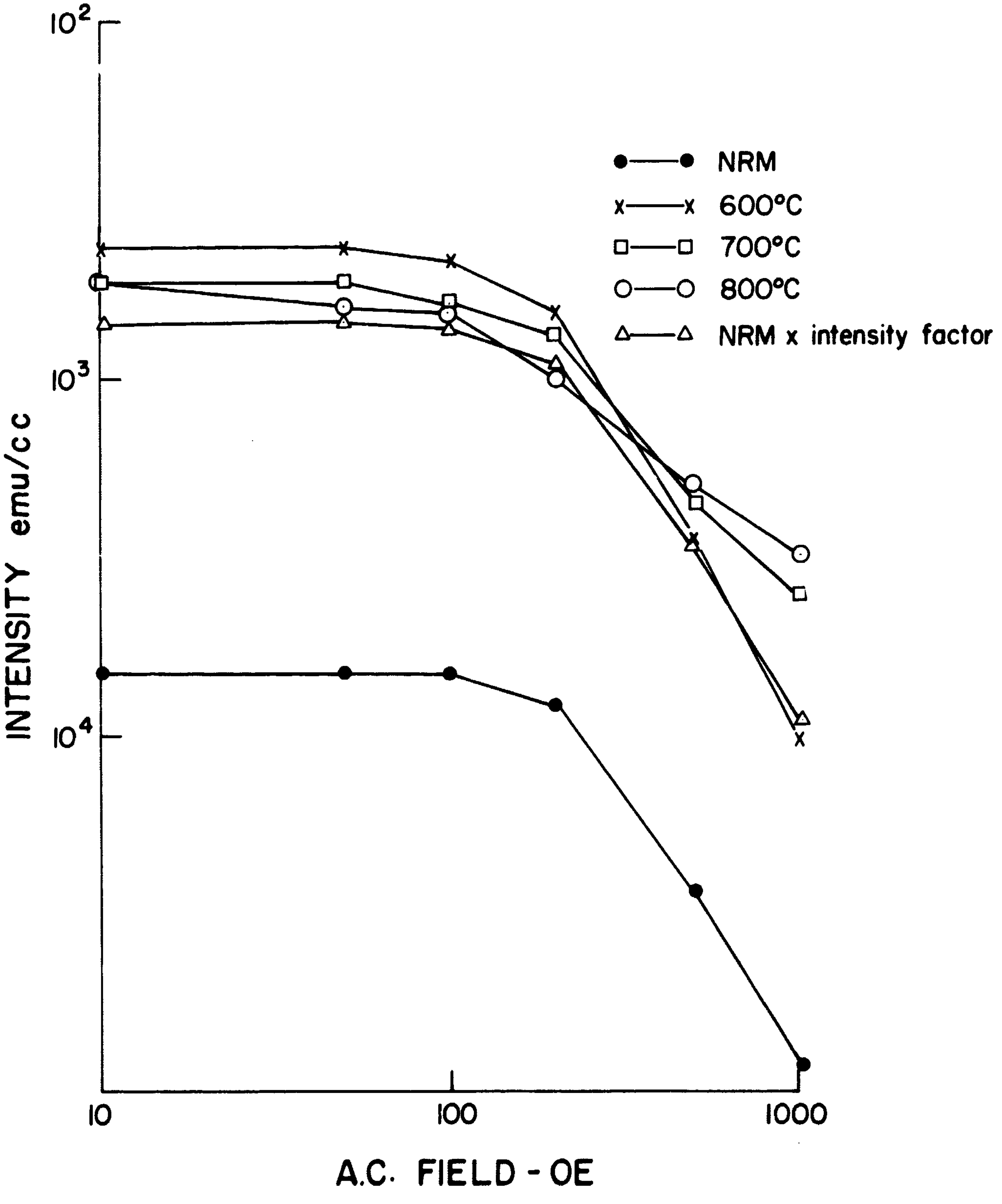

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□—□ 700°C
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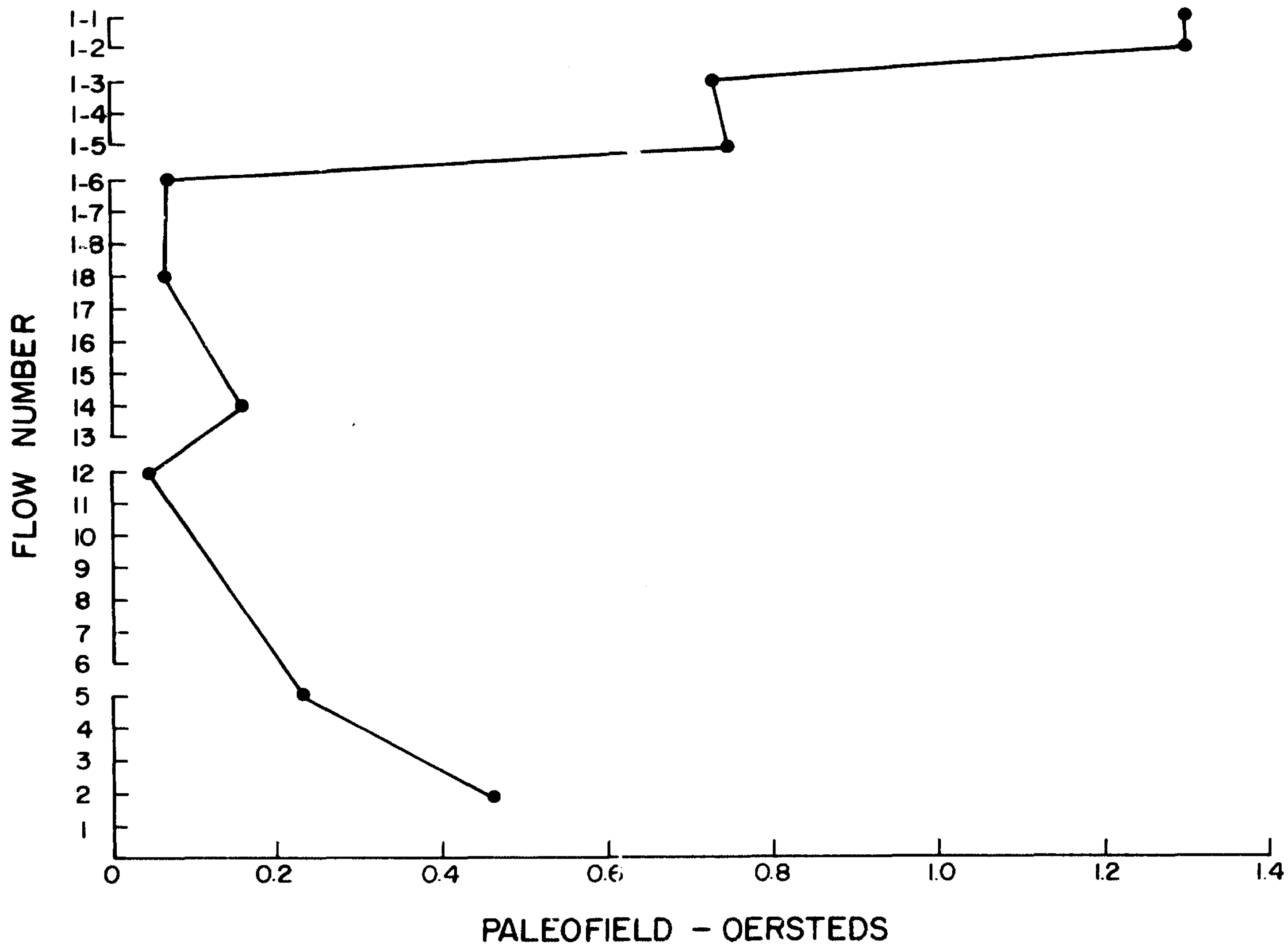
△—△ NRM x intensity factor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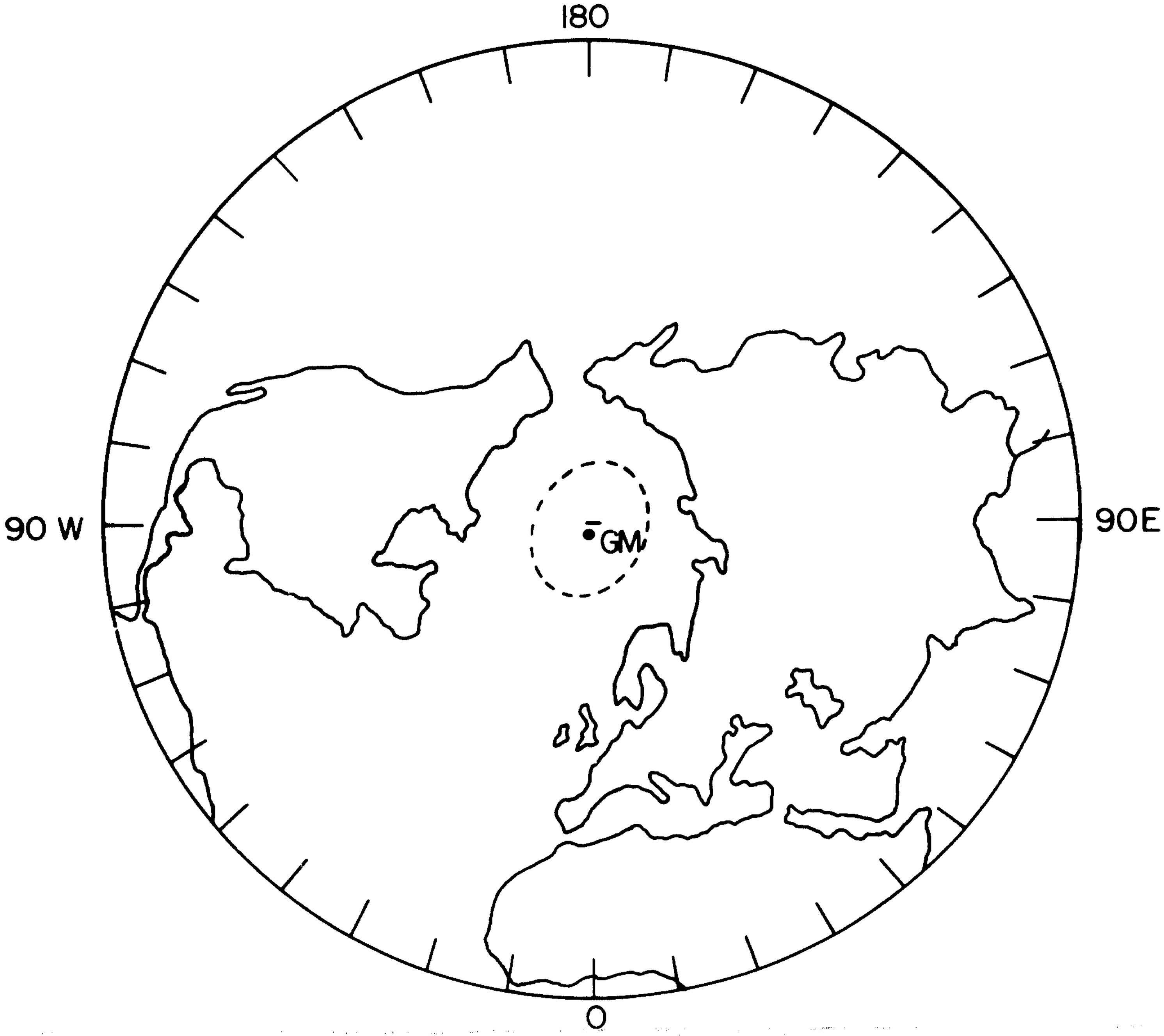
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Paleointensity Determinations from a Variety of Volcanic Rock Types in the Southwestern United States

