PALEOMAGNETISM OF THE MESOZOIC LAMPROPHYRE DIKES IN NORTH-CENTRAL NEWFOUNDLAND

JAGAT NANDAN PRASAD

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A Thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science

Department of Physics
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ABSTRACT

A paleomagnetic study of 86 samples from 18 lamprophyre dikes collected from the Notre Dame Bay area in north-central Newfoundland was done to define their age of emplacement. Published K-Ar dates of 144 to 115 m.y. (Late Jurassic to Early Cretaceous) from the dikes place these among the youngest rocks in eastern Canada. Measurements of natural remanence (NRM) give directions closely aligned to the present field at the site. A detailed alternating-field (AF) demagnetization yielded stable directions with optimum vector grouping for 9 dikes at 10-35 mT peak field. Similarly, the thermal treatment showed stability of remanence with tightest grouping at 300°C for 8 dikes and at 500°C for 7 dikes. The overall mean directions corresponding to thermal and AF cleaning are indistinguishable at 95% confidence level, which gives confidence in the stability of remanence obtained from two independent tests.

The AF and thermal treatment coupled with thermomagnetic analysis and an isothermal remanence (IRM) study indicate that the stable remanence resides in a single component of magnetite or titanomagnetite. Studies of Rayleigh loops and high-field hysteresis loops suggest that the natural remanence is carried by a mixture of fine-grained single-domain and pseudo-singledomain magnetites of stoichiometric to cation-deficient composition. The AF and thermal mean directions correspond to poles 75°N, 168°W (dp, dm = 7.4°, 9.7°) and 72°N, 152°W (dp, dm = 5.2°, 6.6°) respectively, which are in good agreement with each other.

Both poles are of normal polarity, though the present study revealed for the first time the occurrence of a reversed polarity (with well-grouped directions in one dike only) among the Notre Dame Bay lamprophyres. These pole positions are intermediate between the poles reported previously from two other lamprophyre localities in the Notre Dame Bay area, and also are intermediate between the Lower Cretaceous poles and Jurassic poles reported from other parts of the Appalachians. This suggests a good correlation between the age of magnetization and the range of available radiometric dates.

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CHAPTER 1

INTRODUCTION

1.1 Aim of Paleomagnetic research

Paleomagnetism is the study of the history of the earth's magnetic field preserved in rocks. A large variety of rocks can acquire a remanent magnetization in the ambient field of the earth at the time of their formation by one or more of the processes described briefly in Section 1.2. The cause of this magnetization is the presence of a few percent or less of ferromagnetic mineral in the rock, the most common such constituents being iron oxides such as magnetite. The primary aim of paleomagnetic research is to establish a direction of the earth's ancient field from the measured magnetization of a rock unit, either sedimentary or volcanic, of more or less accurately known age; it is assumed that the rock became magnetized in the direction of the earth's field at the time of its origin. Obtaining an ancient field direction from a rock unit is essentially an empirical process and depends upon demonstration of internal consistency at three levels. First, the directions of remanent magnetization in a number of samples from a single exposure of the rock unit, while they may show some scatter, should cluster around a mean direction, sometimes only after removal of less stable components of magnetization. Secondly, the mean directions obtained from several such exposures separated widely within the same sampling locality should themselves be grouped in such a way that a reliable mean direction of a stable component of magnetization can be obtained for the whole locality. Lastly, rock units of the same age in different parts of the same land mass should give consistent directions. When internal consistency is exhibited at these three levels, it may be possible to define an overall mean remanent direction, and hence, a magnetic pole position relative to the land mass in terms of the present geographical co-ordinates. The interpretation of remanent direction in terms of geographic co-ordinates involves a fundamental assumption, that in the geological past the earth's main geomagnetic field, when averaged over periods of secular variation ($\sim 10^3$ years) has been dipolar and coaxial with the earth's spin axis. The determination of a paleopole, under suitable conditions, could then be used as an evidence bearing on certain geophysical and geological hypotheses.

The subject of paleomagnetism and its application to geological and geophysical problems has been lucidly explained by Cox and Doell (1960), Irving (1964), McElhinny (1973), etc. Similarly, the theories of rock magnetism are dealt with in detail in Nagata (1961), Stacey and Banerjee (1974) and several other authors.

1.2 Processes of magnetization of rocks

The mechanism by which the remanence is acquired depends upon the mode of formation and subsequent history of rocks as well as the characteristics of the magnetic minerals. Acquisition of magnetization by cooling from above the Curie point in a magnetic field is referred to as thermoremanent magnetization (TRM) which, in isotropic rocks, is parallel to the applied field. All igneous rocks containing ferromagnetic minerals acquire a TRM upon cooling from higher temperatures and, unless this is modified later in the geological history, will carry a memory of the field which produced it.

Magnetic minerals could also acquire a remanent magnetization, without heating, in a steady magnetic field at constant temperature, leading to the acquisition of isothermal remanent magnetization (IRM). In natural minerals, IRM is usually much less intense than the TRM generated in the earth's field and, except in highly anisotropic rocks, is always found experimentally to be parallel to the applied field. An IRM acquired by most of the rocks in a field as weak as the earth's, however, is very small. Rocks also tend to acquire a secondary magnetization termed the viscous remanent magnetization (VRM), with an average direction parallel to the weak applied field. This results from the gradual, isothermal alignment of the magnetic grains into equilibrium energy configurations. Viscous magnetization is both time- and temperature-dependent and its acquisition, or its decay once acquired, is proportional to the logarithm of time at a constant temperature, but at higher temperatures the process is accelerated. VRM can range from a very soft remanence residing in low-coercivity components to very hard magnetizations acquired by rocks that have been exposed to the steady (earth's) field at elevated temperatures for a relatively long time, e.g., during long-time burial by other rock formations. VRM can be important in rocks, since some rocks change their magnetization when stored in the laboratory even for a few days or months. Rocks whose NRM is prone to large viscous effects are usually unsuitable for paleomagnetic study.

Sediments consisting of magnetic and non-magnetic particles might acquire a stable remanence as the particles settle in water and the magnetic ones are oriented by the earth's magnetic field. This gives rise to depositional or detrital remanent magnetization (DRM) in the subsequently consolidated sedimentary rock.

Remanence may be acquired by a chemical transformation at a temperature less than the Curie temperature, e.g., the reduction of weakly magnetic hematite to highly magnetic magnetite which acquires a stable remanence that is controlled by the field acting at the time of the transition, as the new material is nucleated. This is called chemical remanent magnetization (CRM). In sedimentary rocks it is often difficult to distinguish DRM from a CRM resulting from post-depositional chemical changes in the iron minerals. The latter process is particularly important in the case of red sediments in which post-depositional changes are often demonstrated in the laboratory.

1.3 Applications of Paleomagnetism

The magnetic study of rocks finds its application to problems chiefly of a geological or geophysical nature, described below.

1.3.1 Geomagnetic applications

The study of remanent magnetization of rocks enables one to extend the measurements of the geomagnetic field throughout geological time. Direct observations at observatories do give a detailed picture of the present field going back about 400 years, but are insufficient for studying long-term variations > 400 years ago. To go back to earlier historic times, the remanence preserved in historically dated lavas and archaeological material has been used as evidence. In this context, the strength of the ancient field also can be determined for an igneous rock or baked archaeological sample by a comparison of the intensity of natural remanent magnetization with the intensity of the thermal remanence acquired by the same material during heating and cooling cycles applied in a known field. The average pattern of the geomagnetic field for historical times can be obtained from analyses of the archaeomagnetic site directions from different parts of the world. The distribution of pole positions corresponding to these sites is found to be centered on the earth's axis of rotation, which suggests that during the last few thousand years, the average field has been that of an axial geocentric dipole. This picture has been extended back for a million years or so on the basis of remanence measurements of deep-sea sedimentary cores. For older rocks, however, tectonic movements become significant; nonetheless, rocks less than 20 million years may be assumed to have undergone very little lateral movement since their formation, because 20 m.y. is too recent for much continental drift to have taken place. Mean values of the pole positions derived from lavas and other rock types in this age range from various continents are distributed more or less symmetrically around the earth's axis of rotation, confirming the axial geocentric dipole hypothesis.

1.3.2 Reversals of magnetization

The occurrence of reversed magnetization in rocks was one of the earliest important discoveries of paleomagnetic research.

This raised three possibilities: that either the rocks could sometimes acquire a magnetization in opposite direction to the ambient field, or that the geomagnetic field periodically reverses its polarity, or that either process could occur at different times. Various mechanisms (Néel, 1955) are known by which a rock could self-reverse. This requires the presence of a specific mineral with two magnetic sublattices or of two different mineral components, where the two sublattices or components have different thermomagnetic behaviour. Nagata et al. (1952) produced the first self-reversal in natural minerals on the magnetic extract from the Haruna dacite in Japan, an experiment which was later pursued by Uyeda (1958) using synthetic materials. Natural self-reversal is, however, very rare and it has been established beyond doubt that the earth's magnetic field does periodically change its polarity. This is shown by the worldwide and simultaneous nature of the phenomenon as found from paleomagnetic studies, through correlation with the dates of the observed polarity changes as determined radiometrically in igneous rocks and by fossils in sedimentary rocks. A study of the relationships between rocks of a given normal or reversed polarity and of increasing age in different parts of the world has led to the construction, initially for the past 4-5 million years, of a time scale of polarity changes (the "Geomagnetic Polarity Scale") which can be used for the indirect dating of rocks whose age is unknown, and provides an insight into the nature and cause of the geomagnetic field. The polarity time scale constructed from paleomagnetic and radiometric observations has been qualitatively confirmed by the regular patterns of magnetic field anomalies of the mobile ocean floor (Heirtzler et al., 1968; Isacks et al., 1968), which in turn have made it possible in some cases to extend the geomagnetic time scale back in time beyond 4-5 million years.

1.3.3 Geological applications

Paleomagnetism has been excellently applied to the important phenomena of polar wandering and continental drift. Rocks of increasing age from the same land mass yield pole positions which, in general, are increasingly displaced from the earth's present axis of rotation. It is, therefore, possible to construct a curve connecting the average geomagnetic pole positions for each continent during geological time. The resulting tracks are called "apparent polar wandering (APW) curves." APW curves were first published by Creer et al. (1954) relative to western Europe and by Runcorn (1956) for North America. If it were found that the curves for the different land masses all coincided, this would be evidence for the occurrence of "true" polar wandering relative to an earth with fixed continents. Instead, the polar tracks for different land masses are all different. This divergence of APW paths can be interpreted in two alternative ways--continental drift or expansion of the earth's circumference. Continental drift is defined as the horizontal displacement of parts of the earth's crust relative to each other. That the apparent polar wandering is a consequence of continental drift has been emphasized by various authors and discussed at length in symposium volumes edited by Carey (1956), Runcorn (1962), Blackett et al. (1965), Garland (1966) and Markowitz and Guinot (1968). Independent support for the hypothesis of continental drift has come from paleoclimatology (Blackett, 1956, 1961; Opdyke, 1962).

Various hypotheses have been put forward to suggest that earth has been expanding since its formation and that the observed divergence of apparent polar path is a result of this (Hospers & Van Andel, 1967). Egyed (1956), who was the first to study these hypotheses on various geophysical grounds, estimated that the earth's circumference has increased by 0.2-0.5 cm/year. Fortunately, it is possible in principle to use certain paleomagnetic observations themselves for distinguishing expansion from continental drift in the evidence. If geomagnetic pole positions are determined from contemporaneous rocks in two widely separated regions on the same tectonically stable land mass, these poles should correspond if the radius of the earth at the time of formation was the same as it is today, but should diverge if the earth's radius has changed. From such tests Cox and Doell (1961) and Ward (1963) could neither confirm nor reject the moderate rate of expansion suggested by Egyed. However, they ruled out the larger rates suggested by Carey (1956) and Heezen (1960). Recently, Carey (1975) has presented further arguments for global expansion, but at present an explanation of the observed paleomagnetic data in terms of continental drift on an earth of fixed radius is favoured by most authors.

1.4 Significance of Mesozoic paleomagnetic studies for North America

The problem of the age of opening of the Atlantic leading to the separation of North America from Europe and Africa has long attracted the attention of geologists and geophysicists. On the basis of available magnetic and gravity data bearing on the initiation of sea-floor spreading, and on other geological grounds, it is believed that most of the initial rifting of the Atlantic ocean took place sometime in the mid-Mesozoic. Therefore, a detailed knowledge of Mesozoic poles from various regions of North America could offer a powerful tool in our understanding of the early opening of the Atlantic, especially in the light of African paleomagnetic data (McElhinny, 1972, 1973). To date the positions of the Mesozoic paleomagnetic poles with respect to North America are fairly well established for the Triassic and Cretaceous periods, but few reliable poles exist for the Jurassic, and various determinations diverge widely. However, based on the reliable poles it is seen that the North American apparent polar wander curve passes from a reasonably well determined point in the late Triassic to a Jurassic position which is close to the present axial dipole location, and then southward to a Cretaceous position. The African paleopoles, on the other hand, from early Triassic to early Cretaceous are too close to each other to be distinguishable at the statistical level of confidence of 95% usually specified in paleomagnetism. Hence, the apparent motion of the North American pole could be interpreted as being related to the early opening of the North Atlantic in which a part of the relative movement would be possibly taken up by the North American plate. Furthermore, if it is supposed that the magnetization direction acquired during the Jurassic was close to that corresponding to the present axial dipole, the movement between Triassic and Cretaceous times was approximately 50°. This large amount of polar wandering could be related to actual continental movement of eastern North America occurring between Triassic and Cretaceous times, or it may be due to "true" polar wandering relative to the Earth's crust, or both. Paleomagnetic comparisons with other land masses are needed to decide between these alternatives.

1.5 Previous Mesozoic paleomagnetic studies in the Appalachians

Studies of Mesozoic paleomagnetism in the Appalachians began with the work of Du Bois et al. (1957) who published the first paleomagnetic data for the late Triassic rocks in the Connecticut graben of the United States. Bowker (1960) made an extensive paleomagnetic study of Triassic rocks from various parts of the Appalachians, but his results are of limited value because of incomplete magnetic cleaning of his samples. Further detailed studies were taken up by Irving and Banks (1961), Opdyke (1961), Beck (1965), Larochelle and Wanless (1966), De Boer (1968), Beck (1972), and Hodych and Hayatsu (1980). Most of the results of these studies are in excellent agreement and indicate that the upper Triassic-Lower Jurassic paleomagnetic pole for the Appalachian province is indistinguishable from the mean pole relative to other areas of North America, located at 87-105°E, 60-70°N.

Previous studies on Jurassic rocks of North America have given very inconsistent results, but the few paleopoles so far published for the Appalachian province are in good agreement. Opdyke and Wensink (1966) studied the radiometrically dated Jurassic White Mountain magma series in New Hampshire and Vermont. Their results gave pole positions close to the present rotation pole, that is, corresponding to the axial dipole. However, Steiner and Helsley (1974) do not regard the White Mountain pole as representative of the Jurassic period. De Boer (1967) obtained a pole position from dikes cutting Upper Triassic and older formations and structures along the length of the Appalachian trend and obtained a pole position midway between the Triassic and Cretaceous, concluding that the dikes might be Jurassic in age. Deutsch and Rao (1977), from their studies of Mesozoic lamprophyre dikes of Fortune Harbour, Notre Dame Bay, Newfoundland (Fig. 2.1) obtained a pole position close to the present rotation pole and in good agreement with the two above, presumably Jurassic, poles for the Appalachians. Lapointe (1979) sampled the lamprophyres from the Leading Tickles area of Notre Dame Bay, about 13 km west of Fortune Harbour. His results, however, show pole positions very close to the Cretaceous poles relative to North America. Thus, the two other Lower Cretaceous poles (Opdyke & Wensink, 1966; Larochelle, 1968) from the Appalachians are very close to Lapointe's pole. This suggests that there was either more than one time of igneous activity which produced the Notre Dame Bay lamprophyres or the intrusion and cooling involved a long time. The radiometric dates available for these dikes range from Upper Jurassic to Lower Cretaceous, which also supports the above assertion.

1.6 Objective

The primary aim of the present investigations was to determine the paleomagnetic pole position of lamprophyre dikes sampled from three widely separated areas on the coast of Notre Dame Bay, and to interpret the results in terms of age of magnetization using the few available paleomagnetic results of similar age from the Appalachians. At the time this study was initiated, only one other pole relative to these lamprophyres (Deutsch & Rao, 1977), based on sampling from a single area, was available for comparison with other Appalachian poles. A second result (Lapointe, 1979), which was significantly different from the former, was published when the present work was in progress. The apparent difference between the two poles from the same rock unit provided additional stimulus for the present investigations on the lamprophyres, in as much as these rocks are believed to be the signatures of the tectonic regimes that accompanied the initial opening of the North Atlantic. In the present investigations, the natural remanence magnetization (Chapter 3), and magnetic stability through systematic alternating-field and thermal demagnetizations (Chapters 4 and 5) of the lamprophyres have been studied. A brief discussion on the nature and domain states of the magnetic minerals in the lamprophyres (Chapter 6) is also given. A possibly primary (Jurassic) geomagnetic pole relative to the Appalachians, obtained in the present study, has been compared with other mid-Mesozoic paleomagnetic poles from the Appalachian province (Chapter 7).

CHAPTER 2

GEOLOGY AND SAMPLING

2.1 General geology of Notre Dame Bay

Notre Dame Bay and the land bordering it (Fig. 2.1) is situated in north-central Newfoundland, in the central portion of the Central Paleozoic Mobile Belt. In this area, sequences of volcanic, sedimentary and intrusive rocks of Ordovician to Devonian age are exposed. The area has undergone two major deformational orogenies--the upper Ordovician Taconic orogeny and the late Silurian to Devonian Acadian orogeny. The former has produced open folding on north-trending axes which were redeformed and tightened up, leading to north-east-trending folds and faults (Harris, 1973; Dean & Strong, 1977) during the latter episode. The Budgell Harbour gabbro of probable Jurassic age (Helwig et al., 1974) and the lamprophyre dikes of Jurassic to Cretaceous age (Wanless et al., 1965, 1967; Strong & Harris, 1974) are known to be the youngest rocks of this area. Published radiometric ages from this area are shown in Fig. 2.2. This youngest known igneous event in the Newfoundland Applachians is probably associated with the initial rifting which led to the formation of the present Atlantic Ocean.

2.2 General features and petrology of the lamprophyre dikes

Lamprophyre dikes occur as tabular masses forming radiating patterns around alkaline stocks. They have been described as "petrological curiosities" comprising incompatible mineral assemblages

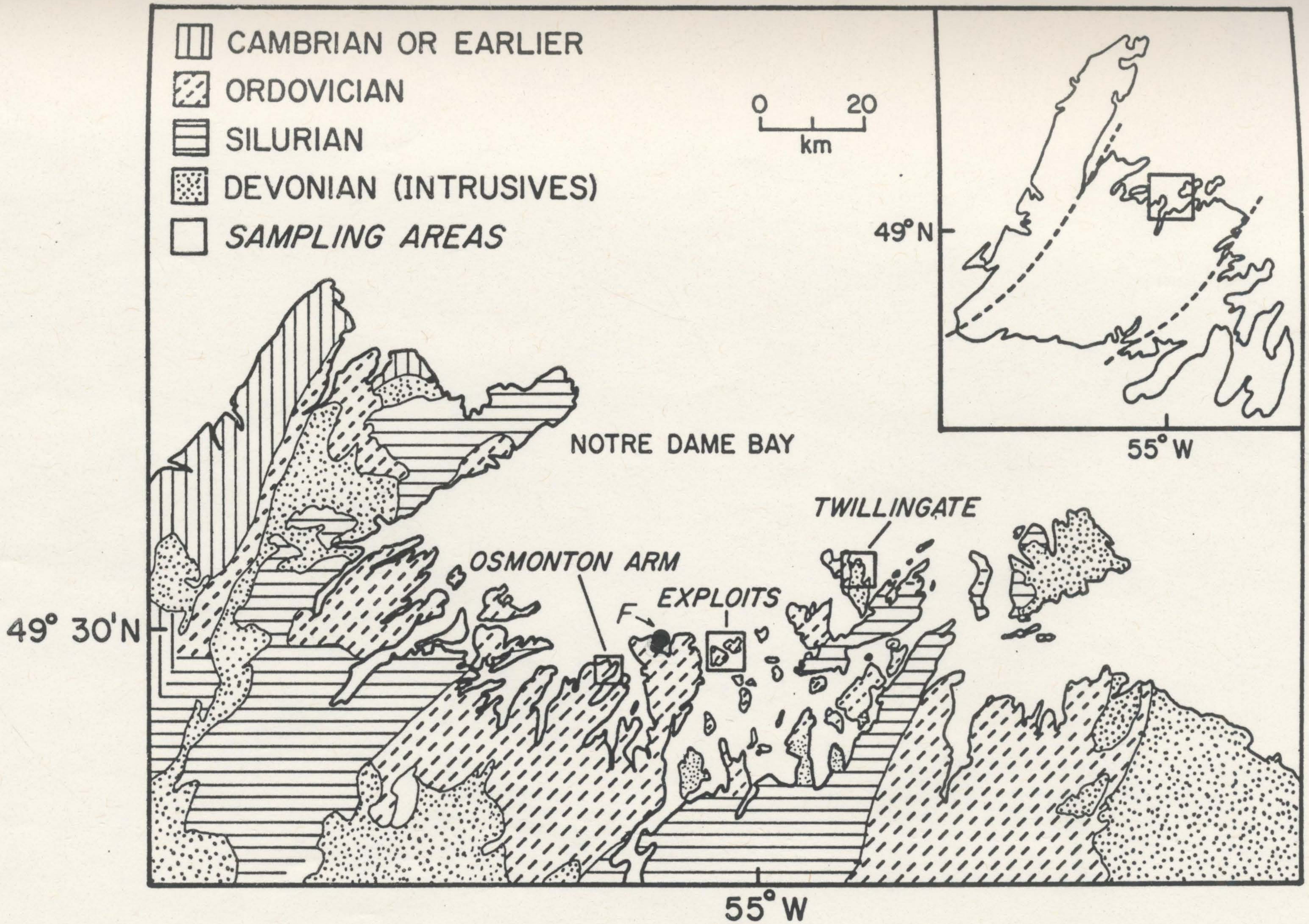


Fig. 2.1. General geological map of the Notre Dame Bay area of Newfoundland. □ Sampling areas. Area within dashed lines in the inset figure shows the Central Mobile Belt. F, Fortune Harbour area (Deutsch & Rao, 1977).

(e.g., olvine + clinopyroxene + biotite + kaersuitite) arising from liquid immiscibility (Strong & Harris, 1974). They range from thin veinlets to 1 m thick bodies and are rich in volatiles, though their composition is generally basaltic. Some features exhibited by these dikes to a varying degree are chilled margins, amygdules, faults, and fractures or joints. Biotite, augite, magnetite and hornblende phenocrysts are common and very fresh. The matrix minerals reported are feldspar, biotite, magnetite, analcite, serpentine and calcite (Helwig et al., 1974). The dikes generally strike NE to SW and are nearly vertical.

2.3 Sampling areas

Lamprophyre dikes were sampled for paleomagnetic studies from three areas (Fig. 2.2), Osmonton Arm/Budgell Harbour, Bay of Exploits, and Twillingate, all being located on the northernmost exposed part of the Central Mobile Belt.

Helwig (1967) has described the lamprophyres of the Osmonton Arm/Budgell Harbour area as being mainly vogesite, spessartite, and kersantite. The Budgell Harbour gabbro is the only pluton in this area which shows a strong correlation with the lamprophyre dikes that surround it in a radiating pattern. Biotite separated from this pluton yielded a K-Ar age of 155 ± 7 m.y. (in Harris, 1973). More recently obtained K-Ar ages for this pluton are 135 ± 8 and 139 ± 9 m.y. (Helwig et al., 1974), which is in fair accord with the previous age. Wanless et al. (1965) have dated a sample of biotite from a lamprophyre dike at the north end of Beach Island (Fig. 2.2) by the K-Ar method at 144 ± 12 m.y.

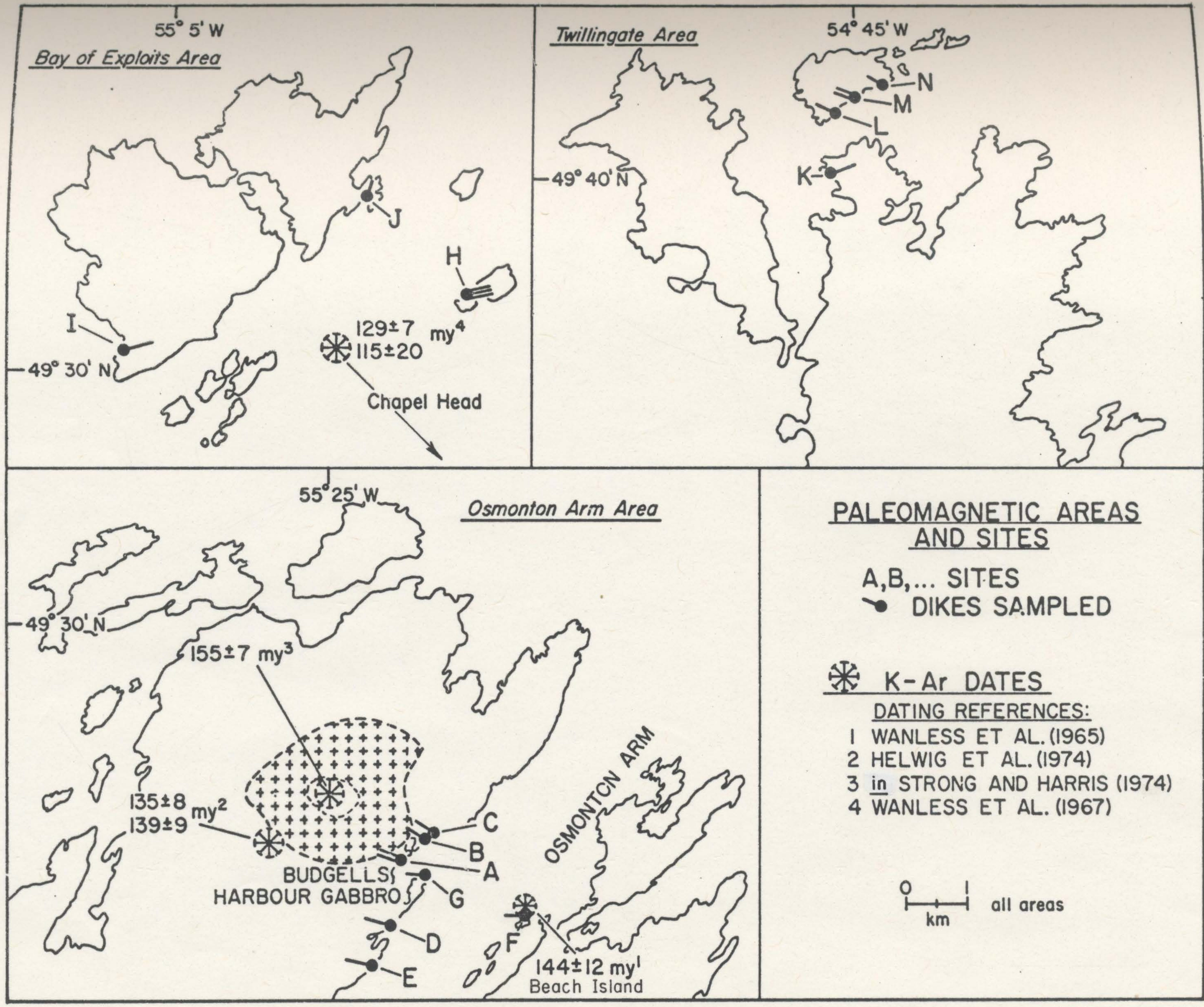


Fig. 2.2. Location of lamprophyre sampling sites in Notre Dame Bay. The Chapel Head radiometric site is 18 km SE of the locality shown.

The Bay of Exploits area lies about 25 km east of the Osmonton Arm area. Structurally this region is characterized by numerous closed folds and faults. Its geology has been studied by Heyl (1935), who describes the lamprophyres of this area as consisting mainly of monchiquites and fourchites. The dikes are steeply dipping, ordinarily very close to the vertical. Usually they are undisturbed, but some are displaced by minor faults. They range in thickness from 30 cm to 1 m and sometimes occur in parallel sets of two or more dikes. A group of three parallel dikes occurring on the western end of Mathew Lane Island was sampled for this study (Site H, dikes 9, 10, 11). In some dikes of this region there are large biotite phenocrysts (> 1 cm) while others are aphanitic throughout. There is an absence of metamorphism of the country rock adjacent to the dikes, which indicates a relatively low temperature at the time of intrusion. Biotite and hornblende from a dike about 1.6 km north-east of Chapel Head have been dated (Wanless et al., 1967) 129 ± 7 m.y. and 115 ± 20 m.y. respectively, these dates comparing reasonably well with the earlier date of 144 ± 12 m.y. from the Beach Island lamprophyre and the pluton dates cited, suggesting a close genetic relationship between different lamprophyre dikes of Notre Dame Bay and between the lamprophyres and the Budgell Harbour gabbro. This is further supported by the chemical evidence discussed by Harris (1973) and Strong and Harris (1974).

The Twillingate area is another 30 km north-east from the Bay of Exploits area. This area consists of Ordovician and Silurian sedimentary and volcanic rocks which have been folded and faulted and intruded by igneous rocks of different kinds. A north-south tectonic trend, superimposed on the north-easterly trend common throughout Newfoundland including the Notre Dame Bay region, is apparent in the rocks of Twillingate Islands and north-western New World Islands (Williams, 1963). Most lamprophyre dikes of this area contain large biotite phenocrysts, some of which measure up to 5 cm in diameter. Though the lamprophyres of this area do not appear to have any genetic relation with the Budgell Harbour gabbro, their similar petrography suggests a source comparable to the Budgell Harbour gabbro.

2.4 Sampling techniques

The sample collections comprised a total of 52 cores (2.4 cm in average diameter) drilled by a portable field drill, and 34 hand samples, from 18 dikes distributed throughout the three sampling areas described above. These dikes were sampled at 14 sites (Sites A to N, Fig. 2.2). Sites A and M consist of two dikes each (dikes 1, 2, and 16, 17, respectively) in close proximity, and similarly Site H consists of three parallel dikes (9, 10, 11). Generally, more than 3 samples, but fewer than 8, were collected from each dike in order to make it possible to detect any gross orientational error and also to allow a comparison of within-sites magnetic properties.

Orientation of the samples with respect to their in-situ attitudes was done by well-established methods, using a Brunton compass with either a level (hand samples) or an inclinometer (cores). It was possible that the rocks are sufficiently magnetic to deflect the Brunton compass by a significant angle from the earth's field direction. As a quick test of this possibility, several spot tests in which the Brunton readings were compared with solar compass readings or with map sightings of distant objects indicated that the Brunton readings were not significantly affected by the magnetization of the rock itself, and Brunton readings were always used in orienting the samples.

In the laboratory, the core samples were cut into one to four specimens of diameter 2.2 cm and average height of 2.1 cm and one to two cores were drilled from each hand sample. Altogether 123 specimens from 52 core samples and 82 specimens from 34 hand samples were thus obtained, giving a total of 205 measurable specimens.

CHAPTER 3

MEASUREMENT OF NATURAL REMANENT MAGNETIZATION

3.1 Techniques of remanence measurements

Remanent magnetization in rocks has been measured until recently with just two main types of instruments--the astatic magnetometer and the spinner magnetometer, both types being available at the Geomagnetic Research Laboratory. In astatic magnetometers, there is an arrangement of two or more magnets with nearly zero net magnetic moment suspended by torsion fibre. While this system is insensitive to an ambient uniform field, it will respond to the non-uniform field of an appropriately placed magnetized rock sample. But the astatic system is not adequately stable against the field variation in magnetically noisy environments. Though many improvements in the system have been made since the pioneering work of Blackett (1952), the use of astatic magnetometer for routine paleomagnetic measurements has been replaced by spinner and cryogenic magnetometers.

In spinner magnetometers the magnetized rock sample is rotated alternately about different spin axes at constant speed. Spinner magnetometers are of two main designs in which the sensing device, located close to the rotating specimen, is either a pick-up coil arrangement or a fluxgate sensor. In the former case the component of remanence perpendicular to the spin axis produces an alternating voltage in the pick-up coil which is proportional to, among other factors, the magnetic moment of the remanent component.

In the fluxgate system the second-harmonic signal from the secondary winding surrounding a fluxgate core, being modulated due to the spin of the specimen, is amplified and filtered. In both types of spinners the analyzed signal is displayed simultaneously in two orthogonal components and, although only two independent spins are needed to determine the declination, inclination and intensity, it is customary to subject any specimen to six spins so as to average out the effects of off-centre positioning of the rock in the holder, imperfect alignment of the holder in the rotor and inhomogeneity of the rock.

In the present study, all remanence measurements were done on a commercial Schonstedt digital magnetometer (Model SSM-1), which is of fluxgate type and has a low spin rate of 5 Hz to permit the spinning of fragile specimens. The minimum detectable magnetization of a specimen on this magnetometer is of the order of 10^{-4} A/m. As the intensity of the rocks in the present study is greater by several orders than this limit, a good result could be obtained with this instrument.

3.2 Results of the NRM measurements

The natural remanent magnetization (NRM) of all the specimens from each sample was measured relative to the in-situ position of the rock. The sample mean direction was obtained by vectorially averaging the specimen directions, giving each unit weight. The sample and dike mean intensities of magnetization (J) were obtained by calculating the arithmetic mean of the specimen and sample intensities respectively. For individual specimens the intensities were in the range of 0.5 to 7.9 A/m which is plotted in the form of a histogram in Fig. 3.1. The declination, inclination and intensity for each specimen were obtained from the spinner data by the use of a TI 59 programmable desk calculator. A separate

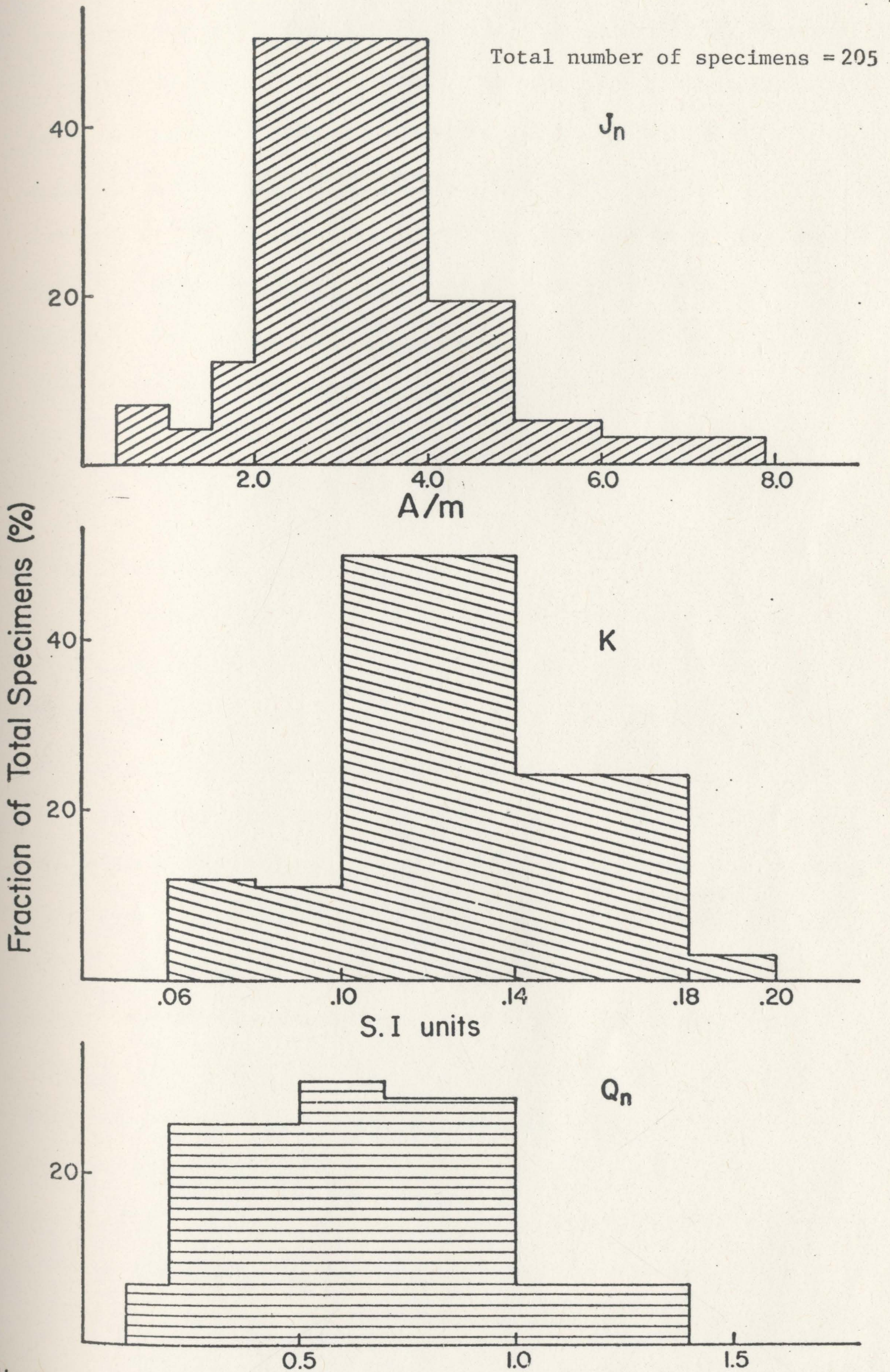


Fig. 3.1. Histograms of NRM intensity (Jn), Magnetic susceptibility (K) and Koenigsberger ratios (Q).

programme was used for the calculation of Fisher's (1953) statistics. The dike-mean directions and Fisher's statistics are plotted in Fig. 3.2 and summarized in Table 3.1. Although within-dike mean directions are not very well grouped, the between-dike mean directions are grouped fairly well (α_{95} = 5.3, k = 44) and this grouping is not significantly different from the present field or the axial dipole field of the earth. With this result, it cannot be inferred whether the NRM directions really represent some stable component of magnetization until any unstable components influencing the magnetization of the rock have been identified and removed by suitable techniques.

3.3 Susceptibility and Q-ratios

Susceptibility (K) of ferromagnetic materials is field-independent only in low field, and is then defined as the induced moment per unit volume in unit field (K = J/H). In natural rocks, the susceptibility depends upon the composition, shape, size and distribution of the constituent ferromagnetic minerals as well as the magnetic field strength, temperature and stress acting on them. Studies of susceptibility with respect to those parameters are of great interest in rock magnetic investigations. In the present study measurements were made of low field initial susceptibility which is important in paleomagnetism as it enters into the Koenigsberger ratio (Qn), defined as the ratio of the natural remanent magnetization to that induced by the present field H (i.e., Qn = Jn/KH) at the collecting site. Though any fundamental significance of this ratio has not been apparent yet, values of about 1 or more have generally been found to be associated with NRM's of stable

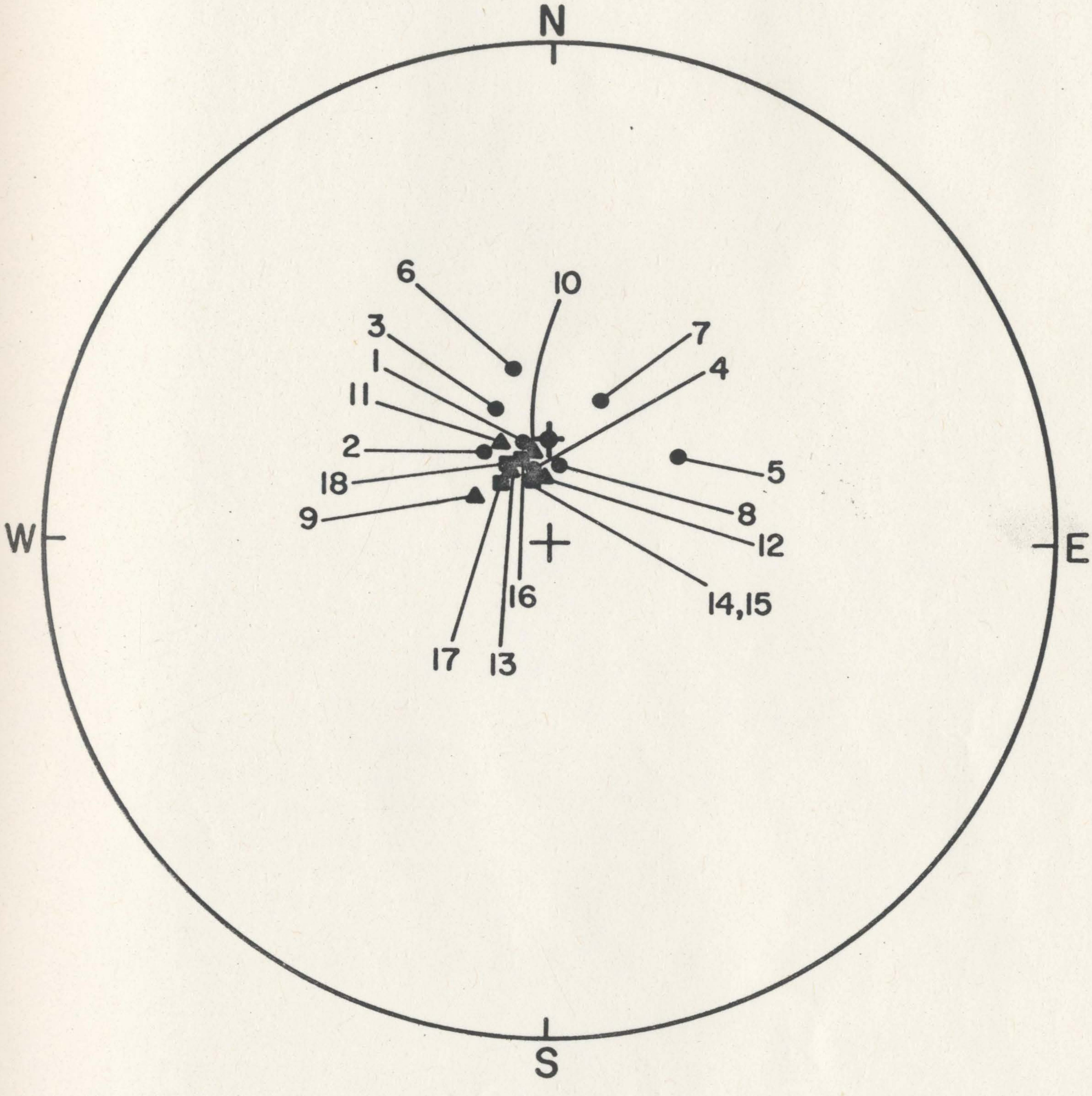


Fig. 3.2. Equal angle projection (Wulff's net) of dike-mean directions of NRM.

Areas: ● Osmonton Arm, ▲ Bay of Exploits, ■ Twillingate (all with N-pole down).

✦ Axial dipole field.

TABLE 3.1

DIKE-MEAN DIRECTIONS OF NATURAL REMANENT MAGNETIZATION (NRM)

Site No.	Dike No.	N	D	I	J(A/m)	R	k	α_{95}
A	1	5	346	+67	3.020	4.709	14	21
A	2	4	324	+65	2.432	3.408	5.1	45
B	3	4	339	+58	2.600	3.834	18	22
C	4	6	347	+73	2.363	5.741	19	16
D	5	4	56	+56	1.720	3.687	9.5	31
E	6	4	348	+51	2.006	2.884	2.9*	71
F	7	6	20	+57	0.563	4.443	3.2	45
G	8	4	8	+72	4.048	3.924	36	16
H	9	4	299	+71	4.769	3.928	42	14
H	10	5	350	+69	5.108	4.270	5.5	36
H	11	4	334	+65	3.810	3.782	14	26
I	12	6	357	+75	2.447	5.791	24	14
J	13	4	332	+72	4.368	3.904	29	17
K	14	6	346	+76	4.222	5.353	7.7	26
L	15	7	343	+76	4.503	6.603	15	16
M	16	4	340	+70	3.205	3.694	9.8	31
M	17	5	320	+73	3.776	4.779	18	18
N	18	4	333	+70	2.599	3.899	30	17
Mean		18	347.5	+69.6		17.6126	44	5.3

N = the number of samples per dike.
D = the mean declination (degrees) of remanent magnetization.
I = Mean inclination (degrees, + indicates north pole in the lower hemisphere.
J = (Arithmetic) mean intensity of magnetization.
k = Precision parameter. Values are rounded off to two significant figures.
α_{95} = Radius of 95% confidence circle (degrees).
R = Resultant magnitude of N unit vectors.
* after a k-value denotes that within-dike vector grouping is random at 95% probability level (Irving, 1964, p. 63).

type, whereas values below 0.1 indicate the presence of substantial unstable components (Irving, 1964, p. 93). Low or high values of Qn, however, should not be regarded as a conclusive criterion of gauging the stability of NRM. Low values may arise as a result of a stable magnetization acquired in a weak field, or co-existing in the rock with unstable components, or because of viscous decay of natural remanence even without the build-up of unstable components. Furthermore, Qn has been found to decrease with increasing age for rocks of the same composition. For pre-Tertiary rocks, its value is frequently less than 1.

The room temperature susceptibilities of all the specimens, after their NRM measurements, were determined by the susceptibility bridge described by Pätzold (1972). Values of susceptibilities and Q-ratios are plotted in the form of histograms in Fig. 3.1 along with the NRM intensities. It is seen from this figure that 50% of the specimens have NRM intensities in the range 2.0 to 4.0 A/m and susceptibilities between 0.10 to 0.14 (S.I. units). The Q-ratios range from 0.2 to 1.0 for most of the specimens, with 50% specimens in the range 0.5-1.0. The fact that there is not much scatter in the values of these parameters probably reflects that the magnetization of these rocks resides chiefly in some stable component.

Stacey (1967) has pointed out on the basis of theoretical calculations and experimental data that the Q-values of igneous rocks with true multidomain grains of magnetite is close to 0.5, and higher values indicate that the thermoremanence is of pseudo-single domain character. As a substantial portion of the specimens in the present study yielded Q-values close to 0.5 and higher, it is tempting to suggest that a good portion of remanence carriers are probably multidomain or pseudo-single domain. However, this conclusion has to be viewed with caution. More reliable tests are needed to ascertain the domain characteristics of the remanence carriers. This aspect of the matter will be discussed briefly in Chapter 6.

3.4 Primary and Secondary Components

It is of paramount importance in paleomagnetic studies to establish whether or not the paleomagnetic directions measured in the rocks were acquired during their formation (or, in some cases at a known and specified time when the rocks became metamorphosed), and not later. The actual time taken up in forming (or re-working) the rocks must be assumed to be insignificant on a geological scale. Depending upon the acquisition process, the "primary" magnetization which originates at that time may remain unchanged in direction even after a geologically long time, but it is often masked by secondary components that may be more intense than the primary and differ in direction from it. The NRM is the resultant of the primary and, as is usually found, of one or more such secondary components added a significant time after the primary component. These secondary components are often relatively unstable and may be separated by suitable laboratory techniques, leaving the original component intact. It may, however, be noted at this point that under certain conditions (Krs, 1967; Storevedt, 1968) the primary component may have been completely destroyed during the history of the rock.

3.5 Field Tests

Field tests for assessing stability are applicable under certain geological conditions which can provide information about the stability over all or part of the geological time interval since the rock was formed. The three most important field tests are the "fold test," the "conglomerate test," and the "baked-contact test" (Graham, 1949; Strangway, 1967). The fold test is applicable in situations where folding has taken place in the beds after the formation of the rock so that the different parts of the same rock unit differ in orientations. If the acquisition of magnetization took place before folding and is stable enough through geologic time, the measured magnetizations on the two limbs of the fold will be divergent and could be brought into agreement when the limbs are fitted back into their original unfolded positions. The conglomerate test is applied to the pebbles derived from the same rock unit, and which have taken up random orientations within the conglomerate. If the original rock has a stable magnetization, the directions of magnetization of the pebbles will tend to be random, provided they have not been remagnetized. Both these tests are inapplicable in the present case, because the lamprophyere dikes are the youngest known igneous event in Newfoundland, and no conglomerates derived from them have been reported; also there has been no folding in the beds afterwards. The baked-contact test is often applied to intrusive bodies and the surrounding rocks. Intrusions of igneous rocks heat up the intruded country rocks increasingly in the direction towards the contact; upon cooling, the country rock can become remagnetized in the same magnetic field as that in which the intrusive rock becomes magnetized. Since the magnetic minerals of the country rock are generally different from igneous intrusion, agreement between their directions of magnetization provides evidence for the stability of the magnetization of the intrusion. However, this test has not been applied in the present study. The verification of stability for the present purpose is confined to the laboratory tests discussed below.

3.6 Laboratory Tests

The two most effective laboratory procedures which tend to test for and remove secondary components in igneous rocks are: alternating-field (AF) demagnetization and thermal demagnetization.

In AF demagnetization the rock is exposed to an alternating field which is increased to a peak value, held there for typically 10-20 seconds, and then decreased to zero; the remanence is then re-measured and the process repeated for progressively higher peak fields. During this stepwise process the specimen alternately experiences the applied field in opposite directions, so that any component with coercive force smaller than the peak value of the applied field is eliminated. As the peak field strengths are progressively increased, one removes selectively the components with increasingly larger coercivities, leaving only the most stable component with the largest coercivities. As it stands, this technique has the drawback that the alternating field is directed along a single fixed axis, making it desirable to expose other directions within the specimen to the same field changes. So, in practice, the specimen usually is tumbled simultaneously about two or three mutually perpendicular axes in the varying alternating field, a process which tends to randomize the directions of magnetization of a given coercivity three-dimensionally within the rock.

The technique of AF demagnetization was first instroduced by Thellier and Rimbert (1955) and was improved by As and Zijderveld (1958), Creer (1959), McElhinny (1966), Doell and Cox (1967), and others.

Thermal demagnetization consists of two alternative types of procedures: the continuous method and the progressive or stepwise method. In the former technique, the specimen is heated in a field-free space and the direction and intensity of remanence is measured at selected increasing temperatures, while in the latter technique, the specimen after being heated to a given temperature is allowed to cool to room temperature in a field-free space and the remanence is remeasured. The specimen is then heated to a higher maximum temperature and the process is repeated, much as in the AF method. In both the thermal procedures, the magnetization of the grains with blocking temperature, T_B, less than the selected higher temperature T is eliminated, by unblocking, while the remanence of the grains with blocking temperature $T_B > T$ remains intact. However, the stepwise procedure is generally faster because several specimens can be treated at a time. Also, because of the high temperatures involved, measurements in the continuous method cannot be done at present by the spinner, but require an astatic magnetometer associated with a furnace, which tends to slow down the measurements. Especially while cooling in the stepwise technique, the field-free space needs to be quite accurately adjusted so that the residual magnetic field is very small and also both field gradients and thermal gradients must be kept small within the space occupied by the specimens. If this is not done, various grains present can acquire a significant TRM upon cooling, which will obscure the remanence under study. The most serious problem in thermal demagnetization methods is the possibility of chemical changes due to heating. Many magnetic minerals tend either to oxidize or reduce during heating. Some of these changes can, however, be reduced by heating in an inert atmosphere.

Thermal demagnetization techniques were first introduced by Thellier (1938) and have been improved by various workers (Leng, 1955; Doell, 1956; Irving et al., 1961a; Wilson & Everitt, 1963; Chamalaun, 1963; Chamalaun & Creer, 1964). Wilson (1962) introduced the continuous technique successfully.

3.7 Stability criteria

As discussed above, secondary components may be removed by AF or thermal demagnetization techniques. In order to determine what value of alternating field or temperature is necessary to minimize the effect of secondary components and yet retain a measurable portion of the primary component, two empirical procedures have been proposed:

(i) As and Zijderveld (1958) and McElhinny and Gough (1963) use the criterion that the step in the treatment (either thermal or AF) at which the vector rotation within the specimen stops and changes occur only in the vector magnitude is considered to be the proper temperature or field.