David W. Strangway

Abstract

A study of procedures to determine the intensity of the magnetic field in volcanic rocks has been conducted using samples from southeastern Arizona and southwestern New Mexico. These volcanics are mid-Tertiary in age and have K-Ar dates ranging between 20 and 35 my. To date only a few samples have been studied in detail and these give paleofield values ranging from 0.13 to 0.66 oe. A variety of volcanic rock types ranging from basaltic andesites to rhyolites have been investigated in this way. In general the basaltic andesites have their natural magnetism carried by magnetite which is present as an intergrowth with ilmenite and these samples can be heated without much change in the magnetic properties. The rhyolites on the other hand, often have their natural magnetism carried by hematite. In the cases where magnetite is present oxidation to hematite takes place during heating and no useful data can be recovered.

Introduction

The preliminary results of paleointensity determinations on a series of volcanic rocks from southwestern New Mexico and southeastern Arizona are reported here (fig. 1). This particular group of rocks is of interest in the present context since they are undergoing intensive geologic investigation by Elston and his coworkers (1965, 1968, 1968) with the thought that this might represent a lunar analogue. Age dates of a few samples have been reported by Damon (1967, 1968) and the rocks are known to range in age from 20 my to 35 my and so are mainly of lower Miocene and Oligocene age. They vary widely in composition from almost pure basalts through basaltic andesites, andesites, rhyolites and ash-flow tuffs. The detailed stratigraphy has been difficult to work out, but good progress is being made by Elston and his group at the University of New Mexico. Our studies have been concentrated on two aspects of the magnetization. Studies of magnetic polarity have been useful in correlating known stratigraphy and it is hoped that this will eventually lead to a rough outline of the reversal sequence in the Oligocene period. These detailed stratigraphic studies will be reported elsewhere. In this report, a preliminary study of paleointensities is presented. (See Thellier and Thellier, 1959, Smith, 1967). This gives a few well-defined intensities in the period and in addition gives an approach to the measurement of intensity in rocks containing a variety of magnetic mineral assemblages.

Procedure for determining paleointensity

Our procedures for determining paleointensity in basalts or basaltic andesites have been described in some detail in previous papers and reports. The approach is a variation of the procedure used by Van Zijl et al (1962). The first study reported was on a historical flow (1300 years old) from Flagstaff, Arizona, (Strangway et al, 1968). This rock was a basalt and measurements were made on fresh samples from a drill core. In some cases the samples were highly oxidized so that lamellae of magnetite and ilmenite were developed, while in other cases no lamellae were present. The former group of samples proved suitable for heating, since they underwent a minimum of change.

The procedure adopted, involves the measurement of the decay curves of the NRM and comparing this with the decay of the TRM. The oxidized samples have A.F. demagnetization curves with the form shown in figure 2a on a log-log plot. Above 100 oe the natural remanent magnetism (NRM) starts to decay quite rapidly but at 200 oe more than half the initial intensity is still present and at 800 oe the NRM has decreased to about 10 or 20% or more of the original magnetization. The unoxidized samples which were not suitable for paleointensity determination are much less stable (compare Larson et al, in press; Wilson et al, 1968). In a demagnetizing field of 200 oe they had generally lost more than 1/2 of the original magnetization and by 800 oe the magnetization is reduced to 1 to 5%. (See fig. 21). On heating these samples, many changes occurred in the magnetic minerals as revealed by microscopic studies and by the change in magnetic properties.

The other studies conducted in the present series of experiments involved the determination of the ancient field in transition zones while the field was reversing. These results are reported by Goldstein et al, (in press) and in the present report by Strangway et al. They show that it is possible to identify fields as low as .05 oe.

In the present study a new category of samples has been found. These samples will be discussed in some detail, but in general they lose very little of their magnetization even when demagnetized in fields as large as 800 oe. At 800,oe the magnetization remaining is at least 60% and often 90% of the original NRM. Most samples fall clearly into one of these three categories and only a few cases show intermediate properties, probably due to combinations of these mineral assemblages.

Discussion of Basaltic Andesites

Data from 10 basaltic andesites from Arizona and New Mexico are given in figure 3 to illustrate the nature of the A.F. decay spectra. These curves are typical of the oxidized magnetite types of basalts. In studying these curves it can be seen that in general the shape of the demagnetization curve of the natural magnetization is quite similar to that found for the thermo remanent magnetism acquired on cooling from temperatures of 600°C, 700°C and 800°C in the earth's field. A curve of similar shape is the main criterion used to determine the reliability of the data, particularly after demagnetization in fields of 500 to 800 oe where possible viscous effects have been reduced. Curves for samples AV 8A, AV 9A, NMV 22A, NMV 22B, NMV 23A and NMV 23B all satisfy this criterion and have similar A.F. decay curves both before and after heating. The ratio of NRM to the TRM after heating to 600°C and cooling in a field of 0.61 oe is given in table 1. These data are for demagnetization at 500 and 800 oe and the two values are averaged to get the mean paleofield. Samples AV 8A and AV 9A are from a transition zone in Arizona in which the field was caught in the act of reversing but they show typical field values of 0.13 and 0.35 oe. No corresponding equatorial field is calculated because of the transition nature of the field. These samples contain oxidized magnetite with ilmenite intergrowths and the magnetic properties hardly change on heating.

Samples AV 15A, AV 27A and AV 31A clearly show the presence of hematite since after heating to 800°C the A.F. decay curve is very nearly flat. In the case of AV 15A the decay of the NRM is very similar to that of the TRM and we conclude that the NRM is carried by hematite. This sample therefore also yields useful paleointensity data and gives a field of about 0.66 oe (see next section for approach). This sample has been dated at about 28 my and samples AV 8A and AV 9A are known to be stratigraphically younger. In the case of sample AV 19A the curves shapes from before and after heating are quite dissimilar and no useful data could be recovered. Samples AV 27A and AV 31A show similar behaviour to sample AV 19A. Evidently the NRM is carried by oxidized magnetite, but on heating as high as 800°C all the TRM acquired is carried by hematite. It is probable that this hematite was developed by the heating process and was not there originally since it does not carry the NRM.

Changes on heating in these volcanic rocks can manifest themselves in two ways. In simple magnetite grains, the TRM goes up rapidly on heating from 600°C to 800°C. This is a result of oxidation of titaniferous magnetite to magnetite and ilmenite with a resultant decrease in grain size. It is also possible for magnetite to oxidize to hematite and in this case there is a resultant change in the A.C. decay curve on heating from 600°C to 800°C. Samples 27A and 31A are rejected on this latter basis since the TRM at 800°C is carried by hematite, while the NRM is carried by magnetite.

Samples NMV 22A, 22B, 23A and 23B represent repeat observations on two successive lavas from the Gila wilderness area of New Mexico. The interesting feature about these samples is that two adjacent flows each give internally consistent and repeatable values but they are 0.16 and 0.51 oe. The precise age of the samples is unknown but they overlie the Bloodgood Canyon formation which has been variously dated at between 23.2 and 26.5 my. Evidently fluctuations in the earth's field strength can occur even on a flow to flow basis.