(ii) Irving et al. (1961a) have proposed an alternative statistical approach. This makes use of the change in dispersion of directions for several specimens from the same site. The step in the treatment which produces minimum disperson is then selected and applied to all the specimens from the same site.

Both the above procedures should, in principle, give the same estimates of the treatment required for the same site, provided a "stable end point" is obtained. But quite often a stable end point is not reached, whereas a minimum dispersion may occur at some field or temperature, in which case the second criterion is used. For this reason, the dispersion criterion has been used in the present study.

CHAPTER 4

ALTERNATING FIELD DEMAGNETIZATION STUDY

4.1 AF demagnetizer and procedure

The first test of stability in the present study was done by alternating-field (AF) demagnetization, using the high-field unit at the Geomagnetic Research Laboratory. In this device the specimen tumbles about three mutually perpendicular axes simultaneously inside a magnetizing coil which can produce fields up to 350 mT. In order to avoid the pick-up of anhysteretic magnetization due to the presence of the earth's field or steady laboratory fields, the working space within the demagnetizing coil is made close to field-free by the use of three mutually perpendicular Helmholtz coils. The currents in these coils can be adjusted to annul the field in the centre of the apparatus by using a Schonstedt station magnetometer. In the beginning of the experiment and after several hours of use the field-nulling is checked and currents are readjusted to make it zero. The stepwise procedure briefly outlined in Section 3.6 was used. At each step, the field was maintained at its peak value, $\tilde{H}$, for 10 seconds and then smoothly reduced to zero.

4.2 Pilot study

In view of the fact that the study involves a large number of specimens, it is common practice to make first a detailed demagnetization study of a few representative specimens. This obviates the need for intermediate steps and cuts down considerably the time needed in the subsequent systematic treatment of the rest of the specimens. Such a "pilot" study was carried out with 25 specimens, selecting at least one from each of the 18 dikes. The NRMs of all these specimens were remeasured before subjecting them to alternating-field treatment. The specimens were exposed to the increasing fields until the remanence was too low to be further measurable. The results are summarized in Tables 1-3 (Appendix). It can be seen from these results that the capacity of the specimens to retain a remanence at higher fields differs from dike to dike. While some specimens had lost all magnetization beyond noise level at fields up to 15-20 milli Tesla (mT), about 50% of them were found to retain a measurable portion of their remanence up to 40 mT. Some of them were demagnetized even up to 100 mT. But the measurements beyond 60 mT showed the rocks to be unstable in most of the cases, and although the directions at these high fields have been given in the table for some specimens, they do not represent the true directions at these fields; especially those at 80 mT and 100 mT represent noise only. Repeated measurements at these fields yield directions which are far apart. In the table, the results of first measurements at these fields have been given. A few representative results of this initial demagnetization are plotted in Figs. 4.1 and 4.2 and discussed below.

4.2.1 <u>Results of pilot study</u>

<u>Specimen LD 11B (Dike 3, Site B)</u>

The NRM direction, which is of normal polarity but differs from the earth's present field by a small angle, changed very little during ten demagnetization steps between 5 and 40 mT (see broken circle in Fig. 4.1). The small change of direction between NRM and this stable direction suggests the removal of a viscous component. Beyond 50 mT, the direction changed by large angles and became apparently random (not shown in the figure but higher values are given in Table 1 of the Appendix). The intensity decreased smoothly during these steps. This suggests that the component maintained up to 40 mT represents a stable magnetization possibly of primary origin.

Specimen LD 35C (Dike 8, Site G)

The NRM direction, which is steep downwards to the N and very close to the present field, remained stable during seven demagnetization steps up to 25 mT. Beyond 25 mT, there was no systematic change in the vector direction up to 80 mT (Fig. 4.1, Appendix Table 1). The intensity during all these steps progressively decreased. This is very similar to the behaviour of specimen LD 11B, except that, in the latter specimen, stability is maintained only up to a lower field and the stable direction differs by a large angle from LD 35C.

Specimen LD 45B (Dike 10, Site H)

The NRM direction for this specimen is towards NE, very close to the axial dipole field, but on AF treatment, the direction keeps on moving systematically to SE up to 15 mT, resulting in a shallower inclination; at higher fields, the directional changes become erratic (Fig. 4.1, Appendix Table 3). The intensity goes down very sharply to 1% at about 15 mT. No stable direction was thus obtained for this specimen, indicating that a soft viscous remanence (VRM) is dominant. This measurement does not give any evidence for a primary component preserved in the specimen.

Figs. 4.1-4.2. Pilot alternating-field (AF) demagnetization of six specimens (one per dike, see Appendix Tables 1-3).

$\tilde{H}$ is the demagnetizing field.
Jn is the intensity of magnetization (J) at NRM.
o Osmonton Arm (N-pole up). All other symbols as in Fig. 3.2.

Right: Directions of magnetization after the step shown (in peak mT). Numbers underlined refer to specimens. Wulff's net.
Within dashed circles, directions are nearly constant during indicated steps.

Left: Normalized intensity of magnetization, J/Jn, corresponding to the treatment steps shown at right.

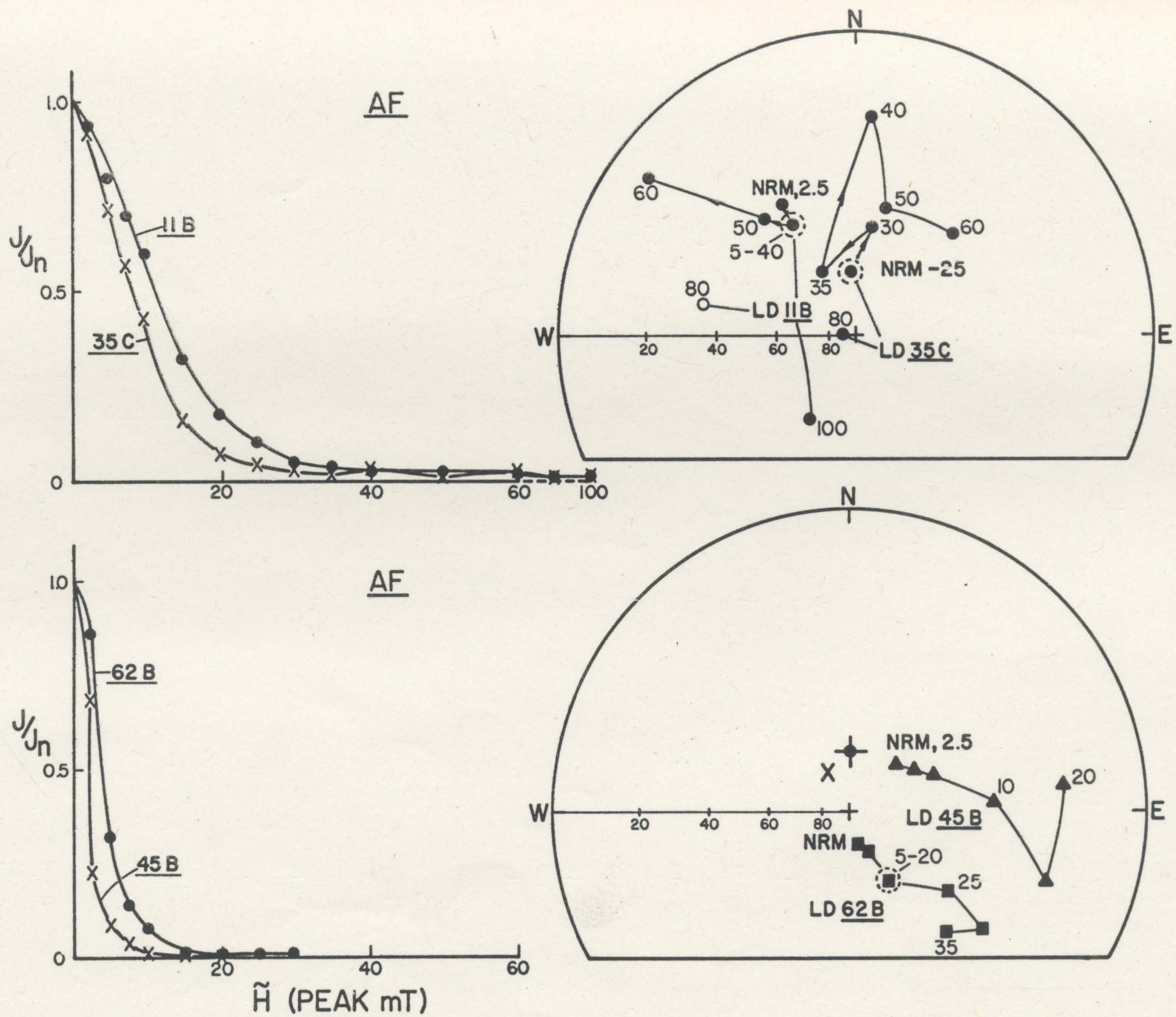
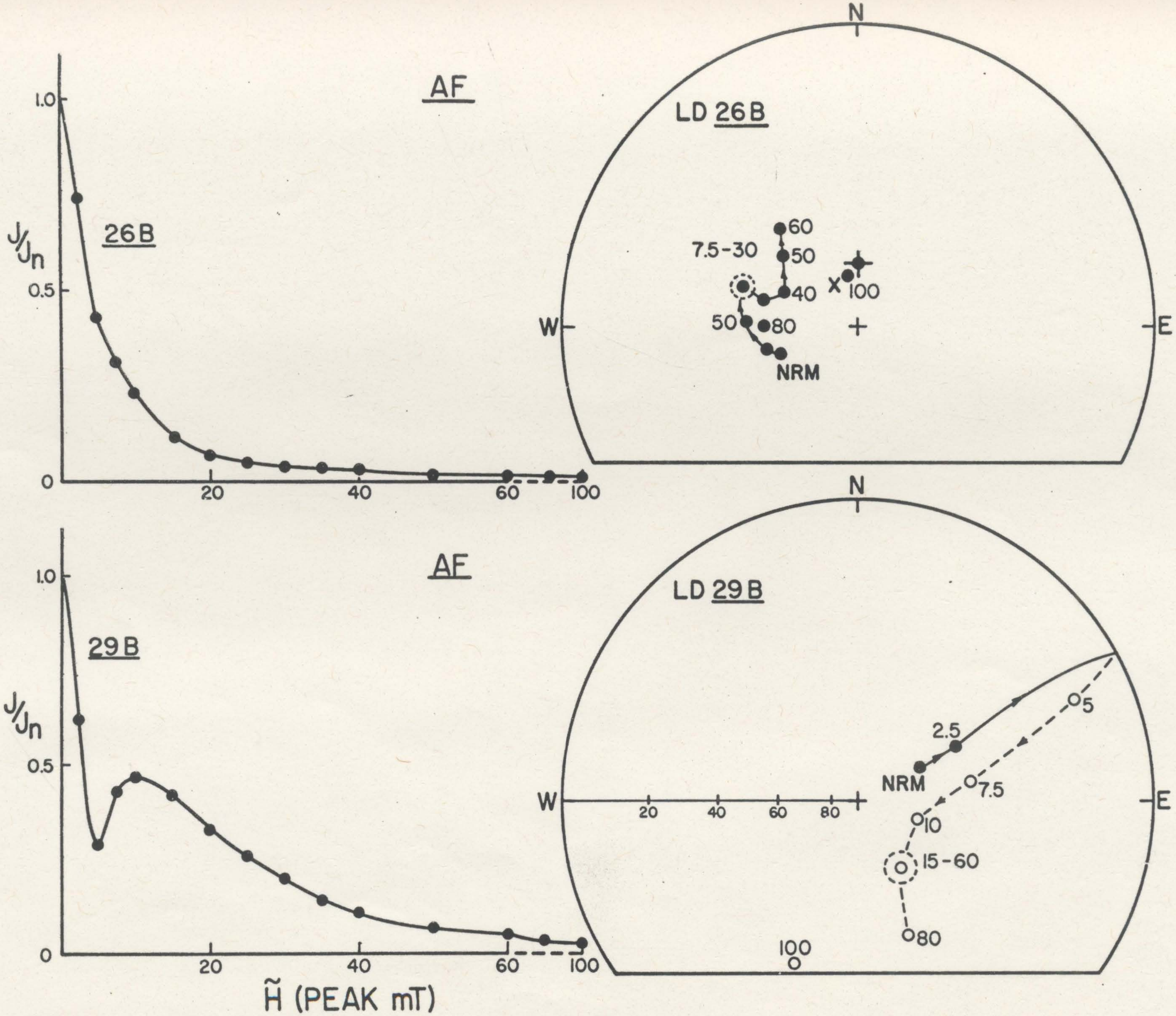

AF
J/Jn
1.0
0.5
0
11 B
35 C
20
40
60
100
N
W
E
NRM,2.5
5-40
NRM -25
LD 11B
LD 35C
AF
62 B
45 B
H̃ (PEAK mT)
NRM, 2.5
LD 45B
NRM
5-20
LD 62B

Fig. 4.1.



AF
26B
J/Jn
1.0
0.5
0
20
40
60
100
LD 26B
N
W
E
7.5-30
60
50
40
X
100
50
80
NRM
AF
29B
J/Jn
1.0
0.5
0
20
40
60
100
H̃ (PEAK mT)
LD 29B
N
W
E
20
40
60
80
2.5
NRM
5
7.5
10
15-60
80
100

Fig. 4.2.

Specimen LD 62B (Dike 14, Site K)

The NRM direction for this specimen was to the SE (with positive inclination) and was greatly misaligned with the present earth's field. The direction moved to shallower SE directions on treatment with increasing demagnetizing fields. A stable direction was obtained during five steps of treatment from 5 to 20 mT. This direction is quite anomalous. The sharp drop in intensity again indicates the presence of a soft VRM component.

Specimen LD 26B (Dike 6, Site E)

The NRM direction lies significantly far to the SW of the present field but moves systematically to the NW with demagnetizing fields up to 7.5 mT. The direction remains stable during six steps of treatment from 7.5 to 30 mT. This stable direction differs by relatively large angles from the axial dipole field and the present earth's field at the site. Beyond 30 mT, no stable direction was obtained. The intensity dropped sharply to 40% of the NRM value at 5 mT, suggesting the removal of a VRM component, and then decreased more gradually to a low value for higher fields. Therefore, the magnetization observed at 7.5 to 30 mT probably represents a stable component, perhaps of primary origin (see Fig. 4.2).

Specimen LD 29B (Dike 7, Site F)

The NRM direction, which is downward and to the NE of the present field, changes systematically to a direction of reverse polarity during two steps of treatment at 2.5 and 5 mT field; the intensity dropped sharply during these steps, which suggests the removal of a soft VRM component. At higher fields, the direction systematically moves to SE (with N-pole upwards) and a stable direction is obtained during eight steps of demagnetization from 15 to 60 mT. Beyond 60 mT, the direction changed by a relatively larger angle at 80 mT and became erratic at the subsequent step at 100 mT (Fig.4.2). The AF decay curve shows that the intensity increases between 5 and 10 mT, indicating that a secondary component close to the present field direction, that is aligned nearly anti-parallel to the stable direction, has been wiped out. The intensity thereafter progressively decreases. The magnetically cleaned stable direction for this specimen suggests that a reversal of magnetization was present in this case.

Two specimens were pilot-demagnetized from each of dikes 1, 2, 7, 12, 14, 16, 18 and one specimen each from the remaining 11 dikes, and the results are listed in Tables 1-3 (Appendix).

4.3 Systematic AF demagnetization

As already mentioned in Section 4.2, a careful perusal of all the 25 pilot results shows that the stability of magnetization differs from dike to dike, although for a majority of specimens the stable direction persisted for fields up to 25-40 mT. There is one group of pilot results where a component that appears to be systematically reversed in polarity can be isolated from the NRM direction. Results of this kind cannot be treated uniformly by adopting a single alternating field as the "optimum" step. Rather, a difference of behaviour for various groups of dikes must be recognized. Using the precision data from the pilot study, three groups of dikes could be easily distinguished:

Group A: This group consists of 10 dikes (Nos. 1, 3, 4, 5, 6, 8, 9, 13, 15 and 17). The NRM vectors of the specimens from these dikes all show normal polarity, with directions to the NW close to the present field (except one specimen, LD 1B directed to the NE by a relatively small angle with the mean specimen direction), which persist with little change for treatments up to 25-40 mT. However, a few specimens in this group could be demagnetized only in fields of up to 20-25 mT, above which the remanent intensity was too low to be further measurable. The directions of individual specimens from these dikes were averaged for each field step and Fisher's statistics were calculated. The results are summarized in Table 4.1. From these results it is seen that, though the mean direction of all specimens combined remains relatively unchanged over a fairly wide range of field strengths, the grouping improves (i.e., the precision parameter, k, increases) with increasing fields up to its highest value (k = 23) at 7.5 mT. The grouping at 10 mT field is practically the same as at 7.5 mT. Beyond 10 mT, k gradually decreases to the final (30 mT) step, except for showing another maximum (k = 16) at 25 mT. Averaging was not done for fields beyond 30 mT, because many specimens in this group had lost all measurable magnetizations at higher fields. Hence, for a systematic treatment the following demagnetizing fields were chosen: (i) a low field, 10 mT, (ii) 25 mT, and (iii) 30 mT.

Group B: In this group the specimens showed systematic reversal from positive to negative inclination upon AF demagnetization. The pilot study had been done on two specimens each from 5 dikes

TABLE 4.1

FISHER'S STATISTICS FOR GROUP A DIKES AFTER STEPWISE AF DEMAGNETIZATION (Pilot Study)

$\tilde{H}$ (mT)	D	I	N	R	α_{95}	k
0(NRM)	335	+60	11	10.2066	13.4	13
2.5	336	+59	11	10.2979	12.5	14
5.0	336	+58	11	10.5031	10.4	20
7.5	337	+57	11	10.5678	9.7	23
10	338	+56	11	10.5377	10.0	22
15	338	+55	11	10.4393	11.1	18
20	337	+55	11	10.1329	14.0	12
25	345	+53	10	9.4435	12.4	16
30	341	+54	8	7.2325	19.4	9

$\tilde{H}$ = Demagnetizing field.

N = No. of specimens averaged.

All other symbols are as in Table 3.1.

(Nos. 2, 7, 12, 16 and 18) summarized in Table 2 (Appendix). Though the specimens from dikes 2 and 7 (specimens 7B, 8A and 29B, 30A) gave stable directions, the directions of the specimens from the remaining 3 dikes failed to reach a stable point. For this set, averaging is not possible for each field. Hence, after remeasuring the NRM it was decided to subject the specimens to the following peak fields: (i) a low field, 5 mT, (ii) an intermediate field, 20 mT, and (iii) a relatively high field, 35 mT.

Group C: This group consists of 3 dikes (10, 11, 14). The NRM directions are of normal polarity and range from NW to SE. The pilot results from the specimens of these dikes show a sharp drop in intensity at relatively low fields and most of the remanence is lost at 15-20 mT, indicating the dominance of a soft VRM component. For this group, therefore, relatively low demagnetizing fields were chosen as follows: (i) 5 mT, (ii) 10 mT, and (iii) 15 mT.

4.3.1 Results of systematic AF demagnetization

One or, wherever possible, two specimens from each sample from all the dikes were treated with the demagnetizing fields of strengths discussed in Section 4.3 for each group of pilot results. In all, 121 specimens were treated with AF fields. Those dike mean directions having a non-random grouping (Irving, 1964, p. 63) for a particular field have been plotted in Fig. 4.3. It can be seen from these plots that more and more dikes are eliminated as the field strengths increase.

Most of the group A dikes yield non-random within-dike mean directions at the chosen demagnetizing fields, the only exceptions

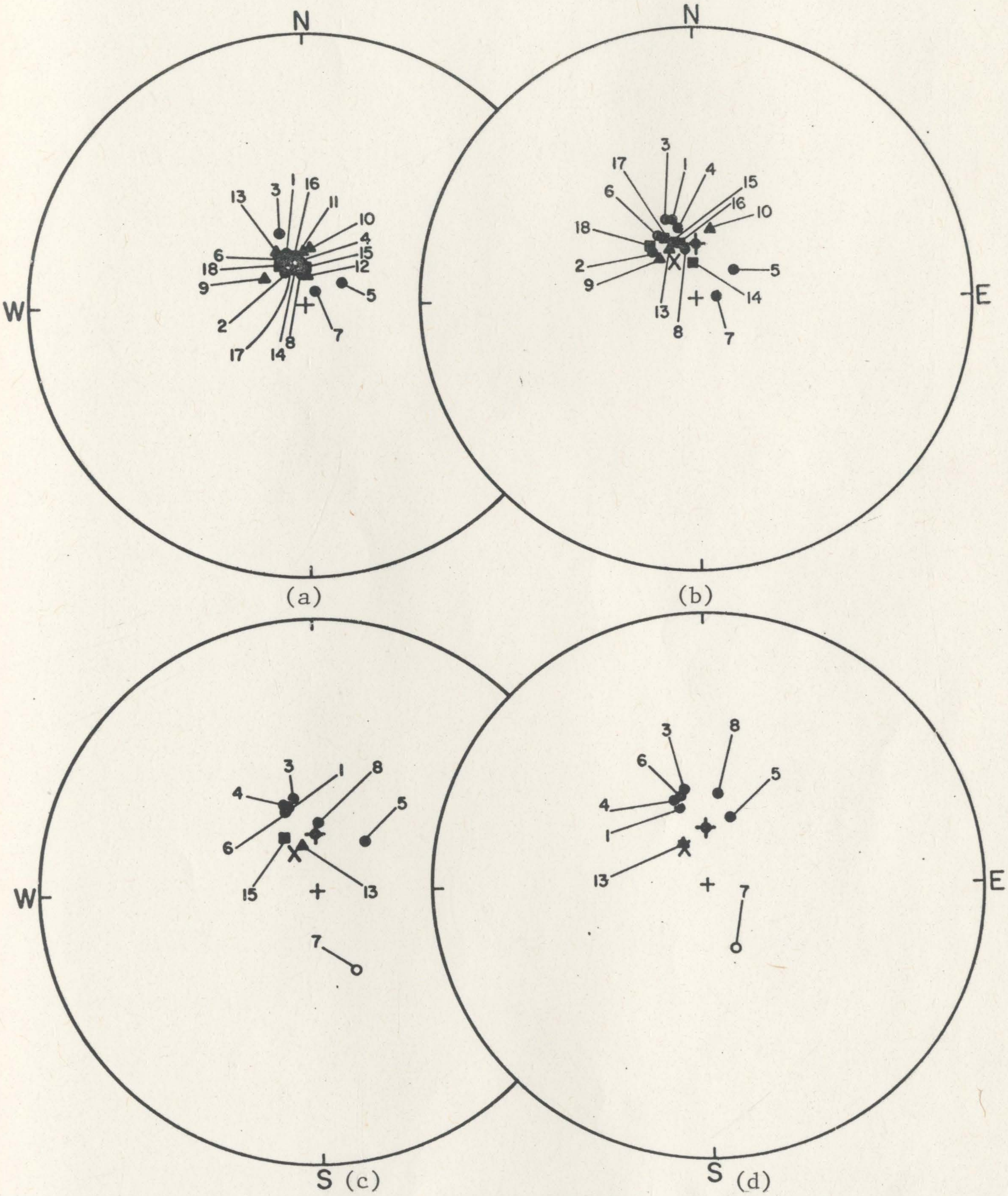


Fig. 4.3. Dike-mean directions before and after stepwise AF demagnetization. (a) NRM. (b) Dikes 2,7,16 & 18 at 5 mT, all others at 10 mT. (c) Dike 7 at 20 mT, all others at 25 mT. (d) Dike 7 at 35 mT, all others at 30 mT. All symbols as in Fig. 3.2 and Figs. 4.1-4.2. Only dikes having a non-random within-dike grouping at any step are indicated.

being dikes 9 and 17, whose directions become random beyond 10 mT.

Although the AF treatment of all the group B dikes showed a tendency toward a polarity reversal, specimens from only one dike (dike 7, site F) yielded a stable remanence with a non-random within-dike grouping, which is nearly antiparallel to the mean of the stable normal directions obtained for other dikes. The specimens from the rest of the dikes in this reversed group did not give a stable remanence direction. In most of the specimens from these dikes a soft VRM component is dominant and typically only 2% of the NRM remanence is retained at 20 mT. However, it is interesting to observe the behaviour of some of the specimens from this group. Fig. 4.4 gives a plot of pilot AF results for four specimens, selected from four different group B dikes (except dike 7). It is seen that only one specimen (LD 7B, dike 2) gives a stable direction upon demagnetization, whereas the directions of the rest of the specimens show a systematic change from normal to reversed for successive AF treatments, without reaching a stable end-point. The unfulfilled tendency for each of these specimens is towards the stable mean direction obtained for dike 7. Systematic AF treatment of the rest of the group B specimens does yield reversed (ranging most from SW to SE and upward-directed) polarity in 90% of the cases (barring a few which give normal directions), but the directions are much scattered and could not be averaged with statistical significance. However, it could be concluded from these results for all five group B dikes that a primary component, which is no longer retrievable in some of the specimens, was possibly acquired when the ambient field was in the reversed direction; where applicable, the loss of this

Fig. 4.4. Right: Pilot AF demagnetization of specimens from Group B (reversed) dikes (Wulff's net).

● ○ Osmonton Arm. ▲ △ Bay of Exploits. ■ □ Twillingate.

✱ Within-dike mean of dike 7. Solid symbols: N-pole down. Open symbols: N-pole up. All other symbols as in Figs. 4.1-4.2.

Left: Normalized intensity of magnetization, J/Jn corresponding to the treatment steps indicated at right.

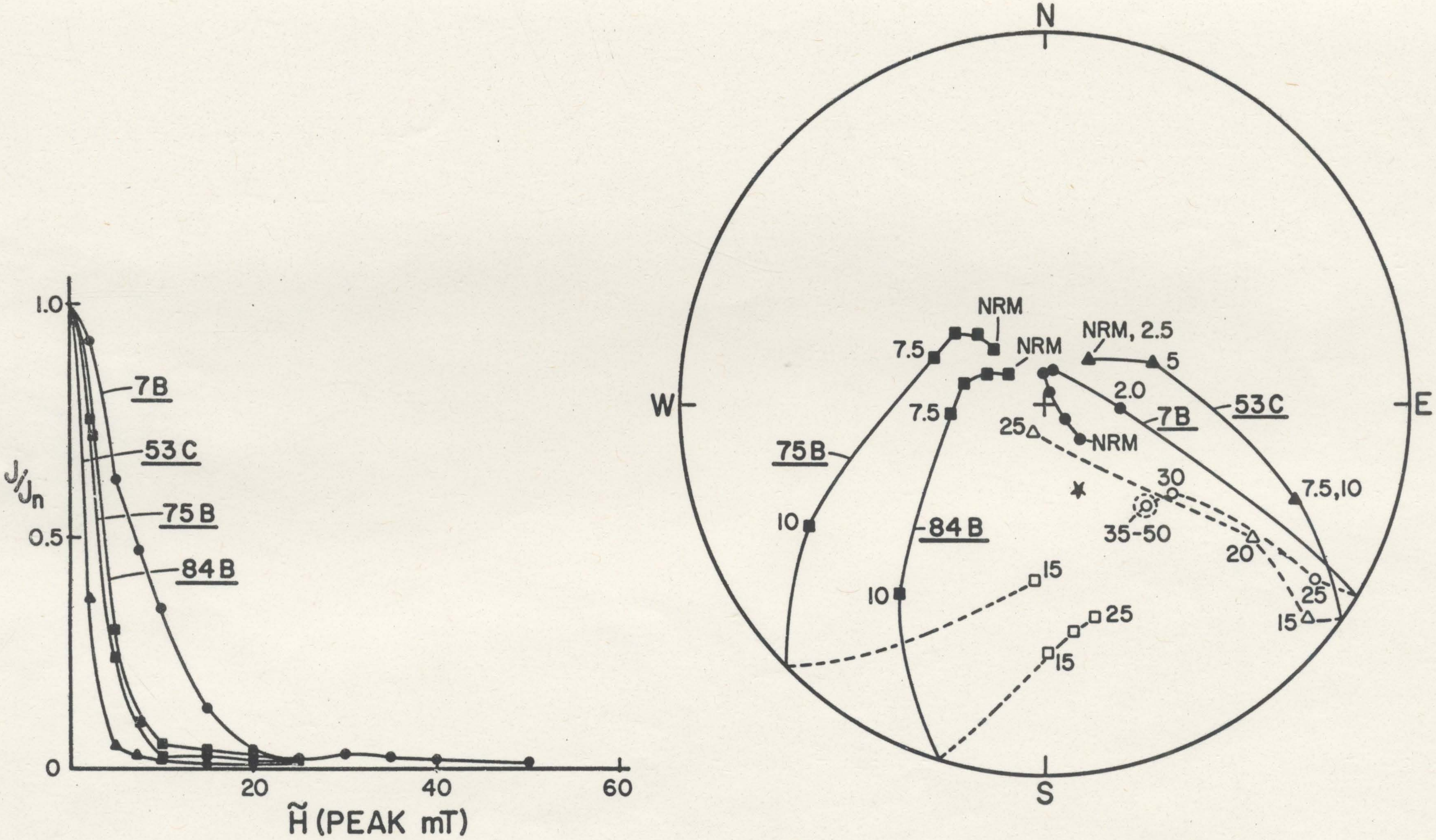

1.0
0.5
0
J/Jn
7B
53C
75B
84B
20
40
60
H̃ (PEAK mT)
N
S
W
E
NRM
NRM
NRM, 2.5
5
7.5
7.5
2.0
7B
53C
75B
NRM
25
30
7.5,10
10
84B
35-50
20
10
15
25
25
15
15

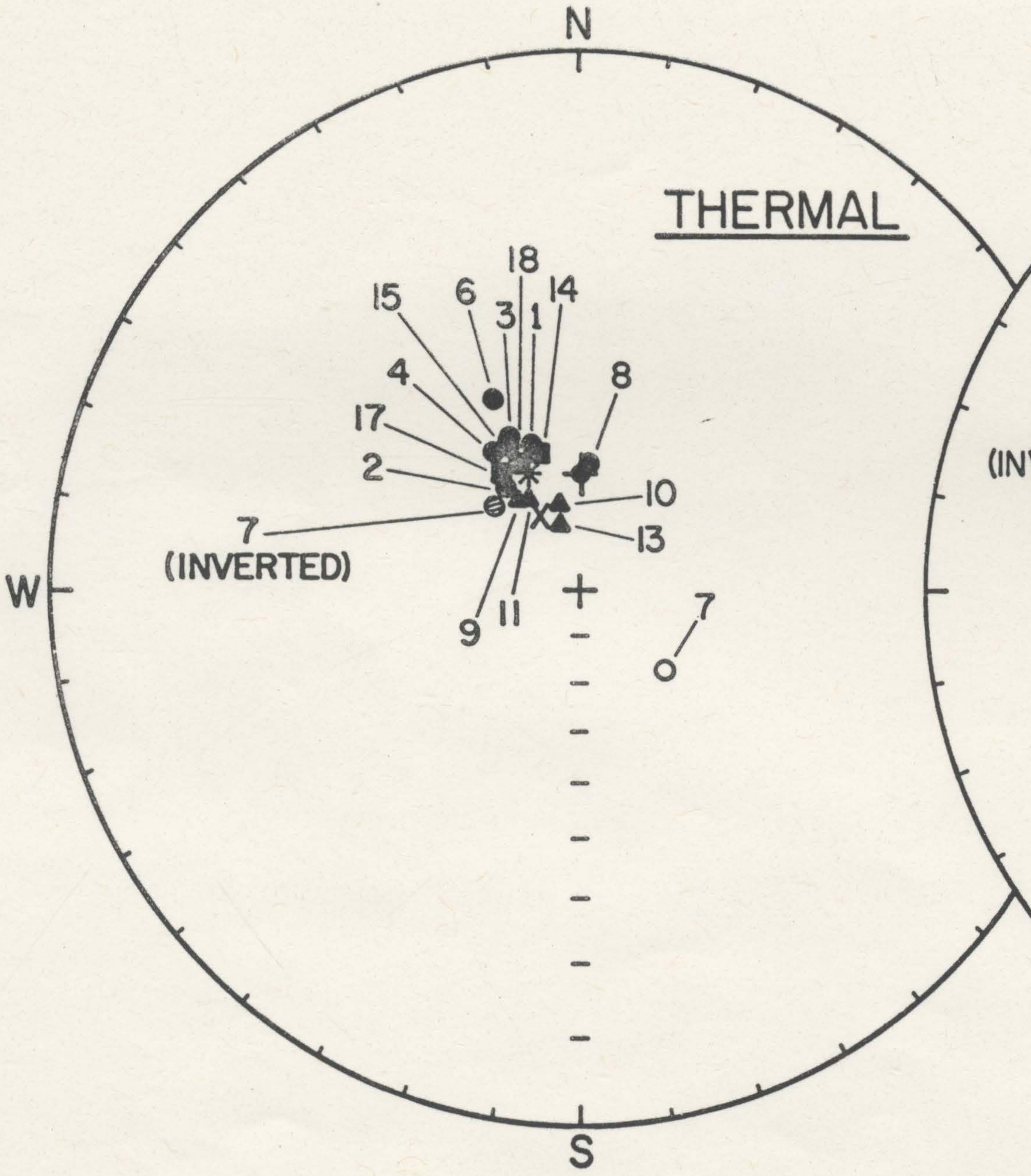
Fig. 4.4.

component then results from the overlapping of coercivity spectra of the components in the NRM, precluding their separation by the AF treatment.

On a systematic AF demagnetization of specimens from group C dikes the directions were found to be scattered more and more as the field strengths increased (i.e., k decreased after treatment) and finally, the within-dike groupings for dikes 10 and 11 became random at 15 mT. Though the within-dike grouping for dike 14 was not random before and after treatment, the precision parameter, k, did decrease on treatments with higher fields with directions scattered most at 15 mT (α_{95} = 32, k = 5).

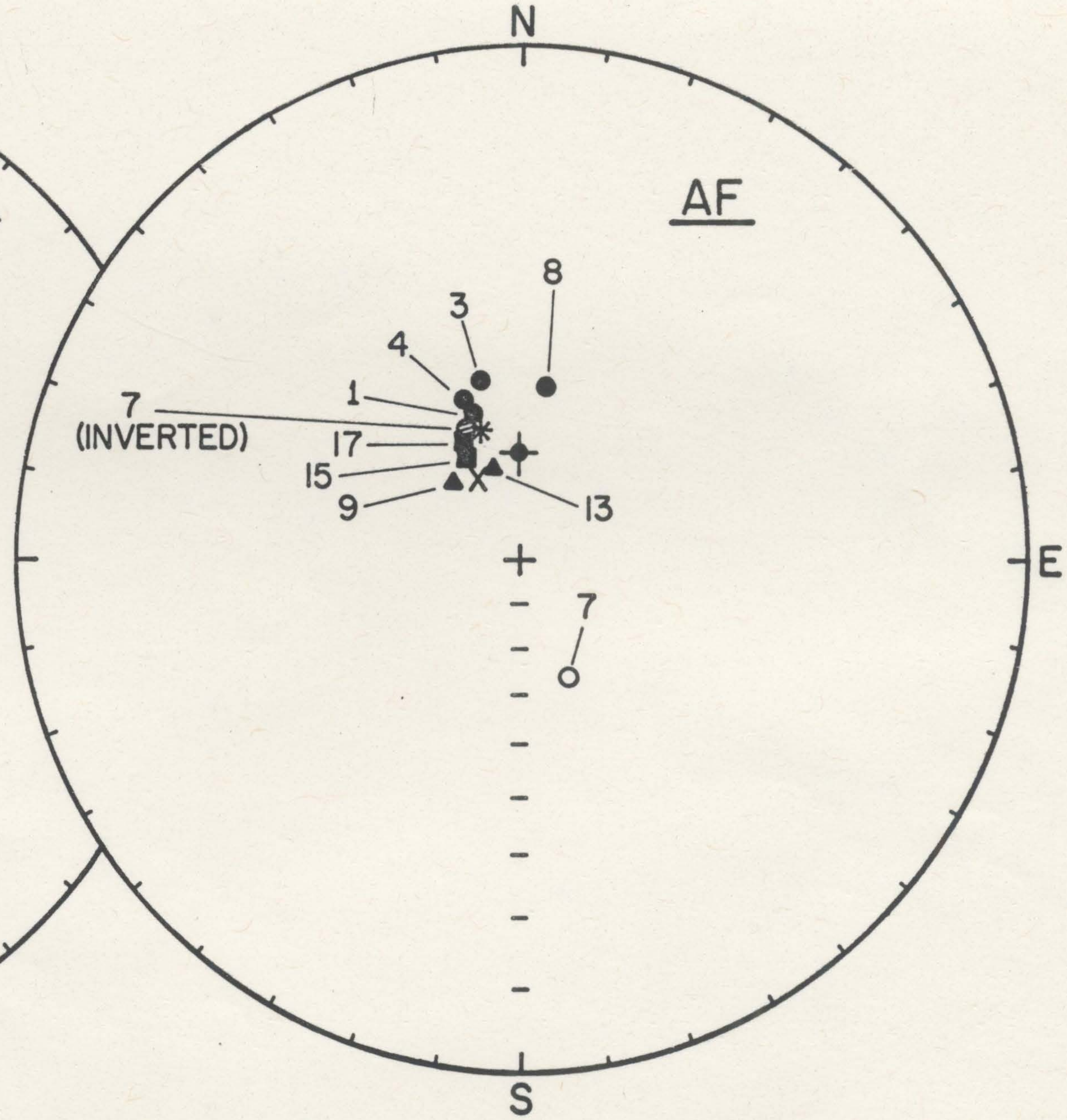
Fig.4.5b gives the dike-mean directions having optimum within-dike grouping, the selection being confined to dikes having α_{95} values not exceeding 30^{o}; the results are summarized in Table 4.2. The overall mean direction giving unit weight to dike-means is fairly well grouped around 342, + 61 (k = 68, α_{95} = 6.3). The results show that out of 18 dikes only 9 dikes yield reliable paleomagnetic directions within acceptable (i.e., $\alpha_{95} < 30^{o}$) statistical errors. It is again seen that the NRM between-dike direction, when averaged for these 9 dikes, is based on better grouping (k = 116, α_{95} = 4.8) than the magnetically cleaned between-dike direction, given above. However, the within-dike mean directions for all but one (dike 13 for which demagnetization does not improve within-dike grouping) are considerably less scattered after demagnetization. This is illustrated in Fig. 4.6 in the case of dike 4. Moreover, there is a small but consistent decrease in dike-mean inclinations after treatment for 8 out of 9 dikes. The one exception, dike 13,

Fig. 4.5. Comparison of dike-mean directions after thermal and AF treatment. Only dikes used in final averaging are included (see Tables 4.2 & 5.1). ✱ Overall mean direction. ✦ Axial dipole field. X Present field. All other symbols as in Figs. 3.2, 4.1-4.2.



N
THERMAL
18
15
6
3
1
14
4
8
17
2
10
7
(INVERTED)
13
W
9
11
7
S

(a)



N
AF
8
3
4
1
7
(INVERTED)
17
15
9
13
E
7
S

(b)

Fig. 4.5.

TABLE 4.2

DIKE-MEAN REMANENCE DIRECTIONS AND FISHER'S STATISTICS[a] AFTER AF CLEANING

Site No.	Dike No.	Natural remanence (NRM) D	I	N	k	α_{95}	Treatment[b]	After demagnetization D	I	N	k	α_{95}
A	1	341	+68	4	17	23	30 mT	342	+57	4	36	16
B	3	341	+60	4	14	26	30 mT	348	+51	4	69	11
C	4	355	+73	6	14	18	30 mT	340	+54	6	115	6.3
F	7	330	+74	6	11	29	35 mT	157	-62	5[c]	91	8.1
G	8	355	+77	4	13	26	30 mT	9	+53	4	28	18
H	9	304	+71	4	89	9.8	10 mT	318	+68	4	125	8.2
J	13	331	+66	4	30	17	25 mT	344	+72	4	29	18
L	15	354	+74	7	31	11	25 mT	330	+65	7	61	7.8
M	17	340	+68	4	33	16	10 mT	333	+62	4	90	9.7
MEAN[d]		338.3	+70.8	9	116	4.8		341.8	+61.2	9	68	6.3

[a]Symbols as used in Table 3.1.

[b]The treatment step chosen is the one for which the precision parameter, k, was maximum.

[c]One greatly divergent sample (>40° from mean) was excluded from averaging.

[d]The mean direction from dike 7 has been inverted and included in the overall mean.

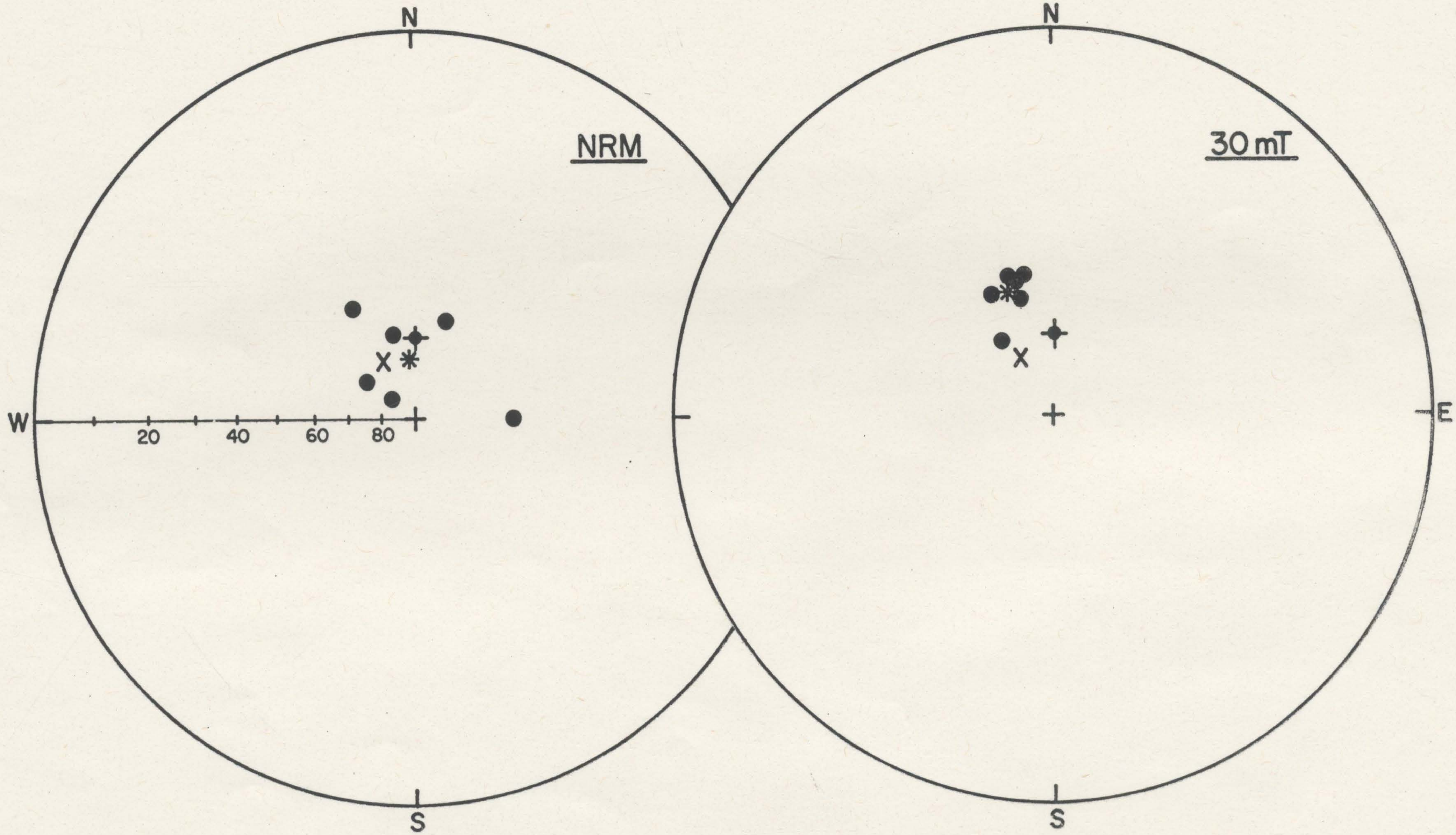


Fig. 4.6. Sample-mean directions of dike 4 before and after AF demagnetization.
✱ Within-dike mean. ✦ Axial dipole field. X Present field.

is also the only case where k decreases after cleaning. The overall mean inclination decreases by 9.6° from NRM and is directly away from the present field direction (very close to NRM) which is consistent with a secondary component in the present field direction having been removed. This in turn adds confidence in the "cleaned" direction and perhaps also explains why k for the NRM is somewhat larger. Therefore, it can be concluded that the magnetically cleaned direction corresponding to the optimum field value represents the direction of the ambient field at the time of acquisition of the primary component, whereas the scatter of dike-mean directions may be due in part to the secular variation of the earth's field.

CHAPTER 5

THERMAL DEMAGNETIZATION STUDY

It is evident from the AF demagnetization study that a stable component is responsible for most of the NRM in at least half the samples. However, volcanic rocks may contain one or more components of magnetization of partial thermoremanent (PTRM) origin besides the primary TRM component. Hence, thermal demagnetization serves a useful supplementary technique to AF demagnetization to isolate components with different blocking temperatures. In some cases, thermal demagnetization is the only useful technique, e.g., when the coercivity spectra of comparably stable components are overlapping and cannot be resolved by AF techniques but are amenable to thermal treatment, provided the blocking temperature spectra are at significantly different mean temperatures. Blocking temperature spectra are of two basic types [Irving & Opdyke (1965)]:

(i) Thermally discrete components which are blocked within a narrow temperature range close to the Curie point and which are very stable up to this blocking temperature.

(ii) Thermally distributed components which are blocked over a wide temperature range. These are less stable and more prone to acquisition of secondary components. Because of low stability, the secondary components have low relaxation time and therefore low blocking temperatures. By partial thermal demagnetization it is often possible to eliminate the secondary components.

5.1 The thermal demagnetizer and procedure

The furnace assembly of the thermal demagnetization unit used in the present study is a scaled-down adaptation of the apparatus described by Irving et al. (1961b) and has been discussed in detail by Somayajulu (1969) and Rao (1970). The whole unit was later moved to the University's Geomagnetic Research Laboratory at White Hills, away from the magnetically noisy Chemistry-Physics Building, and a feedback system for control of the field-nulling through secondary windings in the three Helmholtz coils was added. This ensures that the field at the centre of the oven occupied by the specimens remains almost zero during a run. However, in the present study, the feedback system, being out of order, was not used for field-nulling; instead, the field inside the oven was monitored and maintained near zero by two Schonstedt Station magnetometers with externally mounted probes which are corrected to the oven-field. By a careful manual adjustment of the currents in the Helmholtz coils the field inside the oven was maintained well within $\pm 5\gamma$. For temperatures above $400^{\circ}C$ the specimen stand region was enclosed by an inverted copper pot to reduce the thermal gradient. The specimen stand consists of three shelves. Eight specimens were heated at a time with four each on the top and middle shelves, which are 5.5 cm apart. The difference in temperature between the centres of these two shelves with copper pot on was within $3^{\circ}C$. The lowest shelf was not used because the temperature difference between this and the middle or the top shelf was much larger. The temperature inside the oven was controlled by a temperature potentiometer which in the present study could be maintained within $\pm 2^{o}C$ of the desired temperature. The maximum departures of the actual specimen temperature from the quoted value are estimated to be within $10^{o}C$. All the specimens were arranged in a particular orientation in any run to check if any spurious TRM was added to it during the process. The desired temperature inside the oven was maintained constant for 30 minutes to enable the whole volume of any specimen to acquire the same temperature. Thereafter the heating current was switched off and the oven was raised to the highest position. During all this procedure the field in the region occupied by specimens was regularly monitored and maintained at zero with 5γ maximum error. The specimens were thus allowed to cool in the field-free space and, on reaching room temperature, were quickly transferred into a magnetically shielded can inside which the field is several orders less than the surrounding field ($<10\gamma$). This reduces the possibility of acquiring any significant VRM in the laboratory before measurement. The remanence was then measured on the spinner magnetometer.

5.2 Pilot study

Twenty-two specimens, selecting at least one from each dike, were taken out for preliminary studies to determine some optimum demagnetization temperature for the treatment of specimens from the samples not represented by these pilot specimens. All the 22 specimens were demagnetized at 12 steps beginning with $100^{o}C$ and up to $575^{o}C$. A few specimens were demagnetized to $600^{o}C$. But remanence at $575^{o}C$ and beyond was nearly always unstable and repeated measurements made after demagnetizing a given specimen at either $575^{o}C$ or

$600^{o}C$ yielded widely different directions, indicating the non-existence of any systematic component beyond $550^{o}C$. The results of this pilot study are summarized in Table 4 (Appendix). Results at $575^{o}C$ are based on the first measurement after demagnetization. Measurements at $600^{o}C$ have not been included in this Table as they are extremely unreliable and are of no significance; they probably represent noise only. Fig. 5.1 gives a plot of a few representative specimen directions upon thermal treatment which are discussed below.

Specimen LD 9A (Dike 2, Site A)

The NRM direction of this specimen, which differs from the earth's present field by a relatively small angle, remained practically unchanged during 11 steps of demagnetization from $100^{o}C$ to $550^{o}C$. The intensity progressively decreased up to $500^{o}C$ and dropped sharply beyond this temperature. This sharp drop in intensity indicates that the stable component, presumed to be of primary origin, has a mean blocking temperature at about $500^{o}C$. It may be noted here that two specimens (LD 7B and 8A) from this dike yielded a stable reversed direction on AF pilot study (Fig. 4.1, Appendix Table 2).

Specimen LD 35A (Dike 8, Site G)

This specimen has the NRM direction to the NE of the present field which differs by a fairly large angle from that of specimen LD 9A. On thermal treatment the direction moved by a small angle and remained stable during six steps from $300^{o}C$ to $550^{o}C$, after which it changed by a large angle. The intensity decreases smoothly to $500^{o}C$ and then drops sharply, suggesting a mean blocking temperature at about $500^{o}C$ for the most stable component.

Fig. 5.1. Pilot thermal demagnetization of four specimens (one per dike, see Appendix Table 4).

Right: Directions of magnetization after cooling from the temperature shown by numbers (in $^{\circ}$C). Numbers underlined refer to specimens. Wulff's net. Within dashed circles directions are nearly constant over the range of steps shown.

Left: Normalized intensity of magnetization, J/Jn corresponding to treatment steps shown at right. T is the demagnetizing temperature.

All other symbols as in Fig. 4.4.