Discussion of Rhyolites

A variety of rhyolites from the major ash-flow province of the Mogollon-Silver City area have also been studied. Samples from the Dwyer quadrangle and from the Gila Canyon were studied (Elston, 1957). The Kneeling Nun formation (NMV 7A) has been dated at 33.4 my. Unfortunately, as shown in figure 4, the shapes of the A.F. decay curves of the NRM and the TRM after heating to 800°C are not similar. However, the shape of the decay of the NRM curve indicates the presence of oxidized magnetite initially and the curves at 600°C and 700°C are so similar that a tentative value has been assigned to this unit. This value is 0.37 oe but it must be considered as tentative. Sample NMV 9A from the Razorback formation is between 29.8 and 26.6 my but it did not yield useful paleointensity data. The NRM curves and the various TRM curves do not show similarity and it seems probable that severe changes in the magnetic minerals on heating have occurred.

Samples from the Caballo Blanco (NMV 16A) dated at 29.8 my and from the Bloodgood Canyon (NMV 27B, 29A, 34A, 34B, 35A and 35B) formation dated at 23.2-26.5 my were also tested. These show quite similar A.C. decay spectra for the NRM and the TRM with the exception of 35A, 35B. Since these rhyolite samples clearly have their NRM carried by hematite it is necessary to make the comparison of NRM/TRM ratio after heating to 800°C to be sure that the Curie temperature of hematite has been exceeded. The ratio is also taken after demagnetization to 800 oe to be sure that major viscous effects are removed. The paleofield values are given in table 2. The Caballo Blanco gives a value of 0.41 oe and the Bloodgood Canyon shows a remarkable consistency giving a mean field of 0.38 oe on four samples from two different cooling units.

Basaltic andesite specimen AV 15A was treated in the same way because its NRM was carried by hematite. This value is 0.66 oe in a reversely magnetized unit.

It is thus seen that a variety of types of NRM are found in typical volcanic rocks. In general the acid volcanics appear to have their remanence carried by hematite and so the magnetization is extremely stable. In general basalts and basaltic andesites have their remanence carried by magnetite. In some cases sufficient oxidation has taken place to permit heating to 600°C successfully while others are not amenable to this treatment.

Hysteresis Loops

Several hysteresis loops were run on some of the samples as a means of comparing the bulk magnetic properties with the properties of the magnetization represented by the NRM and the TRM. The results of these measurements are summarized in table 3, in which the saturation remanence (Jr) and the saturation magnetization (Js) are tabulated as well as the ratio. In the case of the basaltic andesites (AV 9A, AV 27A and AV 31A) the initial ratio Jr/Js is about 0.25 and in all these cases the A.F. decay curve indicates that magnetite is the carrier of the NRM. From previous studies (Strangway et al, 1963) this indicates that the magnetite is highly exsolved and present as very small particles. These samples were also subjected to heating in air at 800°C and the hysteresis loops remeasured. In all these cases true saturation was not achieved in fields of 8000 oersteds indicating that magnetite was no longer an important constituent. In the case of samples 27A and 31A the TRM acquired on cooling from 800°C was carried by hematite and it is therefore clear that hematite was created by the destruction of magnetite giving rise to a new carrier for the TRM. In the case of sample AV 9A the hysteresis loop indicates that much of the magnetite has been oxidized to hematite which cannot be saturated in fields of 8000 oe. It is evident from the TRM, which decays in a very similar way to the NRM, that the regions responsible for the NRM are largely unaffected by heating to 800°C. In these cases, therefore, the hysteresis loops show that magnetite is in general being oxidized to hematite on heating. This is indicated by the lack of saturation even in fields as high as 8000 oe and is confirmed by the observation that in some cases the TRM acquired at 800°C is carried by hematite.

In the case of the rhyolites, hysteresis loops have been run, but so far measurements have only been made on unheated samples. In the case of NMV 7A the NRM was carried by magnetite and the sample saturated giving a value of $^{Jr}/Js$ of 0.25 much like the results for the basaltic andesites. On heating the TRM acquired is carried by hematite as shown by the A.F. decay curves. This sample then behaves like the basaltic andesites already discussed.

The remaining samples that were tested in this way will not be fully understood until additional tests have been made. However with the exception of NMV 35A, which did not yield paleointensity data, the values of magnetization are quite small, consistent with the presence of hematite. Some of the samples saturate in fields of 8000 oe and some show a tendency to saturation indicating the presence of a little magnetite. Evidently this is not important in determining the NRM or the TRM however since A.F. curves indicate hematite as the main carrier of both of the remanent magnetization.

Conclusions

A wide variety of minerals carry the remanent magnetization found in volcanic rocks. These can be conveniently divided into three groups:

a) unoxidized magnetite which does not stand up to heating.

b) oxidized magnetite which can be successfully heated to 800°C with little or no change.

c) hematite which can be heated to 800°C successfully.

These conclusions are based on comparing A.F. demagnetization curves of NRM and the TRM acquired by cooling in the earth's field.

Several isolated paleointensity values have been determined from an area of volcanic rocks from southeastern New Mexico and southwestern Arizona. These values appear to range between 0.13 oe and 0.66 oe for rocks ranging in age from 30 my to 23 my. The values are not unlike those of the present field and those reported by others for Tertiary rocks (Smith, 1967). Apparently the field fluctuates considerably in amplitude even without significant direction changes. This conclusion was borne out by a transition zone study given in this report.

Acknowledgements

This work was supported by NASA as part of the returned lunar samples program. D.H. Enggren and G. Olhoeft did most of the measurements and I should like to acknowledge their help as well as many helpful discussions with Prof. Larson of the University of Colorado.

References

Damon, P.E. et al, 1967. Correlation and chronology of ore deposits and volcanic rocks, U.S. A.E.C. report No. C00-689-76.

Damon, P.E. et al, 1968. Correlation and chronology of ore deposits and volcanic rocks, U.S. A.E.C. report No. C00-689-100.

Elston, W.E., 1957. Geology and mineral resources of Dwyer quadrangle, Grant, Luna and Sierra Counties, New Mexico, N. Mex. Bur. Mines and Mineral Resources, Bull. 38.

Elston, W.E., 1965. Rhyolite ash-flow plateaus, ring dike complexes, calderas, lopoliths and moon craters, N.Y. Acad. Sci. Annals, v. 123, 817-842.

Elston, W.E., P.J. Coney and R.C. Rhodes, 1968. A progress report on the Mogollon plateau volcanic province, southwestern New Mexico in Quarterly of the Colorado School of Mines entitled, Cenozoic volcanism in the southern Rocky Mountains, edited by R.C. Epis.

Elston, W.E., 1968. Terminology and distribution of ash-flows of the Mogollon-Silver City-Lordsburg region, New Mexico, Arizona Geol. Soc. Guidebook of southern Arizona III.

Goldstein, M., E.E. Larson and D.W. Strangway. Paleomagnetism of a Miocene transition zone in southeastern Oregon, in press, Earth and Planetary Science Letters.

Larson, E.E., M. Ozima, M. Ozima, T. Nagata and D. Strangway. Stability of the remanent magnetization of rocks, in press, Geophysical Journal.

McDowell, F.W., 1966. Potassium-argon dating of Cordilleran intrusives, U.S. A.E.C. report No. NYO-1669-11.

Smith, P.J., 1967. The intensity of the geomagnetic field: a review and analysis, Geophysical Journal, 12, 321-362.

Strangway, D.W., B.E. McMahon and E.E. Larson, 1968. Magnetic paleointensity studies on a recent basalt from Flagstaff, Arizona, J.G.R., 73, 7031-7037.

Thellier, E. and O. Thellier, 1959. Sur l'intensite du champ magnetique terrestre dans le passé historique et geologique, Annales de Geophys., 15, 285.

Van Zijl, J.S., K.W.T. Graham and A.L. Hales, 1962. The paleomagnetism of the Stormberg lavas, I and II, Geophysical Journal, 7, 23 and 169.

Wilson, R.L., S.E. Haggerty and N.D. Watkins, 1968. Variation of paleomagnetic stability and other parameters in a vertical traverse of a single Icelandic lava, Geophysical Journal, 16, 79-96.

TABLE I

A. Basaltic Andesite

Arizona		Polarity	NRM/TRM 600°C after demag. at 500 oe	NRM/TRM 600°C after demag. at 800 oe	Paleofield-oe
Bryce Mountain	8A	Int.	.19	.25	.13
	9A	Int.	.61	.54	.35
	15A	R	-	1.1 (NRM / TRM 800°C)	.66
Turtle Mountain	19A	N	.60	.69	-
	27A	R	.22	-	-
Sheldon Mountain	31A	N	.58	-	-
New Mexico					
Gila Canyon	22A	R	.23	.26	.16
	22B	R	.25	.30	
	23A	R	.89	.88	.51
	23B	R	.82	.78	

TABLE II

Rhyolites

New Mexico		Polarity	NRM/TRM after demag. at 800 oe	Paleofield oe
Kneeling Nun - Dwyer quadrangle	7A	R - no good	-	0.37 (?)
Razorback "	9A	N - no good	-	
Caballo Blanco "	16A	R	.67	.41
Bloodgood Canyon - Gila Canyon	27B	R	.62	.38
	29A	R	.68	
	34A	R	.62	
	34B	R	.59	
	35A	R - no good		
	35B	R - no good		