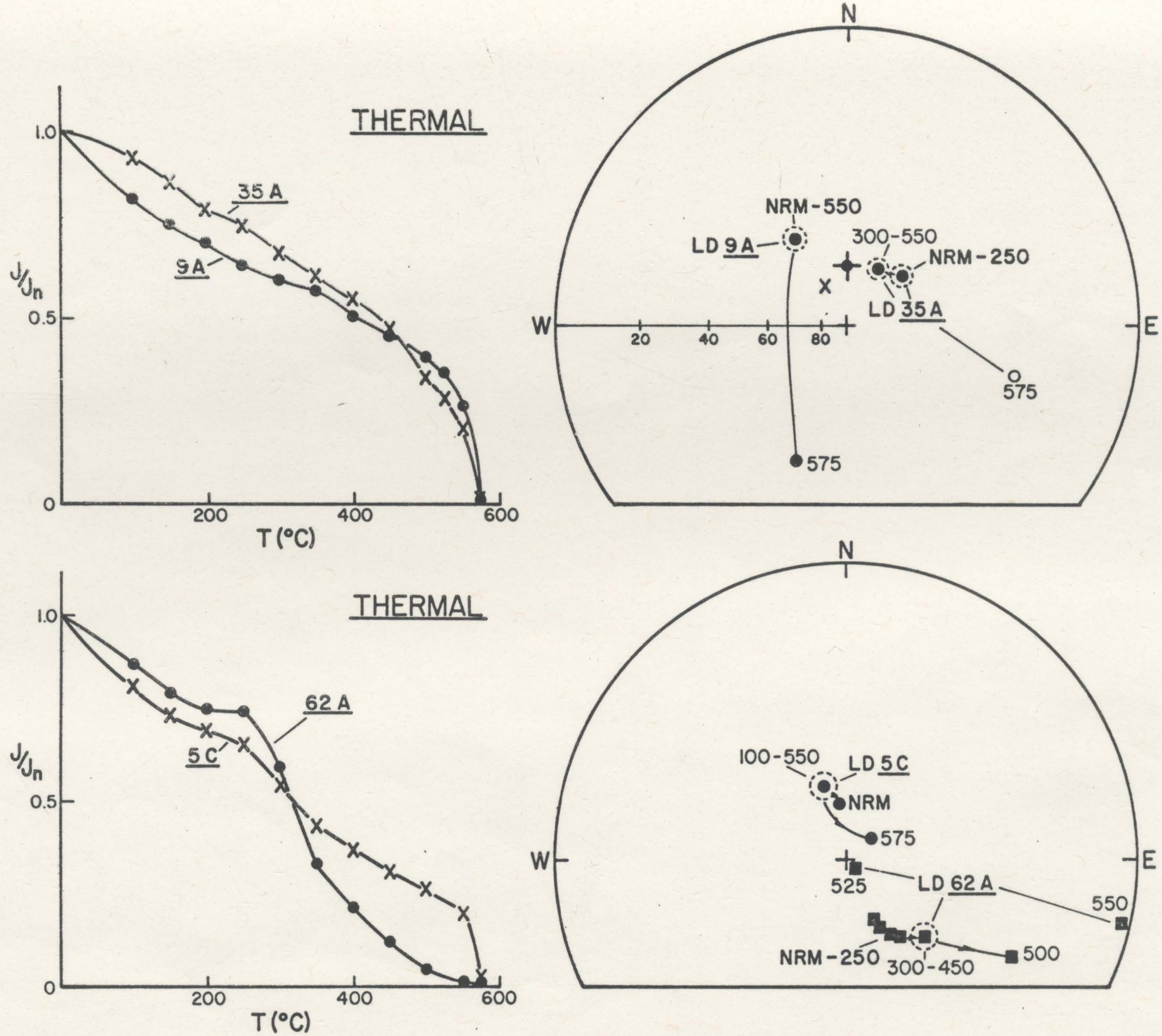

THERMAL
1.0
0.5
0
J/Jn
35 A
9 A
200
400
600
T (°C)
N
W
E
NRM-550
LD 9 A
300-550
NRM-250
LD 35 A
20
40
60
80
575
575
THERMAL
1.0
0.5
0
J/Jn
62 A
5 C
200
400
600
T (°C)
N
W
E
100-550
LD 5 C
NRM
575
525
LD 62 A
550
NRM-250
300-450
500

Fig. 5.1.

Specimen LD 5C (Dike 1, Site A)

The NRM direction is close to that of specimen LD 9A and changes by a small angle on demagnetization to $100^{o}C$, remaining stable on subsequent treatments up to $550^{o}C$. The small directional change at $100^{o}C$ probably indicates the unblocking of a softer component. The sharp fall in intensity beyond $500^{o}C$ indicates that the blocking temperature of the stable component is about $500^{o}C$.

Specimen LD 62A (Dike 14, Site K)

The NRM has a positive inclination but differs approximately by 180^{o} in declination from the present field. On demagnetization the direction changes systematically by small angles up to $250^{o}C$. During four steps of demagnetization from $300^{o}C$ to $450^{o}C$ the direction is stable; beyond this, no stable component is observed. The small plateau in the intensity curve between 200 and $250^{o}C$ suggests the removal of a softer component with a widely divergent direction. The sharp drop in intensity between $250^{o}C$ and $350^{o}C$ suggests a mean blocking temperature of $300^{o}C$. This result may be compared to the AF demagnetization of specimen LD 62B (Fig. 4.1) from the same core, which gives a similar stable direction for treatment between 5 and 20 mT.

5.3 Comparison of thermal and AF pilot results

It is interesting to compare the pilot results for the two types of treatments in order to correlate the blocking temperatures with the coercivity spectra of the components recorded in the lamprophyres, and to compare the directional changes obtained and the stable directions isolated by the two methods. A comparable behaviour in response to the two methods would greatly strengthen confidence in the results. Figs.5.2-5.3 show the response to the AF and thermal demagnetizations of six specimens selected from three different dikes (2 specimens per dike). The comparison is between the two specimens from the same sample--one treated thermally and the other by AF. The results are discussed below:

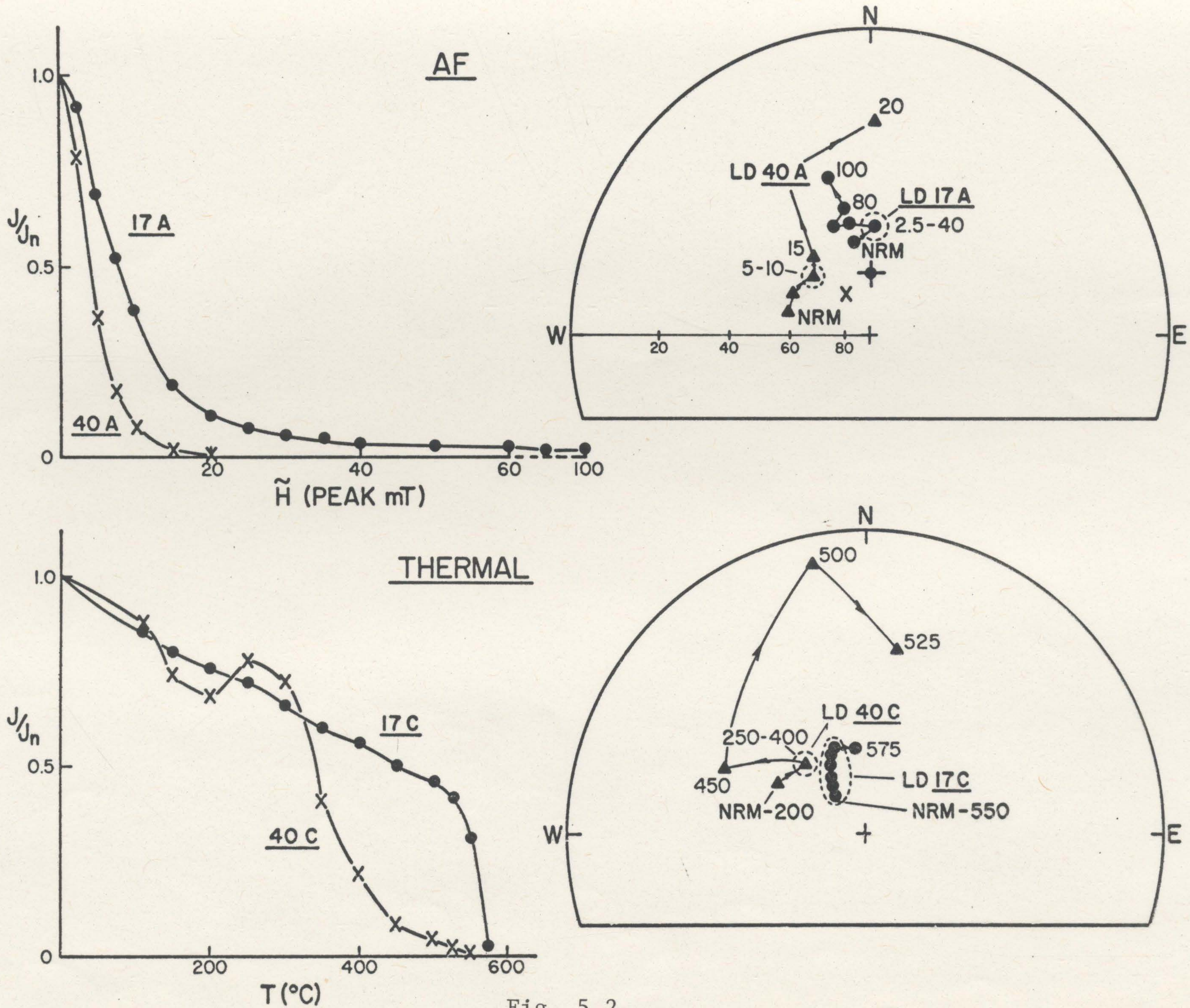
Specimens LD 17A and LD 17C (Dike 4, Site C)

In terms of vector directions, these two specimens agree well on thermal and AF treatment. LD 17A gives a stable direction on AF treatment for 2.5-40 mT, whereas the NRM direction of LD 17C systematically moves northwards on thermal treatment to a point up to 550°C and then moves through a larger angle at 575°C. On thermal demagnetization, the intensity progressively decreases up to 500°C and then quickly drops, whereas for AF treatment, the intensity drops to 10% of the NRM by 20 mT and then smoothly decreases for subsequent treatments. These results show that, after the removal of a soft component, a fairly stable magnetization blocked at about 500°C remains, and the thermal decay curve suggests that both components reside in a single mineral, probably magnetite.

Specimens LD 40A and LD 40C (Dike 9, Site H)

A fairly stable direction is obtained for 5-10 mT with AF treatment and for 250-400°C with thermal treatment, suggesting a lower blocking temperature and a lower mean coercivity of the most stable component compared to specimens LD 17A and LD 17C. This is consistent also with the fact that, for LD 40A, only 8% of the NRM intensity remains after the 10 mT step and the AF decay curve then

5.2. Comparison of AF and thermal pilot demagnetizations. Pairs of specimen from two samples (one per dike, see Appendix Table 4) are compared. All symbols are as in Figs. 4.4 and 5.1. Wulff's net.



AF
1.0
0.5
0
J/Jn
17 A
40 A
20
40
60
100
H̃ (PEAK mT)
N
W
E
20
LD 40 A
100
80
LD 17 A
2.5-40
15
5-10
NRM
NRM
20
40
60
80
THERMAL
1.0
0.5
0
J/Jn
17 C
40 C
200
400
600
T (°C)
N
500
525
LD 40 C
250-400
575
450
LD 17 C
NRM-200
NRM-550
W
E

Fig. 5.2.

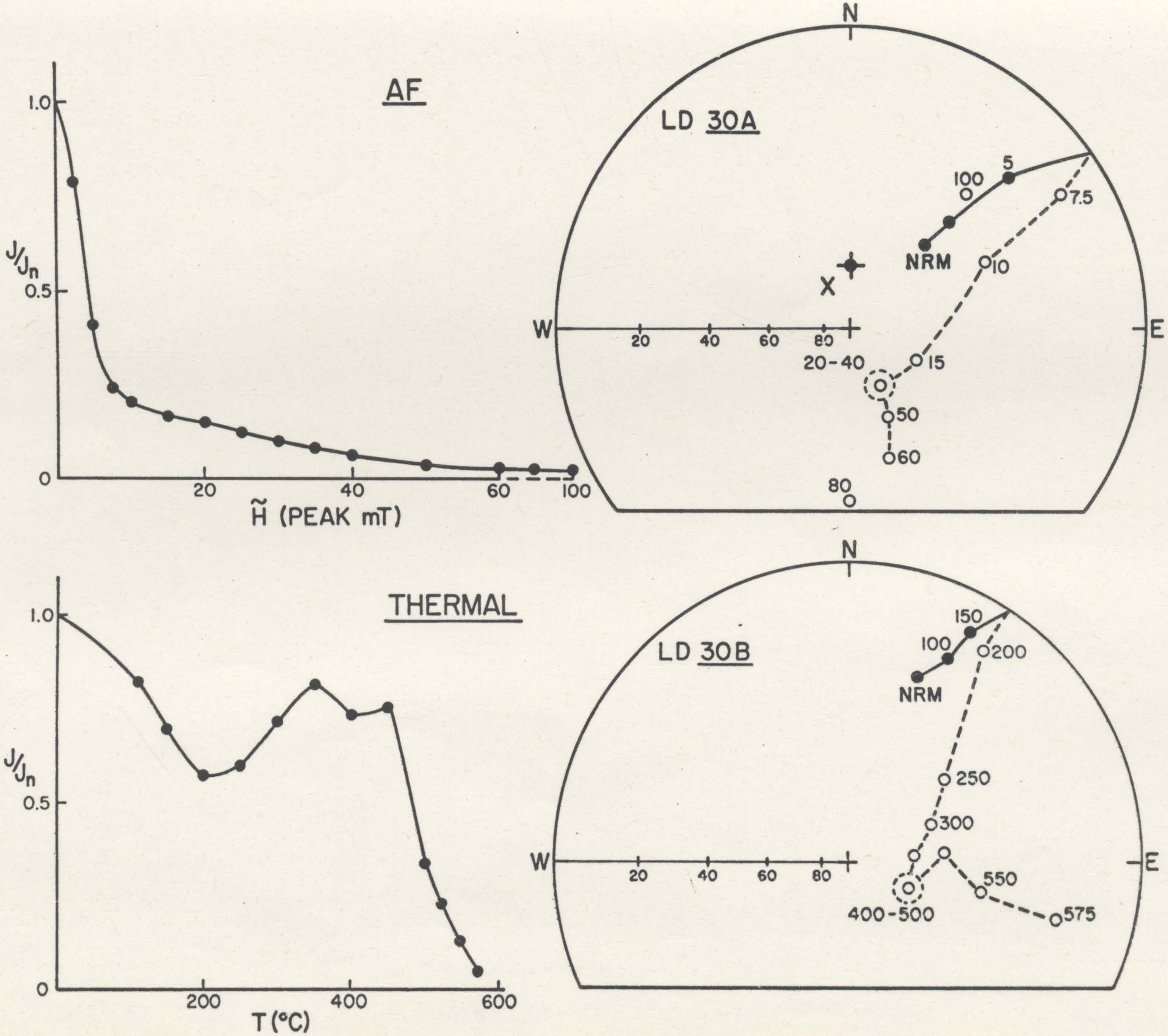


Fig. 5.3. Comparison of AF and thermal demagnetizations. Pair of specimens from dike 7 (see Appendix Tables 2 and 4). All symbols as in Figs. 4.4 and 5.1. Wulff's net.

levels off towards zero. The rise in intensity in the thermal decay curve between 200°C and 250°C indicates that a relatively soft component with a direction sharply divergent from the more stable direction probably has been unblocked. The sharp drop in intensity for LD 40C between 300-400°C followed by a progressive decrease at higher temperatures suggests that the blocking is distributed in the highest temperature range.

Specimens LD 30A and LD 30B (Dike 7, Site F)

The stable directions for these specimens differ by 25-30° over the ranges AF 20-40 mT and thermal 400-500°C, but the two specimens show a similar directional trend upon treatment. There is a fairly smooth angular transition from positive to negative inclination for both the AF and thermal treatment. The AF decay curve of LD 30A shows a sharp drop in intensity to 24% of NRM during three steps of demagnetization up to 7.5 mT suggesting the removal of a viscous component. The intensity then gradually levels off on subsequent treatments at higher fields. In the thermal decay curve of LD 30B it is seen that the intensity, after a sharp fall during the first three steps of demagnetization to 200°C, continues to rise to 350°C after which it drops again by a small amount at 400°C and stays level to the 450°C step. This suggests that an unstable component directed oppositely to the stable direction has been removed at <450°C. Beyond 450°C, the intensity goes down sharply, which probably explains the directional trend observed between 500°C and 575°C (see Fig. 5.3).

5.4 Extended thermal demagnetization

From the pilot results of Sections 5.2 and 5.3 it is seen that the specimens from some of the dikes maintain stable directions in the temperature range 200-400°C, above which no systematic component appears to exist. However, a substantial number of specimens exhibit stability of NRM directions with little change well beyond this range, to 500-550°C. A look at the response of individual specimens to the thermal treatment (Table 4, Appendix) shows that most of the specimens from dikes 1-8 maintain stable directions, to a varying degree, up to 500°C, whereas most of those from the rest of the dikes (9-18) show stable directions only up to 300°C, after which the directions change by larger angles at higher temperatures. Between 300°C and 500°C the directional change appears to be erratic in many cases. This observation makes it easier to choose the optimum demagnetizing temperature for a further, systematic study. It appears that it is sufficient to treat the specimens from all the dikes to two demagnetizing temperatures, 300°C and 500°C. Accordingly, on the average, four specimens (5 in the case of dikes 7 and 10) per dike were uniformly demagnetized at 300°C and 500°C. These four specimens (including the pilot specimens) were chosen randomly from four different samples of any dike. It may be noted at this point that for most of the dikes only four samples per dike were available for thermal studies. For dikes 2, 3 and 4, specimens from only three samples per dike were available, and hence the results for these dikes are based on three specimens only. Altogether 71 specimens were thus thermally demagnetized. Fig. 5.4 shows plots of dike-mean

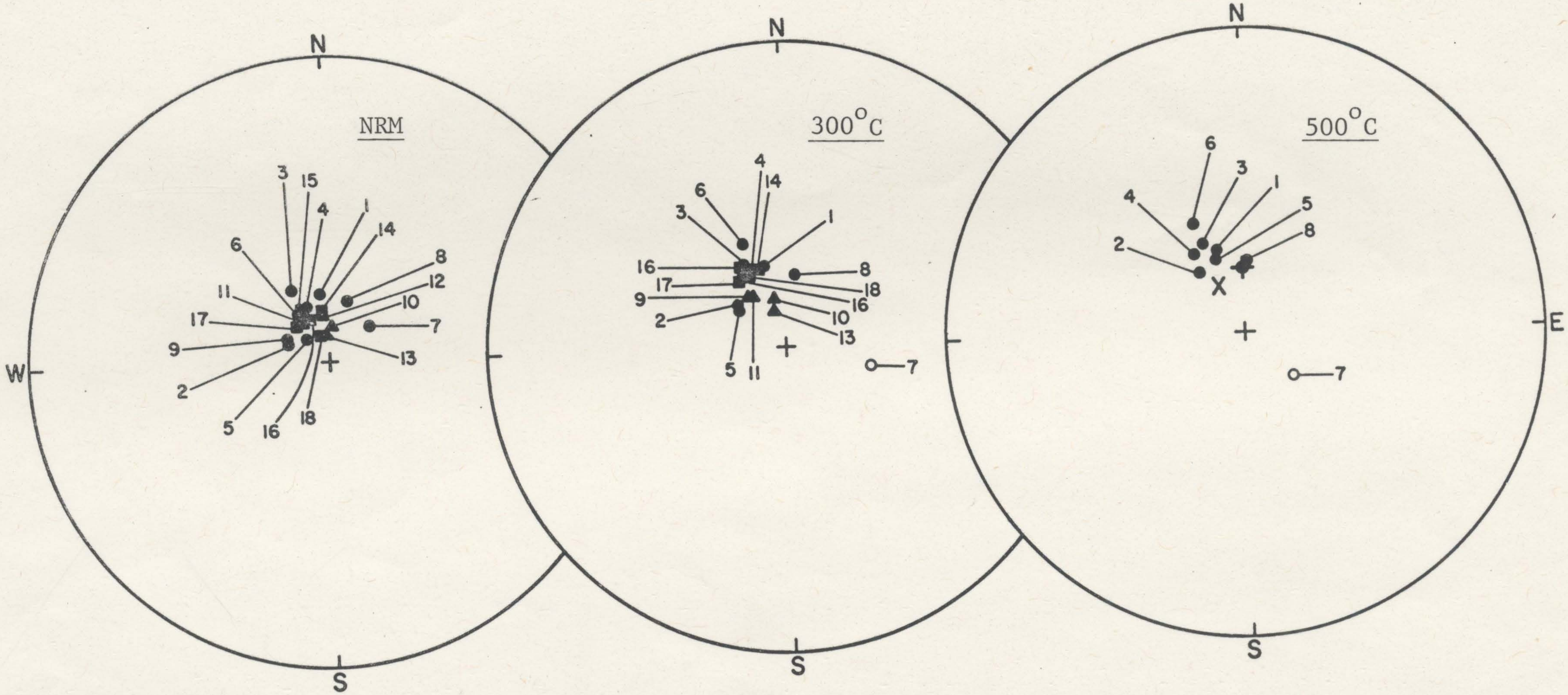


Fig. 5.4. Dike-mean directions before and after stepwise thermal demagnetization (Wulff's net). Dike numbers are as shown. Only dikes having a non-random within-dike grouping at any step are included. Symbols as in Fig. 4.4.

TABLE 5.1

DIKE-MEAN REMANENCE DIRECTIONS AND FISHER'S STATISTICS[a] FOR THERMAL TREATMENT

Site No.	Dike No.	Natural Remanence (NRM) D	I	N	k	α_{95}	Treatment	After demagnetization D	I	N	k	α_{95}
A	1	354	+65	4	22	20	500°C	343	+59	4	93	9.6
A	2	294	+73	3	10	41	500	323	+64	3	66	15
B	3	333	+61	3	42	19	500	336	+55	3	189	9.0
C	4	338	+69	3	35	21	500	328	+57	3	271	7.5
E	6	327	+69	4	5.0	44	500	336	+48	4	49	13
F	7[b]	50	+70	5	6.0	34	500	134	-65	4[c]	12	28
G	8	18	+67	4	23	20	500	5	+65	4	35	16
H	9	297	+73	4	18	22	300	325	+68	4	118	8.5
H	10	4	+77	5	12	23	300	346	+72	5	16	20
H	11	323	+73	4	14	26	300	328	+69	4	14	25
J	13	351	+80	4	17	23	300	342	+76	4	19	22
K	14	353	+72	3[c]	101	12	300	343	+60	3[c]	180	9.0
L	15	332	+69	4	16	24	300	333	+57	4	23	20
M	17	318	+72	4	19	22	300	325	+62	4	18	22
N	18	349	+80	4	30	17	300	332	+61	4	110	9.0
Overall mean		341.0	+73.3	15	60	5.0		334.3	+62.8	15	83	4.2

[a]The symbols are as in Table 3.1.

[b]The mean direction at 500°C has been inverted and included in final averaging.

[c]One greatly divergent sample has been excluded from the final averaging.

directions for NRM, 300^{o}C and 500^{o}C. Only those mean directions are plotted which give a non-random grouping, both before and after treatment. The final results, which are summarized in Table 5.1 with Fisher's statistics and plotted in Fig.4.5a, correspond to the best within-dike grouping at the treatment step shown in this Table. As in the case of AF results, the overall mean direction after thermal cleaning has been determined on the basis of dike-mean directions for which α_{95} does not exceed 30^{o}. This excludes dikes 5, 12 and 16 from final averaging of the thermally treated data. The overall mean direction after thermal cleaning is seen to be well-grouped around 334, $+63^{o}$ (α_{95} = 4.2, k = 83). Unlike the magnetically cleaned overall mean direction, the thermal mean exhibits a slightly improved grouping over the NRM mean (α_{95} = 5.0, k = 60). The within-dike grouping is seen to have improved considerably over its NRM value after thermal demagnetization, the only exceptions being dikes 11 and 17 with practically the same cluster before and after demagnetization. These results indicate that in most cases a stable component probably of primary origin has been isolated by the treatment.

5.5 Comparison of Area means

As discussed in Chapter 2, the sampling in the present study was done in three areas widely separated from each other (about 25-30 km). It is therefore interesting to compare the mean directions obtained for the individual areas after thermal and magnetic cleaning. These are summarized in Table 5.2 and plotted in Fig. 5.5 with their circles of 95% confidence. The circle of confidence for the AF-cleaned means is shown only for one area (Osmonton Arm), because

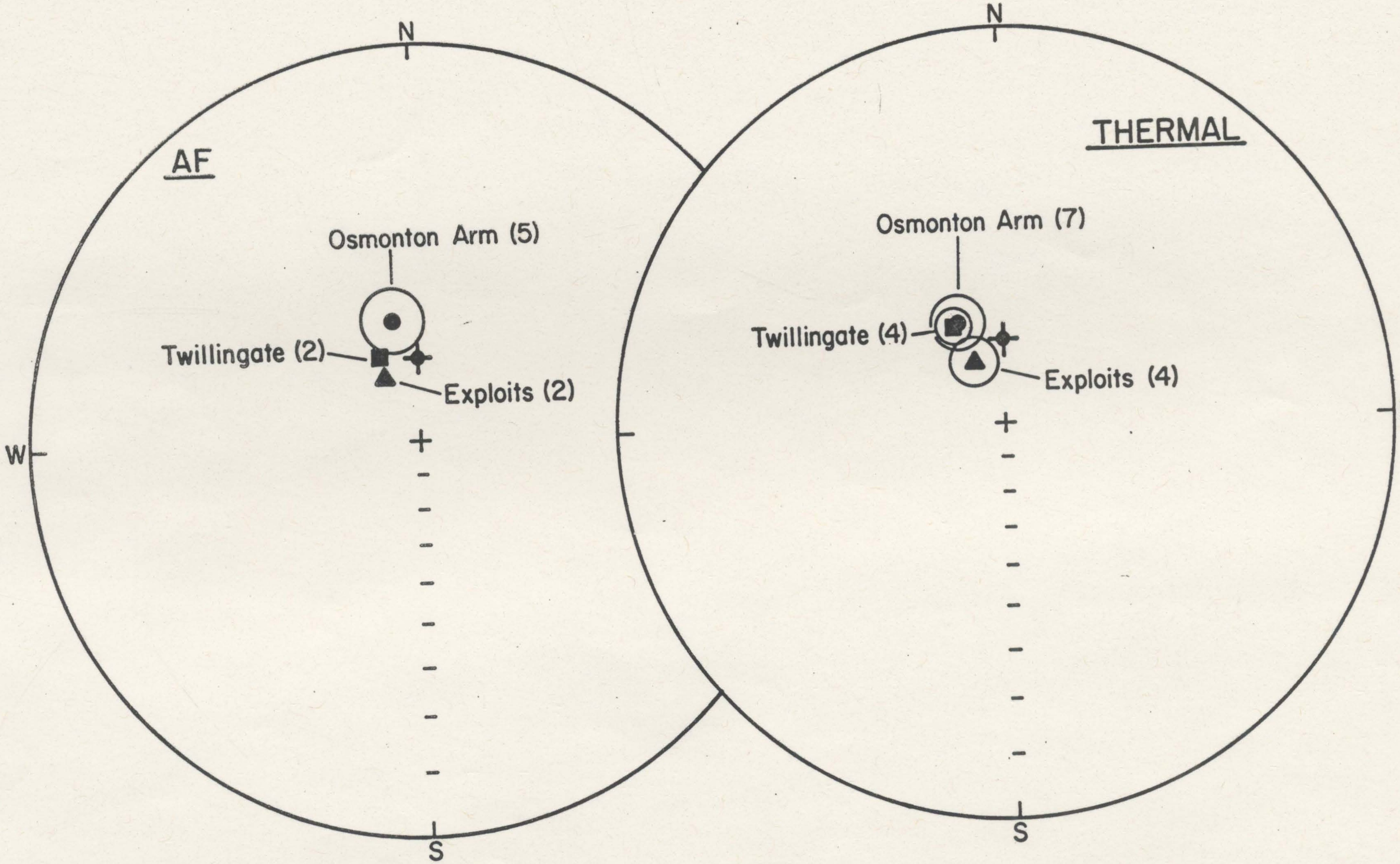


Fig. 5.5. Comparison of Area mean directions with 95% confidence circles. Numbers in brackets denote the number of dikes averaged (see Table 5.2). Wulff's net. Symbols as in Fig. 4.4.

TABLE 5.2

MEAN DIRECTIONS[a] FOR DIFFERENT SAMPLING AREAS

Sampling areas	After AF demagnetization					After thermal demagnetization				
	D	I	N	α_{95}	k	D	I	N	α_{95}	k
Osmonton Arm	347.9	+56.1	5	8.0	92	335.1	+59.5	7	7.4	68
Bay of Exploits	329.9	+70.2	2	-	-	334	+71.4	4	5.8	256
Twillin-gate	333.9	+63.7	2	-	-	332.2	+60.1	4	4.6	402
Overall mean[b]	342	+61	9	5.0	68	334	+63	15	4.2	83

[a] Symbols are as in Table 3.1.

[b] Overall means are as given in Tables 4.2 and 5.1.

those for the other two areas are based on only two dikes each. A comparison of the area means based on thermal demagnetization (Table 5.2) shows that those for the Osmonton Arm and Twillingate areas approximately coincide with each other but differ by approximately 10° from the Exploits area mean, which in turn practically coincides with the present earth's field in that area. An interpretation of this result in terms of small differences in the earth's field direction between areas would be premature, however, because averaging is based on only a few sites from the Exploits and Twillingate areas. Moreover, as seen from Fig. 5.5, the mean direction of the Bay of Exploits area does not statistically differ from the other two areas at the 95% level. The area means after AF demagnetization show larger differences ($16-17^{\circ}$) between the Bay of Exploits direction and each of the two other mean directions, but the AF and thermal means for the same areas agree well ($2-7^{\circ}$). These differences in mean direction based on treatment may be due to the small number of dikes averaged, especially in the former case. However, the overall means after AF and thermal demagnetizations (Fig. 5.6) may be considered to be statistically identical as their circles of 95% confidence intersect each other.

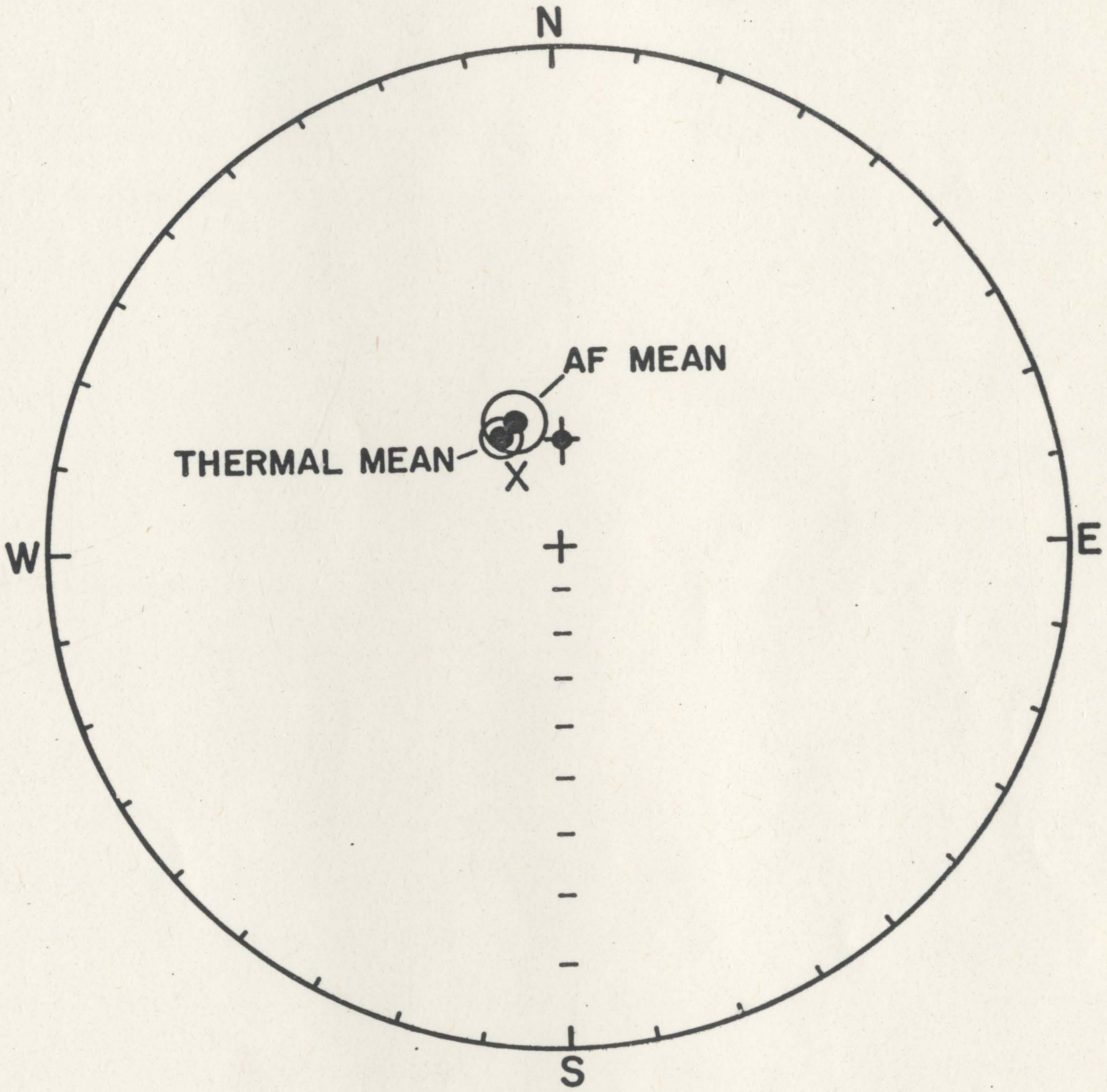


Fig. 5.6. Overall mean directions after AF and thermal demagnetizations with 95% confidence circles (see Table 5.2). ◆ Axial dipole field. X Present field.

CHAPTER 6

ORIGIN OF THE MAGNETIZATION

In this chapter some rock magnetic aspects of the lamprophyres that have been investigated for paleomagnetism are briefly discussed. To this end, thermomagnetic analysis and isothermal remanent magnetization (IRM) studies were done to determine Curie points and, if possible, identify the magnetic minerals. Such studies also may give a valuable clue to the number and relative stability of remanence components present in the NRM and could thus supply an independent test of the results obtained from stepwise thermal or AF demagnetization. Also reported and discussed are studies on low-field hysteresis and high-field hysteresis, the aim of which was to ascertain the domain characteristics and oxidation state of the magnetic grains.

6.1 Thermomagnetic analysis

Thermomagnetic analysis which is concerned with determining the variation of saturation magnetization with temperature is an important and standard procedure in rock magnetic and paleomagnetic studies. This technique can provide valuable information about the nature and state of whole magnetic mineral assemblage in a specimen and not only that portion which carries remanence. Though stepwise thermal demagnetization also gives valuable clues about the minerals, it has a serious drawback that any irreversible physical and chemical changes taking place as a result of heating may not be detected, as the remanence is measured only at the room temperature. The study of change of magnetic moment with temperature in strong external fields in a continuous heating-cooling cycle has the potential of providing more information.

The aim of these studies in the present case was to obtain the Curie point and make a possible identification of the minerals carrying remanence in the light of well-established results and theories (Nagata, 1961; Chevallier, 1951; Larson et al., 1969).

The instrument used for this purpose was the Curie balance. Its design and working is described in detail by Kristjansson (1973) and Deutsch et al. (1971). The balance is capable of measuring the Curie points of most materials within $\pm 10^{o}C$. A small amount of powdered specimen is heated in a quartz cup (as in the present study) or platinum cup surrounded by a stationary furnace. This is placed off-centre between the poles of an electromagnet, in the location of the strongest field gradient to maximize the magnetic force on the specimen. In the present study the field-strength at the specimen location was 585 mT and the field gradient was 137 mT/cm. This gradient deflects the cup carrying the powdered specimen. The current in a compensating coil required to keep the balance vertical is proportional to the magnet moment of the specimen, and is noted at different temperatures.

6.1.1 Results of thermomagnetic measurements

Powdered samples from ten different dikes were studied. Four representative results are shown in Fig. 6.1 in which normalized magnetic moment, M/M_o (M_o is the magnetic moment at room temperature) has been plotted against temperature. Since M is proportional to

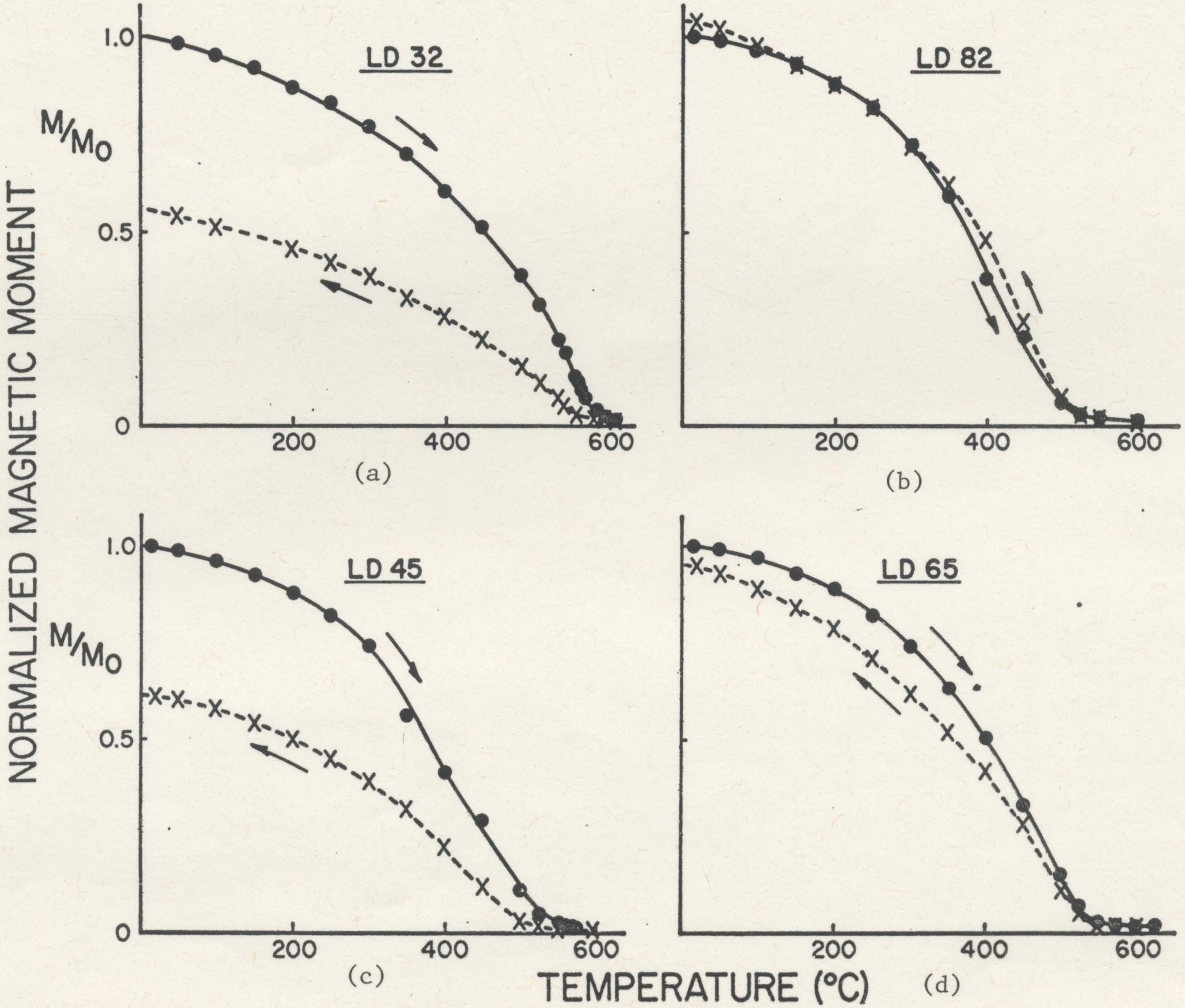


Fig. 6.1. Normalized thermomagnetic, M-T (equivalent to J_s-T) curves. Heating (solid) and cooling (dashed) curves obtained in 585 mT field.

intensity of magnetization, J and since the magnetizing field is sufficient for saturation (except probably in the case of hematite bearing samples), most or all of the curves may be considered equivalent to saturation magnetization-temperature (J_s-T) curves. The curves were found to yield a single Curie point (T_c) in each case. The T_c values for different samples range from 410°C to 600°C (Table 6.1). The other notable feature of these curves are moderate irreversible changes--representing a marked variation in saturation magnetization in the heating and cooling curves in Figs. 6.1(a) and 6.1(c), the cooling curve being downshifted with respect to the heating curve. However, Figs. 6.1(b) and 6.1(d) show little difference between their heating and cooling curves. The smooth, almost "classical" shape of all these curves suggest a single magnetic phase with only a small range in composition. Clearly hematite (Curie point 680°C) is absent or too small in quantity to be detected. However, relatively high Curie points (over 500°C) are characteristic of samples containing (titano)magnetite with low to zero Ti content. In samples with T_c in the range 580 to 600 or 620°C, the ferrimagnetic mineral is probably a cation-deficient magnetite resulting from high-temperature oxidation and perhaps involving ilmenite production in the mafic rocks (Larson et al., 1969). Such material tends to be magnetically very stable. The irreversible behaviour exhibited in the heating and cooling curves may be ascribed to chemical decomposition of metastable phases, oxidation or reduction or changes in the internal crystal structure, in each case resulting in a decrease of saturation magnetization upon cooling.

TABLE 6.1

CURIE POINTS* FROM M-T CURVES

Specimen	Dike	T_c (^oC)
LD 2	1	580
LD 7	2	600
LD 10	3	600
LD 22	5	580
LD 32	7	600
LD 45	10	545
LD 54	12	410
LD 65	14	540
LD 74	16	480
LD 82	18	520

*"Curie point" has been defined as that point on the temperature axis where the steepest part of the heating curve intersects it (see Fig. 6.1).

6.2 Isothermal remanent magnetization (IRM)

As discussed in Section 1.2 IRM is acquired at a constant temperature when the rock is placed in a magnetic field and the field is subsequently withdrawn. Most materials are capable of acquiring such type of remanence, provided the strength of the field exceeds the coercivity of the softest magnetic component. Such IRM's can be imparted in the laboratory by exposing the rock sample to a magnetic field, measuring the remanence thereafter and repeating the process for increasing fields. The value of remanence measured at zero field increases for increasing field steps, up to some maximum field value called the remanent saturating field, H_s. The remanence corresponding to H_s is called the maximum isothermal remanence, I_{RS}. The reverse field required to reduce I_{RS} to zero is called the coercivity of remanence (H_{cr}). Increasing the field further in the reverse direction normally produces saturation magnetization of the same amount as in the forward direction.

The presence of IRM in many natural minerals is not a serious problem, since it is usually much less intense than the TRM produced in the earth's field. But for magnetically soft materials this may not be the case, and tests to detect the presence of a soft IRM are necessary for paleomagnetic studies. Very large IRM could sometimes be acquired by rocks through lightning, and therefore it is important to avoid sampling in places likely to be struck by lightning. It is possible by IRM studies to get some insight into the minerals responsible for one or more observed components of stable remanence. From IRM studies on synthetic powders of magnetite and hematite, Roquet (1954) observed that magnetite became saturated in a field of only a few hundred milli-Teslas, whereas hematite could not reach saturation even in 3000 mT. H_{cr} values were found to be 20-30 mT for magnetite and several hundred mT for hematite. An interesting result of two component stability has been obtained by Carmichael (1961).

As part of the present work, IRM studies were done on 18 rock specimens, selecting one from each dike sampled and previously treated by AF demagnetization. The specimen was placed between the pole pieces of a (Varian) D.C. electromagnet and magnetized by increasing field strengths. Steady magnetic fields were applied for a short time (<2 min.) at each field, after which the specimen was removed and its remanence measured by a Schonstedt Station magnetometer. When the increasing fields produced no further increase in remanence, the specimen was subjected to reverse fields again increasing to saturation. Fig. 6.2 gives four representative plots of normalized isothermal remanence (I_R/I_{RS}) against the applied magnetic field. It is seen from these plots that the intensity builds up to saturation rapidly being complete by 80-100 mT, and on demagnetization falls sharply. H_{cr} values were found to be in the range 10-28 mT (Table 6.2). This behaviour pattern and the values of parameters H_s and H_{cr} are characteristic of igneous rocks with dominating magnetite content. The remanent coercivity of the presumed primary component estimated from the AF demagnetization study corresponding to optimum step was found to be in the range 10-35 mT (Chapter 4, Table 4.2) which is practically in the same range as H_{cr} obtained from IRM study. However, the

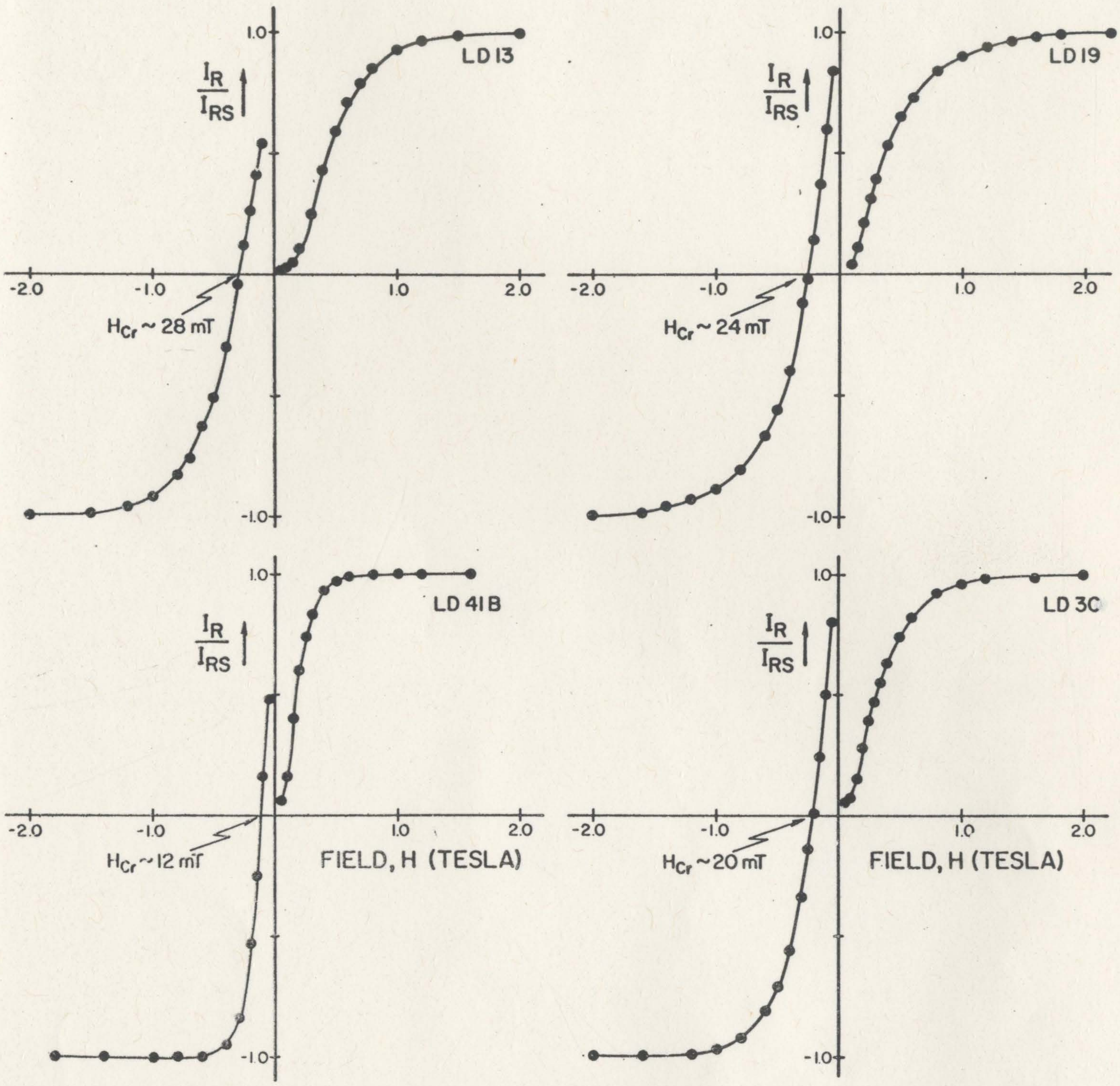


Fig. 6.2. Isothermal remanence (IRM), forward and back-field curves for four specimens (one per dike) obtained at room temperature. I_R, remanence and I_{RS}, saturation remanence each obtained at H = 0 after application of the field shown. H_{cr}, coercivity of remanence.

TABLE 6.2

Hcr VALUES FROM IRM CURVES

OA - Osmonton Arm area; E - Exploits area; T - Twillingate area

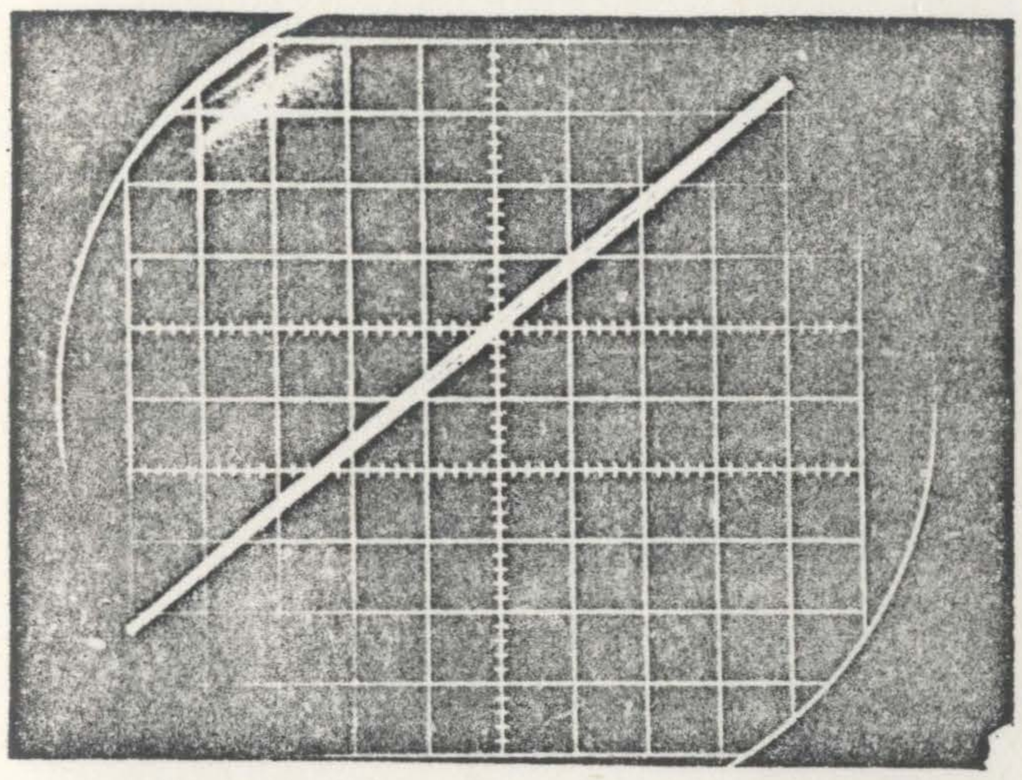
Specimen	Dike	Area	H_{cr} (mT)
LD 3C	1	OA	20
LD 9B	2	"	28
LD 13	3	"	28
LD 19	4	"	24
LD 23A	5	"	18
LD 27B	6	"	20
LD 32B	7	"	22
LD 36A	8	"	26
LD 41B	9	E	12
LD 46A	10	"	14
LD 50B	11	"	12
LD 54C	12	"	15
LD 59B	13	"	17
LD 64A	14	T	10
LD 72A	15	"	15
LD 74A	16	"	12
LD 78A	17	"	14
LD 84B	18	"	12

primary remanence was acquired in the ambient geomagnetic field of very low strength presumably by the TRM process. As there is no possibility that a steady magnetic field of 80-100 mT (responsible for isothermally acquired saturation remanence) could have existed at any time in the geological history of the rock it may be concluded that the primary remanence does not have any significant IRM component.