TABLE III

Hysteresis Loop data

Sample No.	Jr emu/gm.of rock	Js (8000 oe) emu/gm.of rock	J_r/J_s	Saturation achieved	NRM carrier	TRM carrier at 800°C
Basaltic Andesites						
AV 9A	.037	.147	.25	Yes	magnetite	magnetite
AV 9A (heated to 800°C)	$<$0.0018	.062	$<$.03	No		
AV 27A	.032	.127	.26	Yes	magnetite	magnetite
AV 27A (heated to 800°C)	$<$0.006	.154	$<$.04	No		
AV 31A	.0038	.015	.25	Yes	magnetite	hematite
AV 31A (heated to 800°C)	.0026	.0192	.13	No		
Rhyolites						
NMV 7A	.187	.764	.25	Yes	magnetite	hematite
MNV 16A	.00095	.0040	.24	Yes	hematite	hematite
MNV 27A	.0019	.0062	.30	No	hematite	hematite
MNV 34A	.0028	.016	.18	No	hematite	hematite
MNV 35A	.0635	.314	.20	Yes	hematite	hematite

Figure Captions

1. Location map showing the Georgetown quadrangle in Massachusetts.

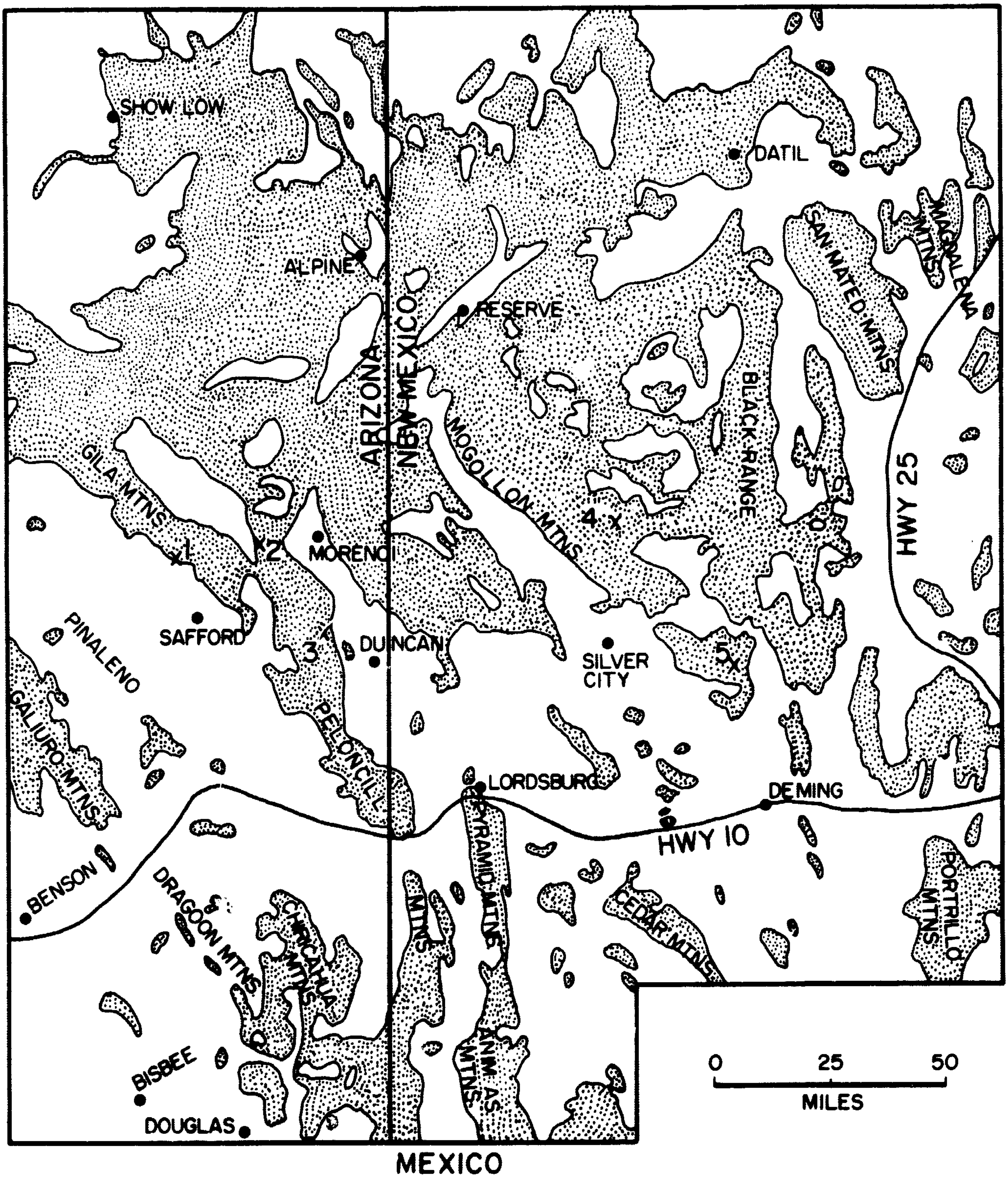
2. Direction of magnetization in conglomerate pebbles derived from a boulder a) before demagnetization
b) after demagnetization at 200 oe.

3. Direction of magnetization of Newbury volcanics with no structural correction a) before demagnetization
b) after demagnetization at 200 oe.

4. Direction of magnetization of Newbury volcanics after structural correction a) before demagnetization
b) after demagnetization at 200 oe.

5. Triassic Pole Positions - North America:

1. Chugwater; 2. Chinle; 3. New Oxford; 4. Newark;
5. Conn. Valley; 6. Mass. lava; 7. Diabase, Pa.;
8. Chugwater; 9. Nova Scotia dike; 10. Maroon fm.,Colo.;
11. Moenkopi; 12. Springdale; 13. Mass. lavas;
14. North Mountain basalt, Nova Scotia; 15. Manicouagan, Que.;
16. Newbury volcanics, Mass.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GILA MTNS
MOGOLLON MTNS
HWY 25
1
2
3
4
5
MORENCI
SAFFORD
DUNCAN
SILVER CITY
PINALENO
GALIURO MTNS
PELONCILL
LORDSBURG
DEMING
HWY 10
BENSON
DRAGOON MTNS
CHIRICAHUA MTNS
MTNS
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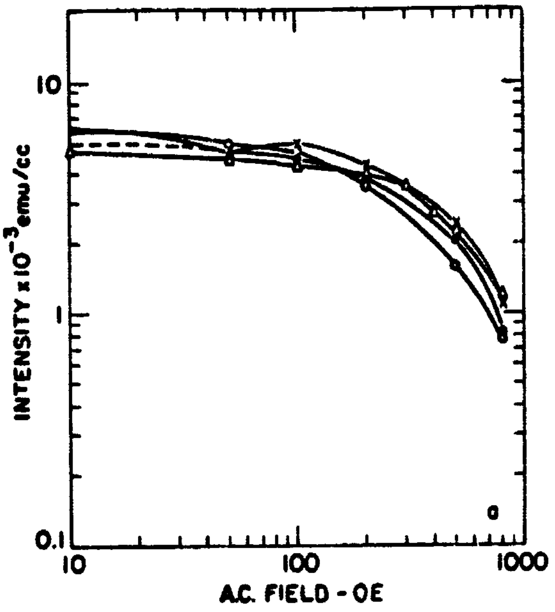
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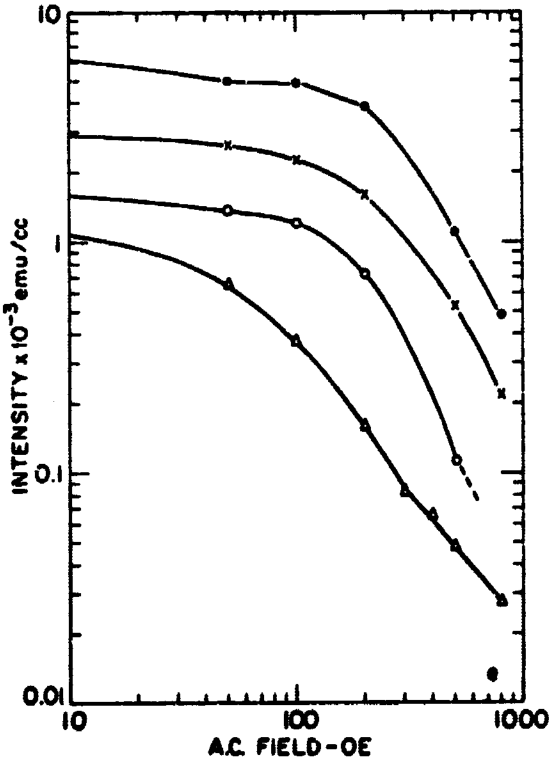
100
1000
A.C. FIELD - OE
a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INTENSITY x 10^{-3} emu/cc
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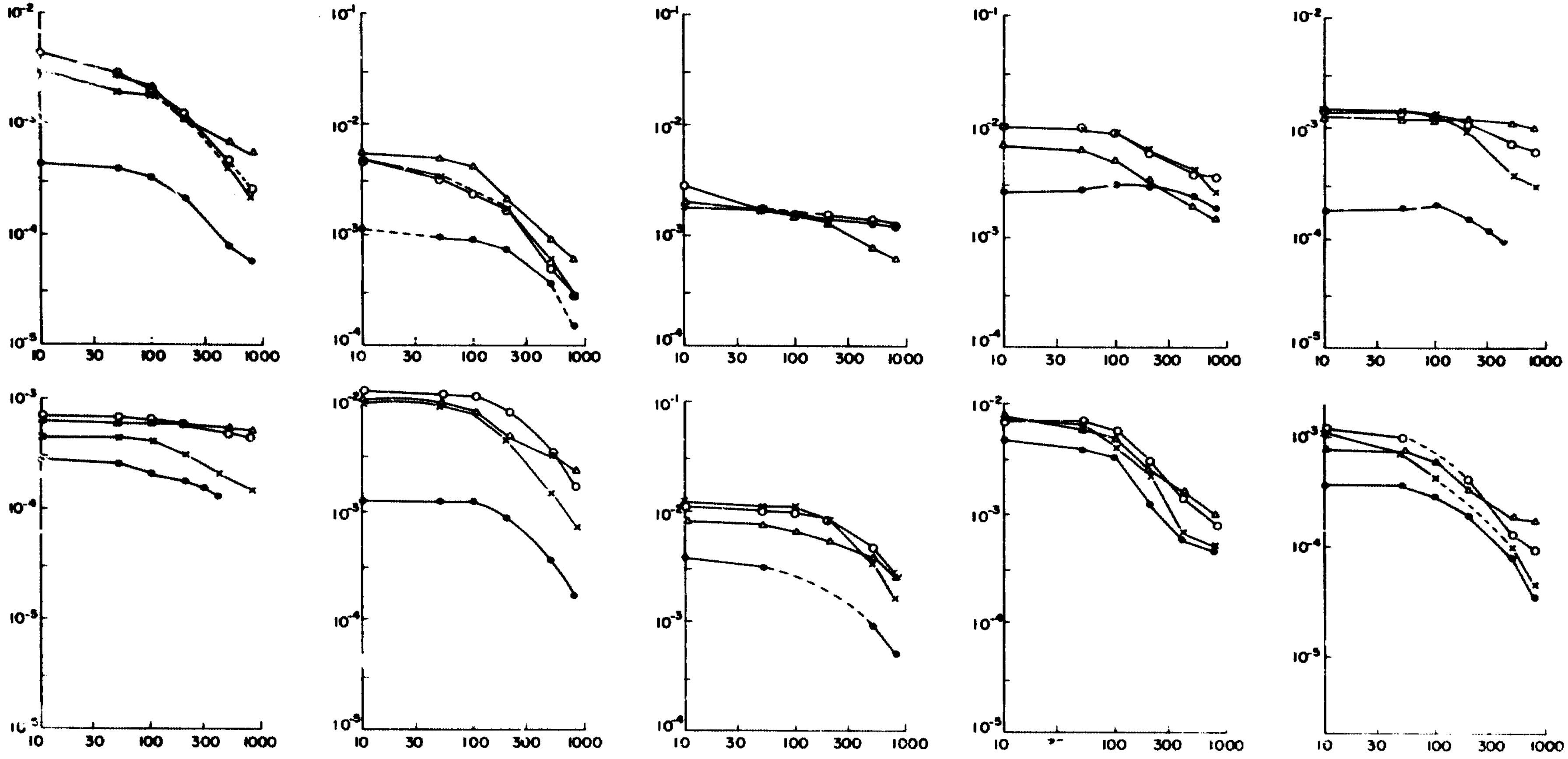
A.C. FIELD - OE
b