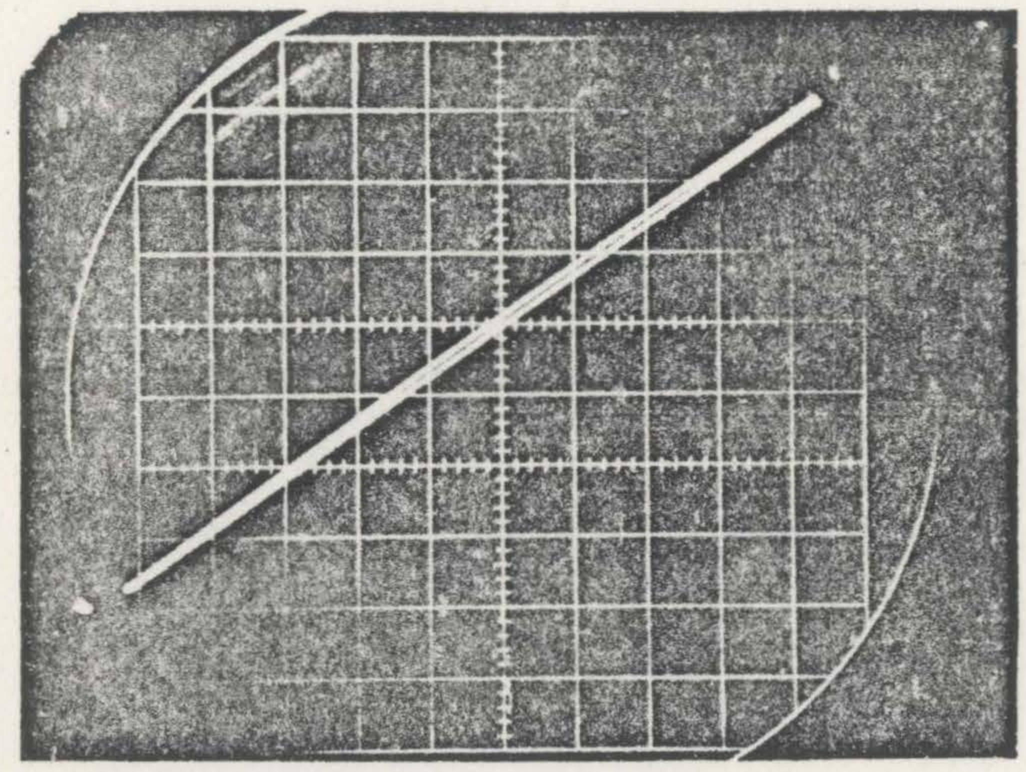
6.3 Rayleigh loops

The hysteresis loops of magnetic materials in fields much lower than their characteristic coercivity (H_c), usually in a field of 1 mT (peak), are called Rayleigh loops. The magnetization of materials in low fields usually obeys the empirical laws deduced by Lord Rayleigh (1887) which has been supported by Néel (1955) on theoretical grounds for rocks containing a few percent of magnetite grains. However, many actual rocks, because of their complex composition, apparently do not obey the Rayleigh laws even in applied field well within the Rayleigh region.

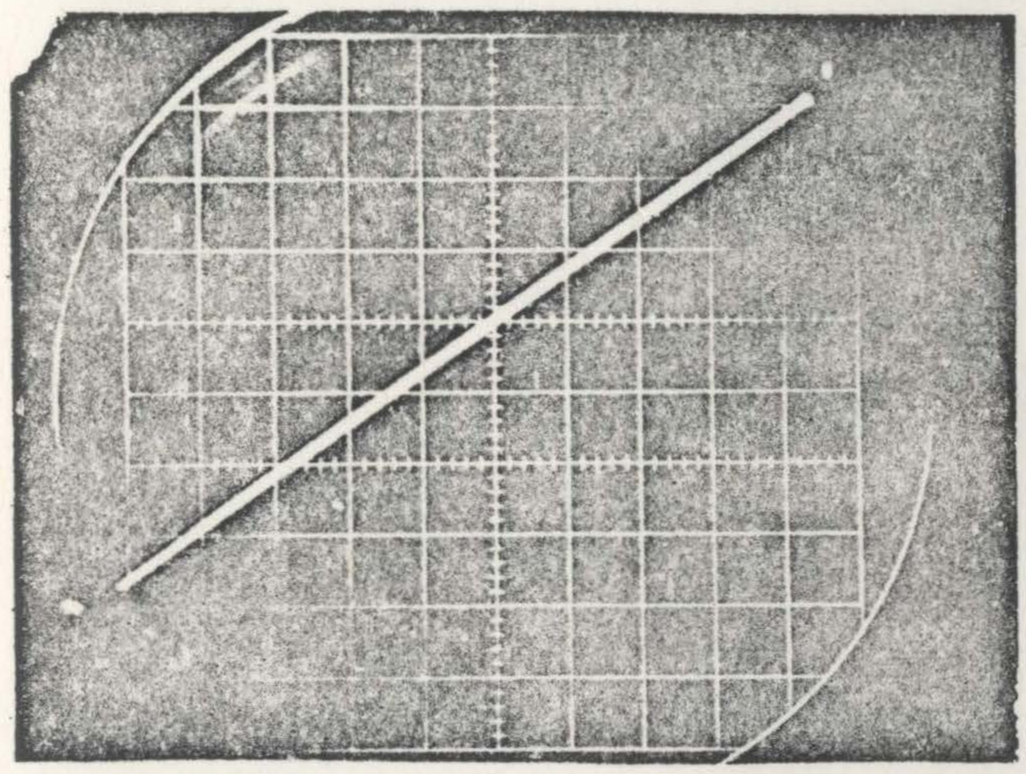
Rayleigh loops in basalts were first studied by Likhite and Radhakrishnamurty (1966) in order to detect any correlation between the stability of the rocks and their low field hysteresis behaviour and thereby to judge the suitability of rocks for paleomagnetic purposes. Their results suggest strongly the need for caution in assuming the stability of paleomagnetic data. Later on Radhakrishnamurty and Sastry (1970), from their studies on many basalts, attributed the open Rayleigh loops to the presence of interacting very fine singledomain (SD) grains in the superparamagnetic (SP) size range (≤ 300 Å in magnetite; Table 1 in Dunlop, 1981). Such extremely small particles have very short relaxation times and can undergo thermal vibrations with energies of the same order of magnitude as the magnetic energy, as a consequence of which they do not have stable magnetization, even though slightly larger particles of the same material do. Large multidomain (MD) grains also may produce Rayleigh loops, but of greatly reduced width compared with those in fine singledomains, due to demagnetizing effects (Néel, 1955). In fact, Rayleigh loops do not seem to be observed with standard equipment in MD magnetite (e.g., Radhakrishnamurty and Likhite, 1970). Study of Rayleigh loops supplemented with susceptibility-temperature (K-T) curves and high-field hysteresis loops can be of great use in quickly ascertaining the domain states in certain rocks having a simple magnetic mineralogy. A number of papers have been published on this subject (e.g., Radhakrishnamurty & Likhite, 1970; Radhakrishnamurty & Deutsch, 1974; Murthy et al., 1976; Deutsch & Pätzold, 1976, 1980). In the present study, a special objective in observing Rayleigh loops was to ascertain the suitability of the lamprophyres for paleomagnetic purposes. Towards this end all the specimens, after NRM measurements, were placed one by one in the alternating (1 mT peak) field of a Rayleigh loop tracer described by Likhite and Radhakrishnamurty (1966). While for all of the specimens from the Osmonton Arm area (dikes 1-8), the J-H curve obtained was a straight line, i.e., loops were absent, many specimens from the Bay of Exploits area (dikes 9-13) and Twillingate area (dikes 14-18) showed small loops. Six



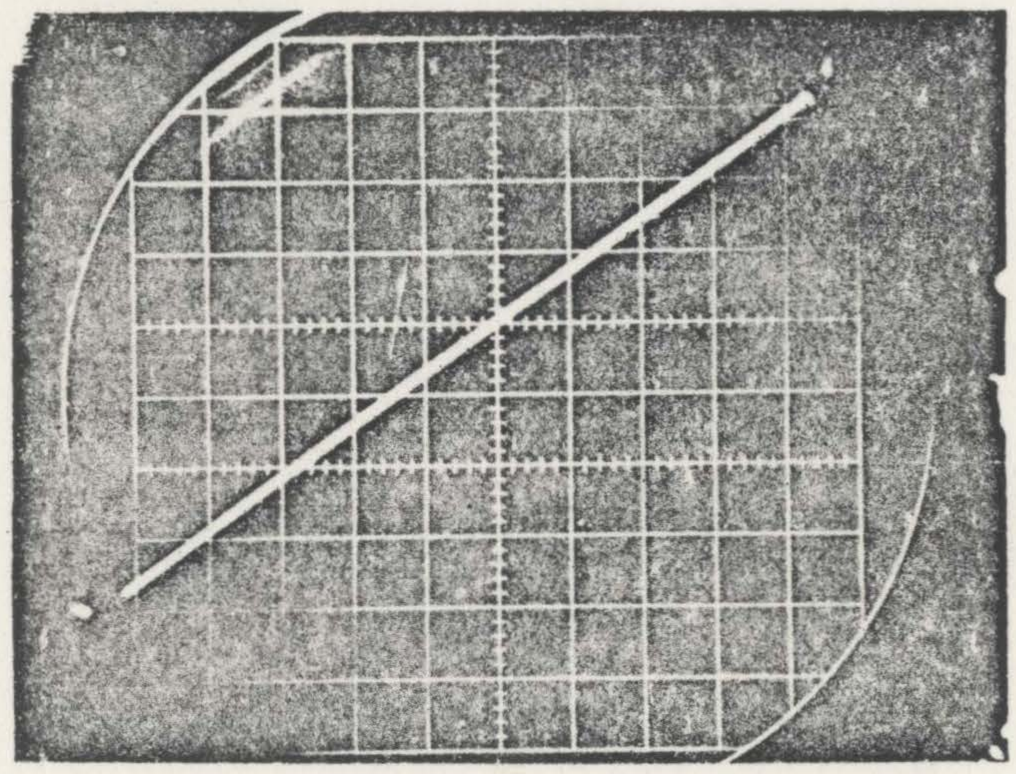
LD 41B (Dike 9)



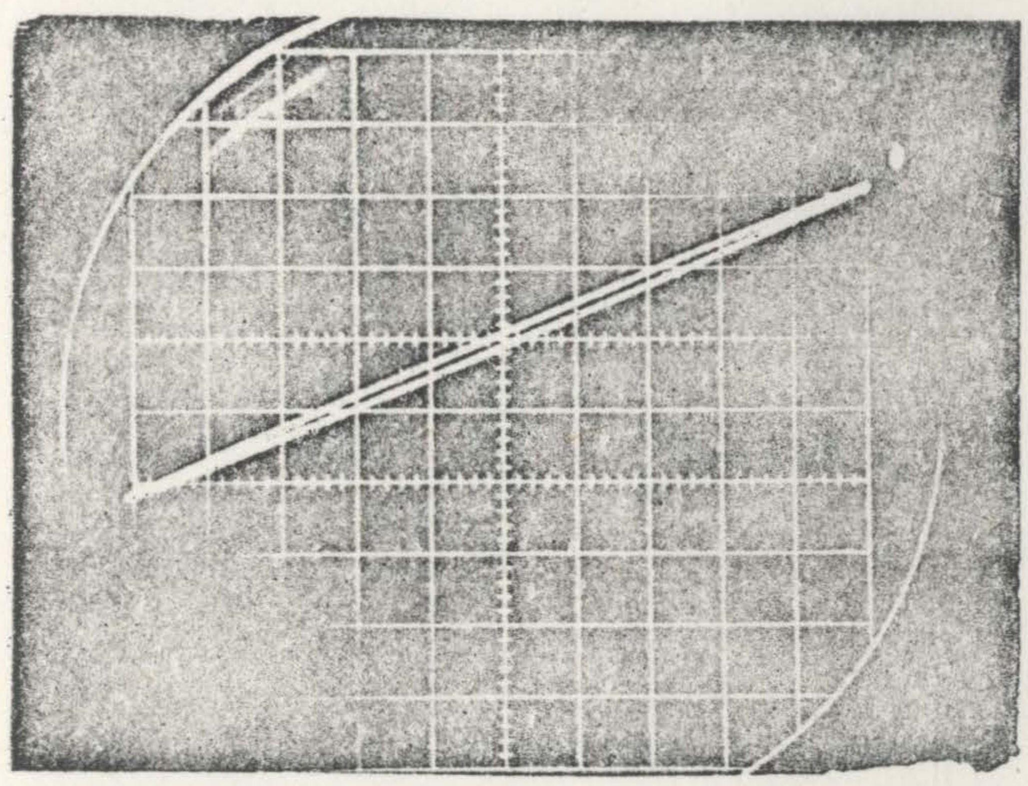
LD 62B (Dike 14)



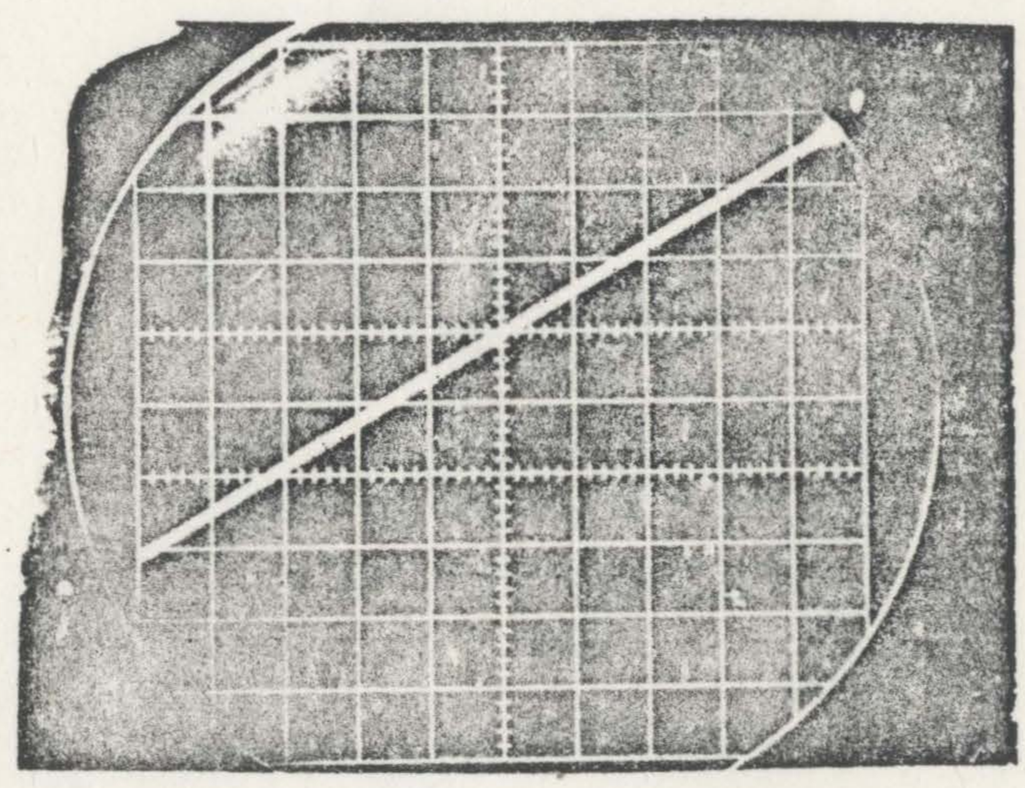
LD 48A (Dike 11)



LD 68B (Dike 15)



LD 51A (Dike 12)



LD 82A (Dike 17)

Fig. 6.3. Oscilloscope photographs of low-field (Rayleigh) loops obtained in 1.0 mT peak field, for six fresh specimens. Vertical (J) scale is in arbitrary units.

representative examples are shown in Fig. 6.3. These loops are not wide, the widest being for specimens from Dike 12. Such small loops have been observed earlier generally on partially stable rocks (Radhakrishnamurty et al., 1968). It is interesting to note that the rocks for which Rayleigh loops were observed either failed to yield a stable direction or behaved erratically upon AF demagnetization, as discussed in Chapter 4. Therefore, it seems as though a significant portion of these rocks contain fine-grained single-domains with short relaxation times that may not be in the super-paramagnetic range in the true sense of the term.

6.4 High-field hysteresis

High-field hysteresis studies at room temperature have been found useful in inferring the domain states of magnetic grains in a rock (Dunlop, 1969; Lowrie & Fuller, 1971; Likhite et al., 1965). Radhakrishnamurty and co-workers (Summary in Radhakrishnamurty & Deutsch, 1974) have extended the hysteresis measurements to liquid nitrogen temperature (-196^{o}C) and outlined procedures of distinguishing SD or SP and MD characteristics of rocks.

In the present study, hysteresis loops were obtained for 13 samples selected from 12 different dikes in a field of 120 mT (peak), by using the apparatus described by Likhite et al. (1965) and available at the Geomagnetic Research Laboratory. Values of coercivity (H_c) and ratio of saturation remanence to saturation magnetization (J_r/J_{max}) at both the room-temperature and -196^{o}C are listed in Table 6.3 along with the ratio H_{cr}/H_c. H_{cr} values are taken from Table 6.2 and are believed to represent the dikes from which samples have been studied for hysteresis, but it may be pointed out that lack of material generally precluded the measurement of H_c and H_{cr} in the same samples. A few representative sets of hysteresis loops are shown in Fig. 6.4. The fact that the loops at room temperature in all cases are fairly wide ($H_c \geq 6$ mT) would seem to rule out the possibility of truly multidomain (i.e., larger than pseudo-singledomain; Stacey & Banerjee, 1974) grains being abundant in the rock. Upon cooling to $-196^{o}C$ it is seen that there is 2-3 fold increase in H_c in many samples, which appears to be indirect evidence of the low-temperature phase transition in magnetite, though this change is much less than the observed increase for truly SD magnetite (Radhakrisknamurty & Deutsch, 1974). Some samples show little or no change in their hysteresis with temperature (Fig. 6.4), which is just opposite to the behaviour of magnetite. Such a character is exhibited by certain rocks and ascribed (Radhakrishnamurty et al., 1971) to the presence of cation-deficient (CD) magnetite phases. This type of behaviour has also been observed in synthetically prepared SD maghemite samples (Radhakrishnamurty & Deutsch, 1974).

The J_r/J_{max} values, which are in the range of 0.08 to 0.20 at room temperature and attain a maximum of 0.4 (in case of Dike 12) at $-196^{o}C$ fall short of classical SD type behaviour for which $J_r/J_{max} \geq 0.5$. However, Dunlop (1972) has reported $0.1 \leq J_r/J_{max} \leq 0.3$ for synthetic magnetite in the lower pseudo-singledomain size range (0.04 - 0.22 μm) where magnetite has most of the TRM properties of true singledomain material. The present result seems to be in good agreement with this.

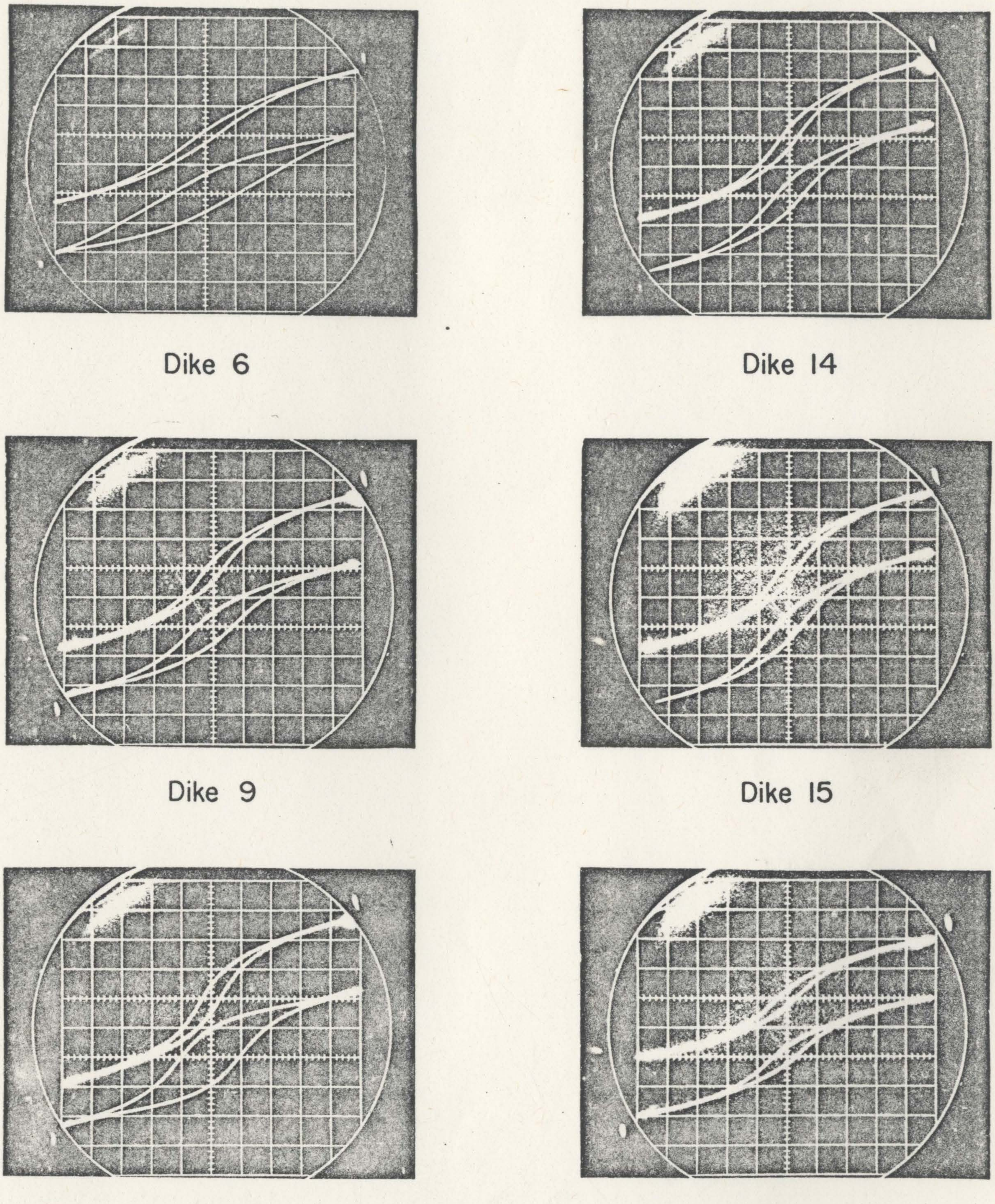


Fig. 6.4. High-field hysteresis loops in 120 peak mT field (lower traces) at room temperature (upper traces) and -196^{o}C for one fresh specimen each from six dikes shown. Vertical (J) scale is arbitrary.

TABLE 6.3

HIGH-FIELD HYSTERESIS RESULTS

Dike No.	Room Temperature			Liquid nitrogen temperature (-196°C)	
	J_r/J_{max}	H_c(mT)	H_{cr}/H_c[a]	J_r/J_{max}	H_c(mT)
3	0.20	17	1.7	0.30	31
4	0.08	7.0	3.4	0.20	17
5	0.09	7.0	2.6	0.28	24
6	0.11	7.0	2.9	0.30	25
7	0.16	9.5	2.3	0.20	19
9	0.13	6.0	2.0	0.20	15
12	0.16	7.0	2.1	0.40	24
13	0.15	7.0	2.4	0.17	9.5
14	0.13	7.0	1.4	0.19	11
15	0.13	6.0	2.5	0.20	9.5
17[b]	0.16	7.0	2.0	0.17	10
18	0.15	7.0	1.7	0.15	8.0

[a] H_{cr} values are for samples different from the ones studied for H_c. Hence the H_{cr}/H_c ratios have only limited quantitative value.

[b] H_c value is based on two specimens from the same dike.

Again, it is fairly well-established (Gaunt, 1960; Stacey & Banerjee, 1974) that H_{cr}/H_c ratio is 2 or less for SD material and substantially larger for MD grains. As is seen from Table 6.3, the H_{cr}/H_c values suggest close to stable SD behaviour.

In view of the above discussion and of Section 6.3 it is rather difficult to draw a conclusive inference on the domain structure of the lamprophyre rocks. The magnetic grains in these rocks possibly consist of mixtures of fine-grained singledomain, pseudo-singledomain and cation-deficient magnetites, each of these states being compatible with moderate to very high magnetic stability.

CHAPTER 7

THE MID-MESOZOIC FIELD RELATIVE TO THE APPALACHIANS

7.1 Calculation of pole positions

With the assumption of an axial dipole field, paleomagnetic pole positions corresponding to the overall mean directions obtained after AF and thermal cleaning were separately calculated and are listed in Table 7.1. For comparison, poles for the corresponding NRM mean directions are also listed. The results show that the laboratory treatment did not make much difference in the final results which points to the dominant presence of one or more stable components in the NRM directions. Thermally and magnetically cleaned pole positions are seen to be not significantly different and are in good agreement with Jurassic poles relative to the Appalachians quoted by other authors. These poles and the associated 95% error ovals are plotted in Fig. 7.1(b) along with the published poles of presumed Jurassic age.

7.2 Comparison with published mid-Mesozoic poles

Since the mid-Mesozoic is an important time-span with respect to the tectonics of the Atlantic-bordering continents, it is worthwhile to make a detailed comparison of the present pole with the other, contemporaneous poles and also with those corresponding to the time-spans immediately preceding and succeeding the present one. This could provide an insight into the movement of the pole during

TABLE 7.1

PALEOMAGNETIC POLE POSITIONS FROM THE MEAN DIRECTIONS OF MAGNETIZATION BEFORE AND AFTER LABORATORY TREATMENT

Treat-ment	N	Mean directions[a]				Pole position	Antipole position	dp	dm
		D	I	k	α_{95}				
NRM	9	338	71	116	4.8	76°N, 114°W	76°S, 66°E	7.2	8.3
AF	9	342	61	68	6.3	<u>75°N, 168°W</u>	75°S, 12°E	<u>7.4</u>	<u>9.7</u>
NRM	15	341	73	60	5.0	76°N, 97°W	76°S, 83°E	8.0	9.0
Thermal	15	334	63	83	4.2	<u>72°N, 152°W</u>	72°S, 28°E	<u>5.2</u>	<u>6.6</u>

[a] See Tables 4.2 and 5.1.
N is the number of dikes averaged.
dp, dm are the semi-axes of the 95% oval of confidence.
Underlined pole positions and oval dimensions are as shown in Fig. 7.1.