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10^{-3}
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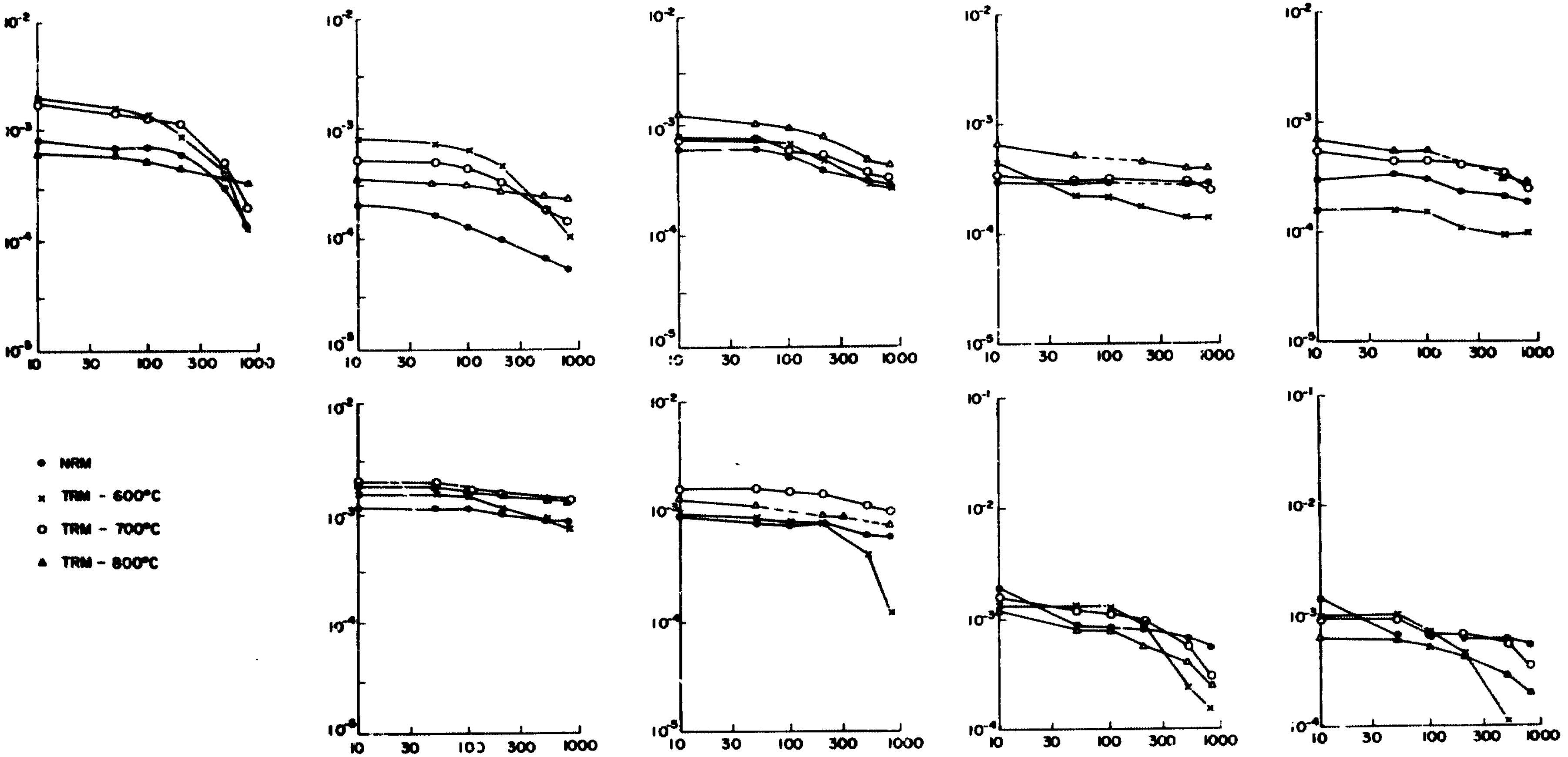

10^-2
10^-3
10^-4
10^-5
10
30
100
300
1000
10^-1
● NRM
× TRM - 600°C
○ TRM - 700°C
▲ TRM - 800°C

Paleomagnetic Study of the Newbury Volcanics, Massachusetts

David W. Strangway

Abstract

The Newbury volcanics are located a few miles north-east of Boston, Mass. and on the basis of fossils are considered to be Upper Silurian or Lower Devonian in age (about 400 my.). Dating has shown them to be about 350 my. but this may be younger than the true age due to regional tectonic activity since they were formed. These volcanics are steeply dipping and it was possible to conduct a fold test. A conglomerate derived from the volcanics was also present and a conglomerate test was done. These tests show that the magnetization was acquired after folding and after the conglomerate was formed indicating that a secondary magnetization is dominant. The direction of magnetization corresponds closely to that found for Triassic rocks in North America. It is tentatively suggested that this material was remagnetized during the Triassic, perhaps corresponding to the final stages of the Appalachian revolution or to the Palisades revolution. Due to the secondary magnetization no attempt has been made to determine paleointensity.

Introduction

The Newbury volcanics are located in Essex county in the Georgetown quadrange (fig. 1) a few miles north-east of Boston and have been under study by the United states Geological Survey (N. Cuppels, Pers. Comm.). Their age is not precisely known but fossil evidence points to an upper Silurian or lower Devonian age (about 400 my.). The fossils are contained in interbedded marine shales and limestones. The volcanics are highly contorted and dip very steeply to the east and west. The total thickness of the sequence may be about 5000 feet. Rubidium-strontium age dating on these rocks gives an age of about 345 ± 10 my. for upper Devonian, while the nearby Cape Anne granite gives an age of 420 my. (Bottino, 1963). The discrepancy between the fossil and isotope dating of the volcanics may be due to metamorphism after the formation of volcanics, so that a subsequent thermal event may be involved. The volcanics consist of rhyolites and andesites and have been thought to be related to the Cape Anne granite.

Paleomagnetic Results

[illegible] samples were taken from each of nine locations (one of these from the Cape Anne granite). In general one or two cores were taken from each specimen and the direction of magnetization measured. One sample was a single conglomerate boulder containing a group of randomly oriented pebbles. Seven pebbles were separated and measured for a conglomerate test. The boulder was initially unoriented so that the actual direction of magnetization was unknown. The test was only for randomness. These results are shown in figs. 2A and 2B before and after demagnetization at 200 oe. Some scatter is evident in the data before a.f. cleaning, but after demagnetization a quite consistent grouping is found. This indicates that a magnetization was acquired after the conglomerate was formed and was not a result of initial cooling of the magma. It seems probable that this was due to subsequent reheating.

The results from the rest of the sample sites are displayed in figures 3 and 4. These sites were selected to sample stratigraphically through the sequence as well as on structural blocks with various orientations. Figure 3 shows the results of making no structural corrections. Before demagnetization the data are quite scattered but after the demagnetization a fairly well grouped set of directions is found. Two specimens of Cape Anne granite have a different direction. Some of the volcanic samples are reversed indicating that the magnetization was not acquired at a single time or else a self-reversal has taken place. The pole position derived from these data (excluding the Cape Anne granite) is given in table I and shown in figure 5. It is seen that this pole position corresponds fairly closely to the Triassic pole positions which have been found for North America although it tends to lie too far west. If the unit has been remagnetized it is therefore possible that this was accomplished during the Triassic, long after the original rocks were extruded as a series of pyroclastic volcanics and folded.

The same magnetic data are presented in figure 4 after correction for the structure. Here it can be seen that the magnetization is considerably more scattered than if no structural correction had been applied. This application of Graham's fold test indicates that the magnetization was acquired after folding. In view of the conglomerate test, the fold test and the approximate Triassic direction of magnetization it appears that these volcanics were remagnetized long after their formation, probably in Triassic times at the time of the formation of the Triassic valleys of the Appalachian area.

On demagnetization, the intensity of magnetization decreases slowly as is typical of other acid volcanics. It seems probable that hematite is carrying much of the magnetization found in these samples. Studies in progress on a series of samples from New Mexico support this observation.

Acknowledgements

Norm. Cuppels of the USGS showed the locations for sampling and discussed the problems of the geology in great detail. D.H. Enggren made the measurements reported here. The work was supported by NASA as part of the returned lunar samples program.

References

Bottino, M.L., 1963, Whole-rock Rb-Sr studies of volcanics and some related granites. 11th Annual Progress Report, U.S. A.E.C., Report from M.I.T. by P.M. Hurley, et al.

TABLE I

Pole Position - Newbury Volcanics - uncorrected for structure and after A.F. demagnetization at 200 oe

N	D	I	K	α_{95}	Long.	Lat.	δ_M	δ_P
13	22	31	29.5	7.8	294	58	7	5

Figure Captions

1. Location map of sample areas from southwestern New Mexico and southeastern Arizona.

   1. Bryce Mtn; 2. Turtle Mtn; 3. Sheldon Mtn; 4. Gila Canyon;

   5. Dwyer Quadrangle.

   Shaded areas covered by Tertiary volcanics.

2. Representative A.F. demagnetization curves.

   a) unoxidized magnetite; b) oxidized magnetite.

   NRM   TRM acquired on cooling from 700°C.
   TRM on cooling from 600°C   TRM acquired on cooling from 800°C.

3. A.F. demagnetization curves for basaltic andesites.

   NRM
   TRM acquired on cooling in earth's field from 600°C.
   "   "   "   "   "   "   "   "   700°C.
   "   "   "   "   "   "   "   "   800°C.

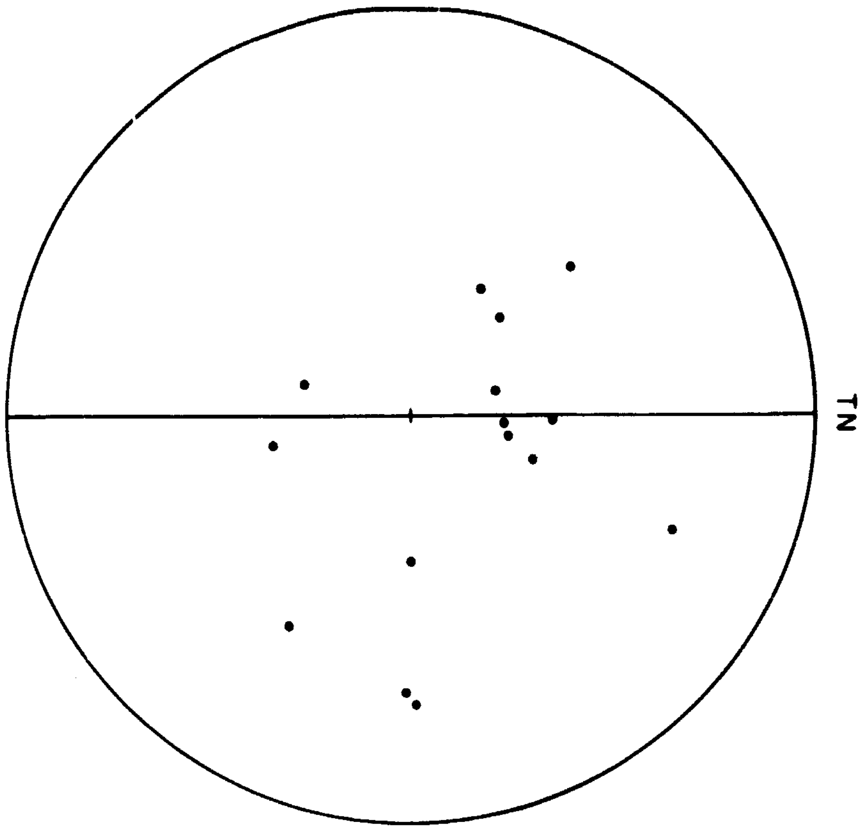
   horizontal scale - peak demagnetizing field in oersteds.

   vertical scale - intensity in emu/cc.

   a. AV8A; b. AV9A; c. AV15A; d. AV19A; e. AV27A; F.AV31A;
   b. NMV 22A; h. NMV22B; i. NMV23A; j. NMV23B.

4. A.F. demagnetization curves for rhyolitic lavas - legend as in figure 3:

   a) NMV7A; b) NMV9A; c) NMV16A; d) NMV27B; e) NMV29A;
   f) NMV 34A; g)NMV34B; h) MNV35A; i) NMV35B.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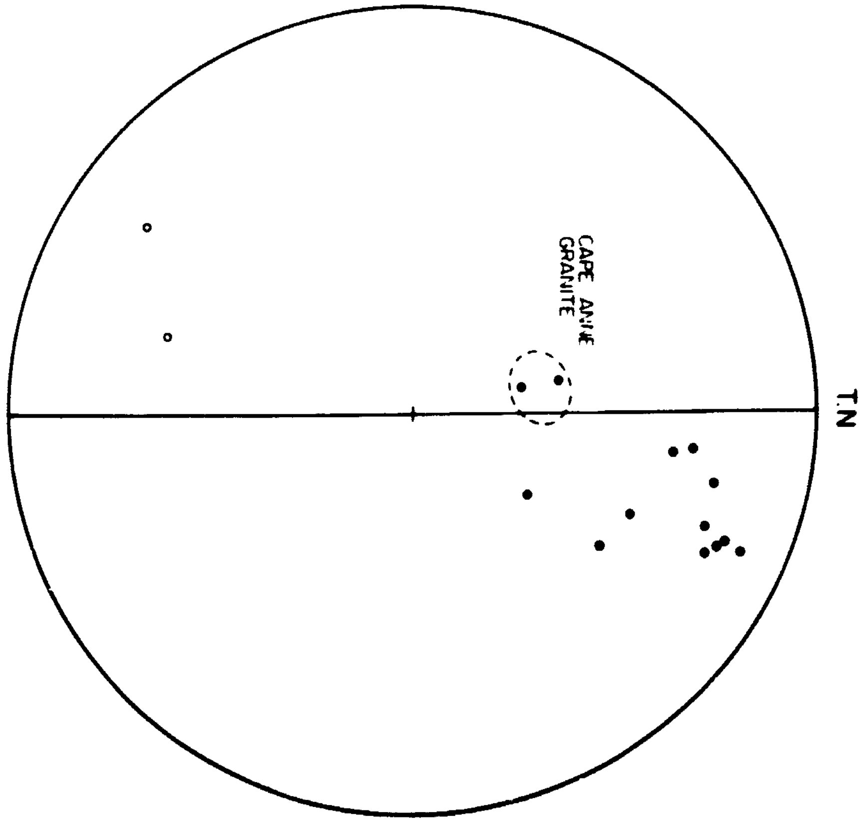
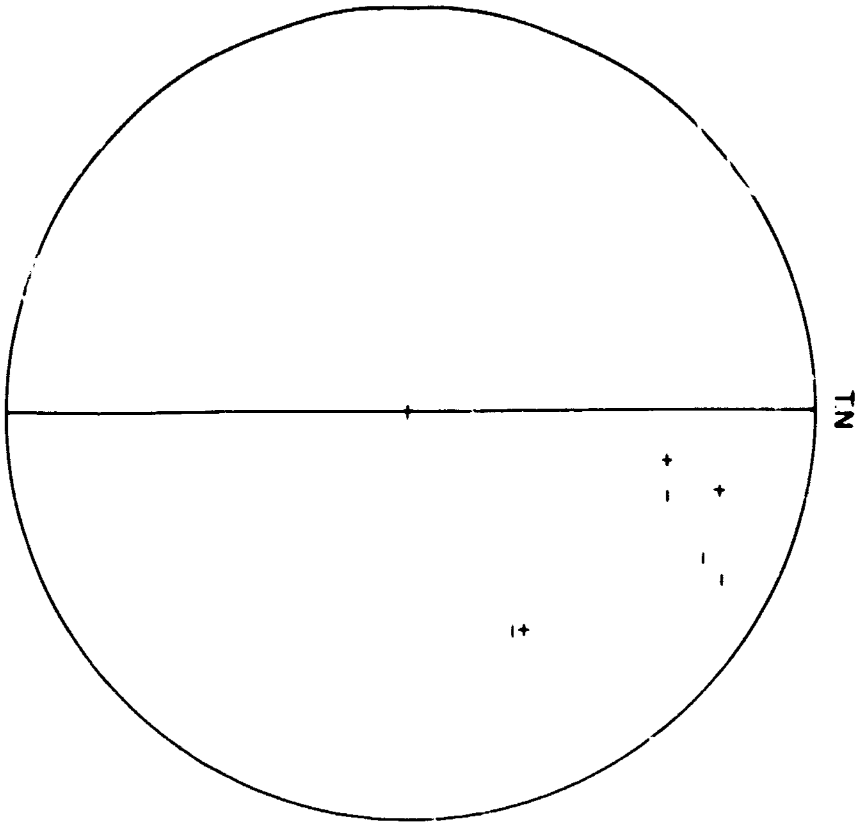

CAPE ANNE GRANITE
T.N



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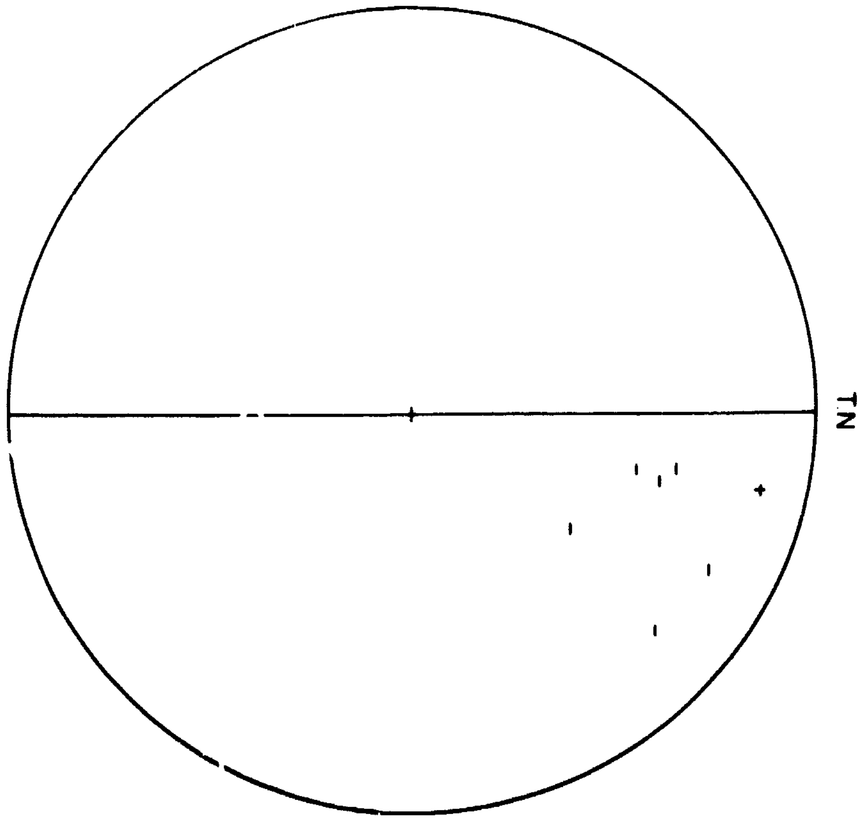

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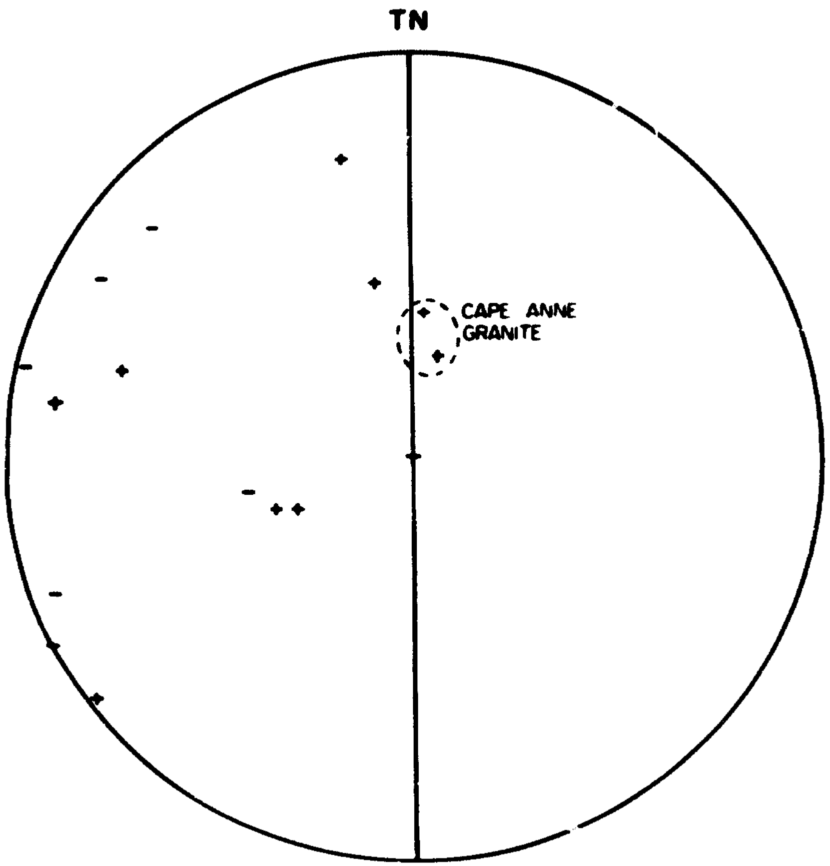
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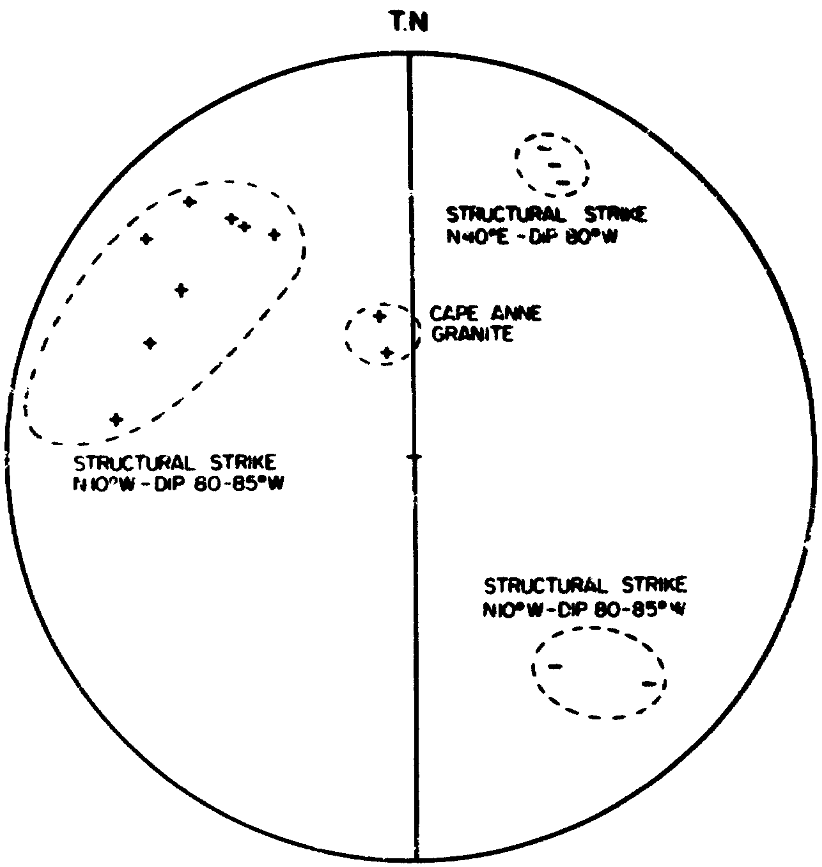
CAPE ANNE
GRANITE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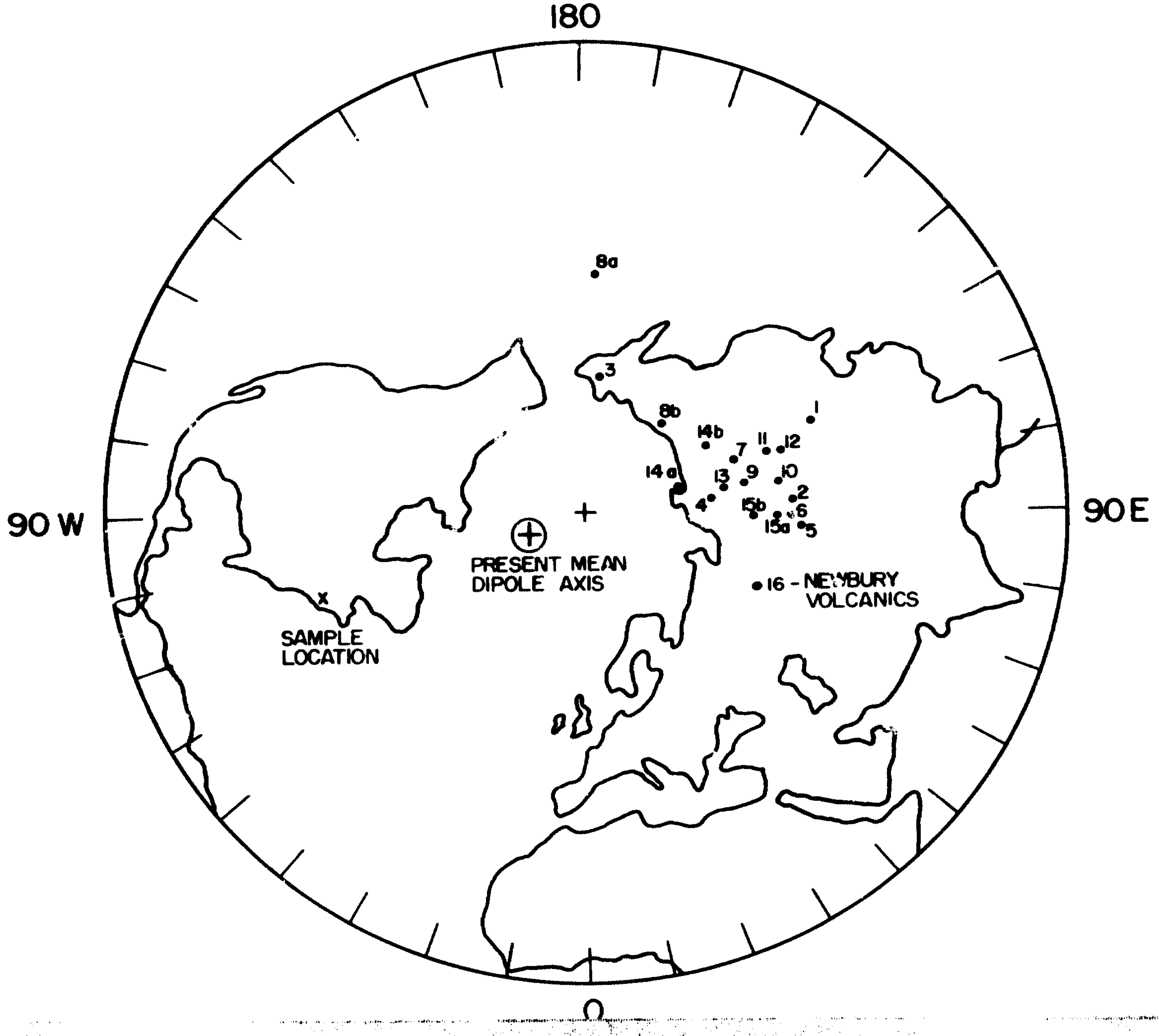
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11
12
7
14 a
13
9
10
2
4
15b
6
15a
5
16 - NEWBURY VOLCANICS
PRESENT MEAN DIPOLE AXIS
x
SAMPLE LOCATION

The convective acceleration is expressed above partly in terms of the spherical coordinates r and θ. If desired, the spatial coordinates corresponding to the spherical coordinates can be obtained numerically from the transformation relations between the two coordinate systems. Using the above relationships the momentum equation can be easily resolved into components along the $\hat{i}_{\parallel}$, $\hat{i}_{\perp}$ and $\hat{i}_{\varphi}$ directions.

5. Conclusions

In order to investigate the properties of a plasma in a dipole field, the coordinates and the form of the equations expressed in this paper are very useful in determining the coupling between the different processes occuring in the medium. This is especially true for a thermal plasma with non-vanishing macroscopic velocities since the coordinate directions selected correspond to the directions in which the most significant physical processes occur.

Bibliography

Angerami, J. J. and J. O. Thomas, Studies of Planetary Atmospheres, J. Geophys. Res., 69, 4537-4560, 1964.

Gothard, N., A Note on the Description of Dipole Fields, Radio Science, 2, No. 9, 1105-1108, 1967.

Tamao, T., Temperature Distribution in the Magnetosphere, Report Ionosph. and Space Res. in Japan, 20, 312-321, 1966.

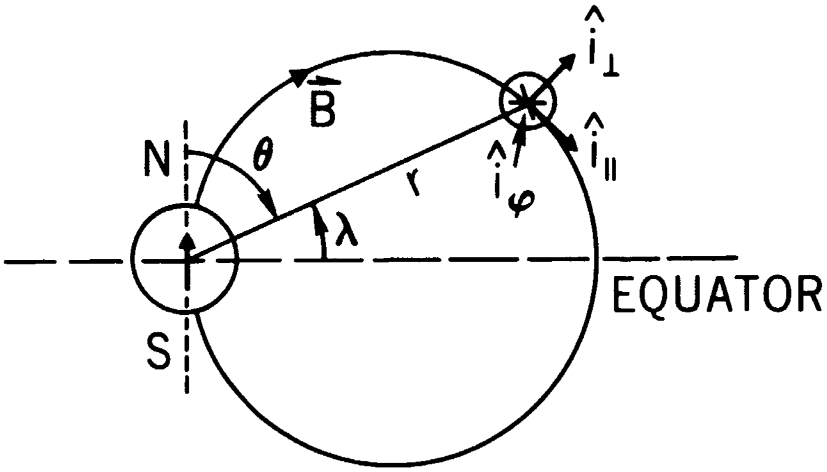

Figure 1(a)–Coordinates and directions pertinent to a dipole field line in a meridian plane

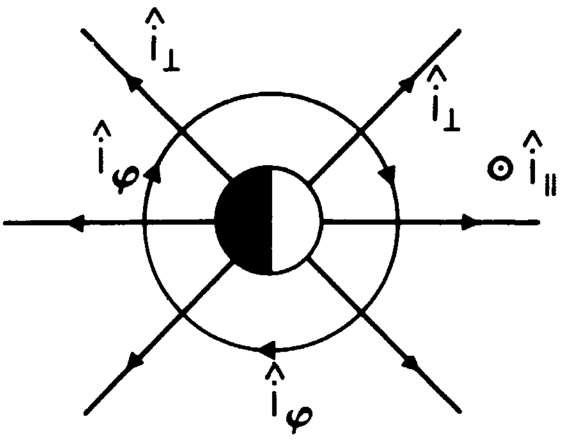

Figure 1(b)–Coordinate directions in the equatorial plane

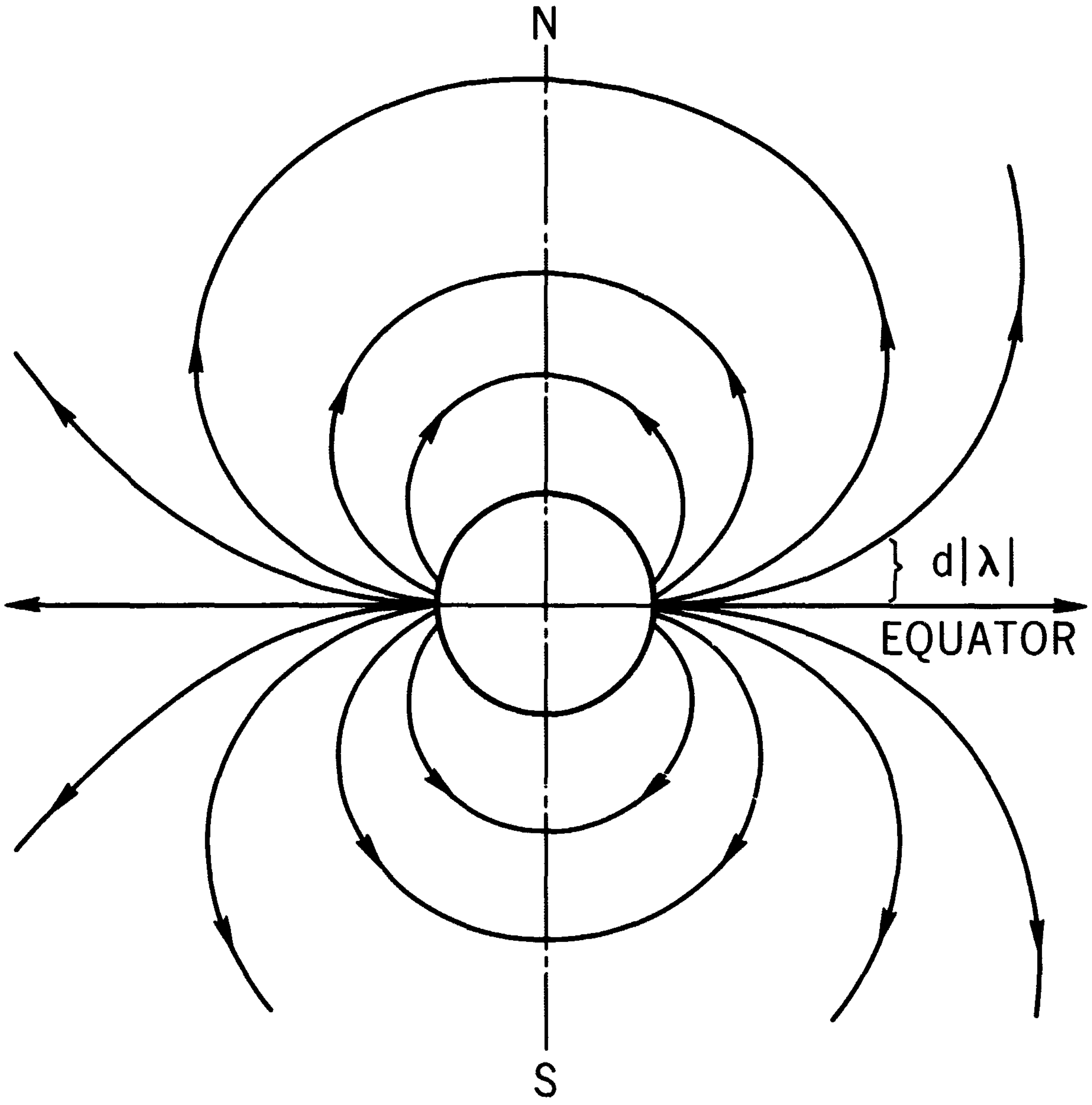

Figure 2–Equipotential lines in a meridian plane