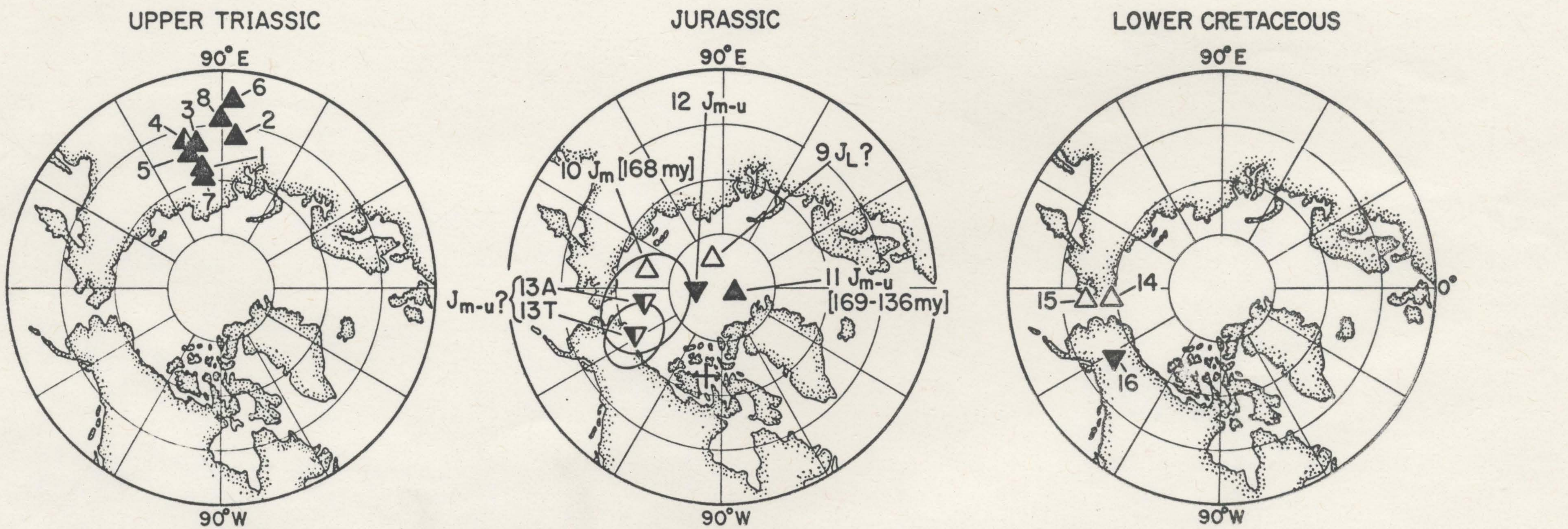


Fig. 7.1. Pole positions for Notre Dame Bay lamprophyres (this study) with published results from other Mesozoic paleomagnetic studies in the Appalachian region. Results are listed in Table 7.2 with the same pole numbers as shown here. Numbers in square brackets are reported K-Ar dates. + present magnetic pole. Polarity: ▲▼ Normal. △ Reversed. ◭▽ Mixed. Notre Dame Bay lamprophyre poles; ▽▼ . ▽ 13A, 13T. Paleomagnetic poles from the present study, for AF and thermal treatment, showing 95% confidence ovals.

the presumed tectonically active time interval when the lamprophyres were injected. For this purpose, published paleopoles for the Upper Triassic and Lower Cretaceous relative to the Appalachians have been listed in Table 7.2, and are plotted in Fig. 7.1 along with the Jurassic poles. Among the Jurassic group of poles, the pole (118^{o}E, 85.5^{o}N) from Mistasin Lake volcanics of Labrador (Currie & Larochelle, 1969) is also included which according to the radiometric (K-Ar) dates (~ 202 m.y.) belongs to Upper Triassic. However, in view of its proximity to the White Mountain volcanics pole one suspects that these volcanics might be Lower Jurassic in age. Moreover, the Mistasin Lake volcanics are of reversed polarity whereas, of the eight Upper Triassic poles listed, seven are normal and one is of mixed polarity. Opdyke and McElhinny (1965), however, have reported an important reversal at the Triassic-Jurassic boundary, located at 190 m.y. by McElhinny and Burek (1971). The reversed polarity in the Mistasin Lake rocks might well be correlated with this event. Previous paleomagnetic results for the Jurassic group of rocks from the Appalachians are of either normal or reversed polarity. In the present study, the rocks are predominantly of normal polarity, with the exception of one site giving consistently well-grouped, reversed directions. Assuming that these are primary directions, this indicates that the intrusion of the dikes must have been spread over an interval of time including at least one polarity transition. McElhinny and Burek (1971) recognize three short reversed polarity intervals in the predominantly normal Jurassic period, with the single Mateke event (~ 168-170 m.y.) occurring in the Middle Jurassic time and the time interval 150-110 m.y., straddling the

TABLE 7.2

MESOZOIC (UPPER TRIASSIC-LOWER CRETACEOUS) POLE POSITIONS RELATIVE TO APPALACHIANS

Geologic Age	Pole No.[a]	Rock unit, locality	N	Pole position (deg.) (α_{95}^{o} or dp^{o}, dm^{o})	Reference
Upper Triassic	1	Dikes,[b] Connecticut	41	69N, 100E (2)	Smith (1976)
	2	Sills,[b] Connecticut	8	62N, 88E (4)	DeBoer (1968)
	3	Diabase sheets, Pennsylvania	4	63½N, 103E (3)	Beck (1972)
	4	Newark Lavas and red beds, New Jersey	20	62N, 105E (2,3)	Opdyke (1961)
	5	Sills and dikes[b] (Mean), Maryland	20	64N, 105E (3)	Smith (1976)
	6	Meridian lavas, Massachusetts	5	55N,88E (6,11)	Irving & Banks (1961)
	7	North mountain basalts and Shelburne dike[c] (Mean), Nova Scotia	44	69½N,105E (7)	Larochelle & Wanless (1966); Larochelle (1967); Carmichael & Palmer (1968);
	8	Manicouagan Volcanics (Mean), Quebec	2	59N, 90E	Larochelle & Currie (1967); Robertson (1967)
Jurassic	9	Mistasin Lake volcanics,[d] Labrador	10	85½N,118E (3,4)	Currie & Larochelle (1969)
	10	White Mountain volcanics,[e,f] gabbro and basalt dikes; Sites 6-8 (Mean), New Hampshire	3	76N, 169E (9)	Opdyke & Wensink (1966)

TABLE 7.2 (Cont'd)

Geologic Age	Pole No.	Rock unit, locality	N	Pole position (deg.) ($\alpha_{95}{}^{o}$ or dp^{o}, dm^{o})	Reference
Jurassic	11	White mountain volcanics,[e] Lamprophyre, Monzonite, Essexite dikes; Sites 4,5,11,12 (Mean), Vermont and New Hampshire	4	88½N, 1W (3)	Opdyke & Wensink (1966)
	12	Lamprophyre dikes, Fortune Harbour, Newfoundland	11	83N,165W (5,7)	Deutsch & Rao (1977)
	13	Lamprophyre dikes, Notre Dame Bay, Newfoundland	9) 15)	75N,168W (7,10) 72N,152W (5,7)	This study
Lower Cretaceous	14	Monteregian Intrusives, Quebec	16	69N,173W (5,4)	Larochelle (1968)
	15	White Mountain volcanics,[e] Mount Ascutney gabbro A,B sites, New Hampshire	2	64N,187E	Opdyke & Wensink (1966)
	16	Lamprophyre dikes, Notre Dame Bay, Newfoundland	10	67N,168E (4)	Lapointe (1979)

Pole positions have been plotted in northern hemisphere with polarities as indicated in Fig. 7.1.

N is the number of units averaged (dikes, sites or areas).

α_{95} is the radius of 95% core of confidence.

dp, dm are the semi-axes of the 95% oval of confidence.

[a] Pole numbers are as shown in Fig. 7.1.

(Notes Table 7.2 cont'd)

[b] Smith (1976) considers these to be Lower middle Jurassic by stratigraphic and inferred stratigraphic position, but Armstrong and Besancon (1970) cite sills and dikes to be Upper Triassic (~ 200 m.y.) based on K-Ar determinations.

[c] Armstrong and Besancon (1970) consider these to be Upper Triassic based on K-Ar data.

[d] Radiometric (K-Ar) date ~ 202 m.y. (Wanless et al., 1966) suggests Upper Triassic age.

[e] New radiometric (K-Ar and Rb-Sr) dates of White mountain volcanics are summarized by Foland and Faul (1977) and most range from Lower Jurassic to Lower Cretaceous.

[f] Radiometric date 121 ± 3 m.y. (Foland & Faul, 1977).

Jurassic-Creataceous boundary (~ 135 m.y.) is characterized by a mixed polarity interval (5 reversed events). Therefore the observed case of a reversed polarity might be identified with any of the above events, including the Mateke zone, though a shorter, so far undetected reversed event within the normal polarity sequence of Middle to Upper Jurassic time cannot be excluded. Since the radiometric dates suggest the lamprophyre intrusion age to be Jurassic to Cretaceous, it could be argued that most of the dikes were intruded during normal polarity time within the mixed polarity interval close to the Jurassic-Cretaceous boundary, with the only observed reversed episode being perhaps correlated with a reversed polarity time span during the Jurassic-Cretaceous mixed polarity interval. That the pole from the present study lies intermediate between the other Notre Dame Bay lamprophyre poles, obtained by Deutsch and Rao (1977) and Lapointe (1979), may indicate that the lamprophyres in the present investigations are intermediate in age to those poles and again this is compatible with the (unfortunately imprecisely defined) age span of magnetization given by the radiometric dates. Also, the Jurassic poles relative to the Appalachians show much more scatter than do the Upper Triassic results, a fact which may be indicative of considerable apparent polar wander. The movement of the pole by a relatively large angle between Upper Triassic and Jurassic times (Fig. 7.1) is probably associated with the early phases of opening of the Atlantic Ocean.

It is interesting at this point to compare the present Jurassic pole to a Jurassic pole relative to stable Western Europe. From a study of the Upper Jurassic Limestones of South Germany, Heller (1977) obtained the pole position at 69^{o}N, 128^{o}E which is significantly displaced from the present pole and other Jurassic poles relative to the Appalachians. Considering the European pole a reliable representative of the Jurassic period, it could be argued that eastern North America had already separated from Europe during the Upper Jurassic as a result of a partial opening of the Atlantic Ocean. However, the significance of Heller's paleomagnetic data (1977) remains ambiguous as the "Jurassic" pole cited by him is based on the resultant directions obtained on an older, normal polarity sequence and a younger, mixed polarity sequence, the latter directions being close to those reported from European Tertiary rocks. This led Heller (1978) to conclude that the magnetization in the higher layers yielding mixed polarity originated more recently than the time of deposition of the normally polarized, presumably late Jurassic layers. For this reason, it may be premature to speak of a reliable pole position relative to "stable" Europe for any part of the Jurassic, and a meaningful comparison with North American Jurassic results must await additional paleomagnetic results from stable Europe for that time span.

SUMMARY AND CONCLUSIONS

(1) The aim of the present investigation was to determine the pole position of the lamprophyre dikes in north-central Newfoundland and to compare this with existing paleomagnetic information for mid-Mesozoic time relative to the Appalachians, in order to define the age of magnetization of the lamprophyres and make a possible interpretation of the tectonic implications of their emplacement.

(2) For this purpose, 18 dikes located in three main areas spread over 55 km from east to west were sampled and natural remanence (NRM) measurements were done on 205 specimens derived from 86 oriented hand and drill samples. Their remanence was measured with a Schonstedt digital spinner magnetometer (Model SSM-1).

(3) The NRM directions were found to be well-grouped and closely aligned with the earth's present field.

(4) Stepwise alternating-field (AF) and thermal demagnetizations were carried out with 121 and 71 specimens respectively, selected to give adequate statistical coverage for all 18 dikes, with respect to both kinds of treatment.

(5) An AF pilot study of 25 representative specimens showed three sets of remanence directions after cleaning: (i) Stable directions of normal polarity close to the present field direction, with inclinations somewhat shallower than that observed in the NRM; (ii) Directions of reverse polarity nearly antiparallel to (i), but not all directions being stable; and (iii) Normal to anomalous directions ranging from NW to SE in remanent declination, most of the specimens

concerned failing to show more than minimal magnetic stability. In all the three cases, the remanence intensity drops very sharply in the initial few steps of demagnetization up to 10 mT peak field, after which it gradually levels off at higher fields, indicating the removal of secondary components of low coercivity aligned nearly along the present field direction.

(6) A systematic AF demagnetization study yielded stable directions well-grouped around D = 342°, I = +61°, and possibly of primary origin, for 9 dikes, with $\alpha_{95} = 6.3^{\circ}$ and k = 68. The remanent coercivity of the stable direction estimated from the AF demagnetization results was found to be in the range 10 to 35 mT. It may, however, be noted that the directional scatter between dikes after magnetic cleaning was larger than that of the NRM ($\alpha_{95} = 4.8^{\circ}$ and k = 116), whereas the within-dike scatter was substantially less after cleaning than before hand. This suggests that magnetic cleaning was effective in removing secondary components and that the between-dike differences remaining after cleaning are due to real effect (i.e., not noise), such as secular variation.

(7) Pilot thermal demagnetization studies done on 22 specimens showed the stability of NRM to some varying degree up to 550°C for almost half of the specimens, with the only exception of one specimen which showed a systematic reversal to a stable point opposed to the present field. For the rest of the specimens, moderate to high stability was maintained at relatively lower temperatures between 250 and 400°C.

(8) The systematic thermal treatment, however, gave well-grouped mean directions for 15 out of the 18 dikes, with 7 among these

dikes having maximum within-dike grouping (highest precision, k) at $500^{\circ}C$ and the remaining 8 dikes giving maximum k at $300^{\circ}C$ (with the exception of two dikes among these for which k at $300^{\circ}C$ is practically the same as for NRM). The thermally cleaned directions averaged over 15 dikes yielded the overall mean at $D = 334^{\circ}C$, $I = +63^{\circ}$, with $\alpha_{95} = 4.2^{\circ}$ and $k = 83$, which was, unlike the AF results, an improvement in between-dike grouping over the NRM mean direction ($\alpha_{95} = 5^{\circ}$, $k = 60$). These results indicate that the thermal treatment, even more generally than the AF demagnetization was successful in isolating a stable component of presumably primary origin.

(9) A thermomagnetic analysis on powdered specimens from 10 dikes gave saturation magnetization vs. temperature (J_s-T) curves with single Curie points (T_c) in the range 410-600°C which is typical of (titano)magnetites in igneous rocks. The highest T_c values found (~ 580°C to 600°C) suggest highly oxidized or cation-deficient magnetite as the remanence carrier.

(10) Isothermal remanence (IRM) tests performed on one specimen per dike (Total: 18 specimens) yielded coercivity of remanence (H_{cr}) values in the range 10-28 mT, which seems to be in good agreement with the coercivity values estimated from the AF demagnetization study, although the remanence acquired in the two cases was through different processes. This study also revealed a single-component stability in the rocks under investigation.

(11) Studies of hysteresis in low field (~ 1 mT) and high field (120 mT) showed that the stable remanence carriers in the lamprophyres are probably mixtures of fine-grained singledomain and cation-deficient magnetites.

(12) The paleopoles obtained after AF and thermal demagnetizations are in good agreement with each other and are most closely associated with Jurassic poles relative to the Appalachians, though a possible affinity with published Creataceous poles for that region cannot be ruled out.

(13) The present pole position is intermediate to the pole positions obtained by Deutsch and Rao (1977) and Lapointe (1979) on the lamprophyre dikes sampled from the Fortune Harbour and Leading Tickles area respectively, suggesting an age intermediate to those (ie., Upper Jurassic to Lower Cretaceous).

(14) The intrusion of the lamprophyre dikes is the result of one of the youngest recorded phases of igneous activity in eastern Canada and is probably related to the White mountain series, the Monteregian Hill intrusion and, generally the mafic dike intrusions of eastern North America (Foland & Faul, 1977; McHone, 1978).

That the origin of the lamprophyres of Newfoundland is related to the opening of the North Atlantic has been suggested by Laughton (1975) and McHone (1978) on geological grounds. The intrusion probably took place in the areas of tensional weakness created by the compressional regimes between northern Eurasia and the Arctic Alaskan plate, as the North Atlantic ocean opened (Sweeney et al., 1978). The general agreement in the ages and paleopoles of the lamprophyres and other igneous rocks from this tectonically affected area indicate that a major initial phase of the opening of the North Atlantic took place during Upper Jurassic to Lower Cretaceous time. However, more paleomagnetic results on the contemporaneous rocks from Eastern North America and especially from "stable" Western Europe are needed to establish the validity of this hypothesis.

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APPENDIX (Tables 1-4)

Detailed Pilot Demagnetization Results

$\tilde{H}$ = Demagnetizing field (peak mT)

D = Declination (degrees, E of N)

I = Inclination (degrees, negative upward)

J = Intensity of magnetization (A/m)

J/Jn = Normalized intensity of magnetization (Jn is J at NRM)

* Indicates that no measurement was made

For explanation of dike groupings (Groups A,B,C), see pp. 41, 43.

TABLE 1

PILOT ALTERNATING-FIELD (AF) RESULTS (GROUP A DIKES)

Specimens	LD 1A (Dike 1)			LD 1B (Dike 1)			LD 11B (Dike 3)			LD 17A (Dike 4)			LD 20C (Dike 5)			LD 26B (Dike 6)		
$\tilde{H}$ (mT)	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn
0	354	42	1.00	13	66	1.00	332	38	1.0	350	55	1.00	352	30	1.00	250	59	1.00
2.5	356	40	0.949	14	63	0.756	331	41	0.941	358	55	0.922	349	33	0.820	256	55	0.735
5.0	360	46	0.557	14	56	0.385	327	44	0.802	359	55	0.688	342	38	0.521	274	49	0.428
7.5	360	46	0.363	12	54	0.246	328	46	0.703	360	54	0.525	340	41	0.35	280	48	0.311
10	359	44	0.086	11	53	0.168	326	47	0.606	1	55	0.393	346	34	0.283	285	47	0.228
15	358	41	0.082	14	50	0.067	328	47	0.318	3	53	0.189	343	31	0.124	286	44	0.113
20	353	39	0.059	18	45	0.034	333.1	46	0.175	9	49	0.105	351	31	0.078	286	43	0.060
25	342	48	0.034	17	41	0.023	337	46	0.107	7	50	0.078	358	33	0.048	292	42	0.040
30	344	50	0.030	11	49	0.018	343	44	0.053	2	48	0.058	340	31	0.031	289	49	0.025
35	348	57	0.027		Unstable		334	46	0.040	2	48	0.052	346	52	0.040	285	54	0.018
40	336	53	0.022		*		330	49	0.023	359	48	0.043	24	53	0.024	295	60	0.015
50	340	48	0.018		*		321	38	0.022	349	49	0.034	50	17	0.011	313	52	0.009
60	343	54	0.024		*		306	10	0.007	341	49	0.028	57	41	0.015	320	45	0.010
80	6	46	0.020		*		279	-35	0.008	349	45	0.019	104	68	0.028	273	53	0.011
100	270	48	0.005		*		210	55	0.017	345	33	0.015		*		339	71	0.003
Jn(A/m)	2.529			3.088			2.376			1.909			2.761			2.214		

TABLE 1 (Continued)

Specimens	LD 35C (Dike 8)			LD 40A (Dike 9)			LD 57A (Dike 13)			LD 73C (Dike 15)			LD 80A (Dike 17)		
$\tilde{H}$ (mT)	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn
0	359	64	1.00	285	59	1.00	329	56	1.00	360	73	1.00	304	71	1.00
2.5	1	63	0.917	298	58	0.787	327	55	0.869	347	71	0.739	314	67	0.788
5.0	358	61	0.717	312	61	0.369	326	61	0.575	335	65	0.322	326	62	0.540
7.5	357	60	0.570	317	60	0.165	323	63	0.324	336	63	0.154	327	60	0.404
10	356	60	0.434	319	59	0.075	322	65	0.193	336	62	0.075	325	59	0.289
15	353	58	0.163	327	57	0.020	327	70	0.063	320	70	0.019	321	57	0.119
20	354	56	0.074	1	20	0.008	317	71	0.023	256	59	0.010	338	53	0.082
25	356	53	0.045		Unstable		348	77	0.015	319	64	0.008	339	48	0.058
30	9	50	0.029		*			Unstable		150	72	0.004	334	43	0.047
35	333	64	0.021		*			*			Unstable		339	41	0.044
40	5	19	0.032		*			*			*		337	41	0.043
50	14	44	0.017		*			*			*		330	45	0.030
60	46	39	0.031		*			*			*		337	38	0.014
80	275	85	0.010		*			*			*			Unstable	
Jn(A/m)		3.866			6.316			4.719			4.113			4.657	

TABLE 2

PILOT ALTERNATING-FIELD (AF) RESULTS (GROUP B DIKES)

Specimens	LD 7B (Dike 2)			LD 8A (Dike 2)			LD 29B (Dike 7)			LD 30A (Dike 7)			LD 51B (Dike 12)		
$\tilde{H}$ (mT)	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn
0	133	74	1.00	296	58	1.00	64	64	1.00	44	50	1.00	27	66	1.00
2.5	125	82	0.924	296	52	0.871	62	49	0.618	44	39	0.788	34	55	0.513
5.0	38	86	0.627	293	47	0.591	66	-13	0.291	47	18	0.410	46	-20	0.109
7.5	9	83	0.472	293	47	0.446	81	-56	0.430	58	-10	0.244	53	-59	0.128
10	4	81	0.350	293	47	0.316	108	-64	0.474	64	-36	0.198	47	-63	0.096
15	23	80	0.131	294	41	0.117	140	-63	0.420	116	-62	0.165	46	-19	0.028
20	94	66	0.039	285	24	0.043	144	-61	0.327	145	-65	0.150	60	41	0.026
25	123	-8	0.020	264	-8	0.018	148	-61	0.258	153	-63	0.122	11	27	0.014
30	124	-43	0.027	206	-73	0.014	154	-59	0.201	169	-64	0.096		Unstable	
35	137	-47	0.026	169	-63	0.013	159	-62	0.140	161	-60	0.078		*	
40	138	-47	0.021	173	-68	0.010	148	-59	0.109	153	-65	0.058		*	
50	132	-47	0.016	174	-68	0.005	148	-63	0.064	156	-55	0.035		*	
60	124	27	0.005	56	-1	0.003	144	-56	0.056	164	-41	0.029		*	
80	320	77	0.010	340	37	0.004	157	-39	0.035	179	-31	0.026		*	
100	32	47	0.004		*		199	-31	0.025	41	-29	0.003		*	
Jn(A/m)		1.845			2.085			0.517			0.900			2.098	

TABLE 2 (Continued)

Specimens	LD 53C (Dike 12)			LD 75B (Dike 16)			LD 77A (Dike 16)			LD 84B (Dike 18)			LD 86C (Dike 8)		
$\tilde{H}$ (mT)	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn
0	52	71	1.00	319	68	1.00	334	62	1.00	309	77	1.00	354	62	1.00
2.5	42	71	0.365	317	61	0.721	338	58	0.786	298	71	0.754	351	59	0.884
5.0	71	54	0.049	309	56	0.239	350	55	0.308	286	65	0.291	350	56	0.469
7.5	111	17	0.027	294	55	0.083	351	54	0.126	263	61	0.114	349	57	0.226
10	110	17	0.022	243	19	0.023	350	49	0.054	218	24	0.047	1	58	0.087
15	129	-4	0.018	182	-39	0.028	139	-71	0.007	179	-22	0.040	132	-41	0.038
20	122	-21	0.024	184	-26	0.014		Unstable		171	-27	0.025	141	-39	0.026
25	195	-81	0.016	136	75	0.005		*		167	-29	0.009	148	-25	0.010
30		Unstable			Unstable			*			Unstable			Unstable	
35		*			*			*			*			*	
40		*			*			*			*			*	
50		*			*			*			*			*	
Jn(A/m)		2.438			3.135			3.106			3.537			3.329	

TABLE 3

ALTERNATING-FIELD (AF) RESULTS (GROUP C DIKES)

Specimens	LD 45B (Dike 10)			LD 49A (Dike 11)			LD 62B (Dike 14)			LD 65A (Dike 14)		
$\tilde{H}$	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn
0	45	65	1.00	20	62	1.00	163	77	1.00	230	86	1.00
2.5	46	65	0.695	17	53	0.742	154	73	0.858	192	83	0.680
5.0	57	61	0.231	7	44	0.323	150	62	0.323	157	74	0.261
7.5	68	56	0.093	8	42	0.149	153	58	0.143	150	68	0.126
10	86	38	0.044	19	32	0.082	151	60	0.076	148	64	0.067
15	109	20	0.013	49	34	0.022	148	56	0.027	145	72	0.015
20	83	18	0.008	77	40	0.015	157	60	0.012	16	58	0.007
25		Unstable			Unstable		224	60	0.012		Unstable	
30		*			*		131	28	0.012		*	
35		*			*		140	35	0.008		*	
Jn(A/m)		4.828			4.348			5.048			4.452	

TABLE 4

PILOT THERMAL RESULTS

Specimens Temperature (^{o}C)	LD 1C (Dike 1)			LD 5C (Dike 1)			LD 7A (Dike 2)			LD 9A (Dike 2)			LD 11A (Dike 3)			LD 16A (Dike 4)		
	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn
0	47	61	1.00	351	68	1.00	206	67	1.00	332	56	1.00	334	46	1.00	349	54	1.00
100	42	59	0.799	343	66	0.812	223	69	0.788	332	52	0.820	333	45	0.928	350	51	0.789
150	37	60	0.719	339	63	0.736	230	71	0.698	331	51	0.750	334	45	0.899	346	52	0.685
200	30	61	0.656	341	53	0.692	238	73	0.623	333	50	0.696	333	45	0.860	345	53	0.661
250	27	61	0.561	340	63	0.653	247	77	0.529	327	52	0.643	332	46	0.802	341	52	0.599
300	25	61	0.495	339	62	0.543	261	77	0.479	327	52	0.599	335	48	0.759	343	54	0.524
350	18	62	0.430	339	61	0.432	279	77	0.434	324	53	0.566	329	47	0.719	337	55	0.448
400	13	60	0.378	344	60	0.372	293	75	0.388	325	53	0.501	331	48	0.676	330	55	0.382
450	11	60	0.327	341	60	0.310	303	74	0.348	324	54	0.45	333	48	0.626	327	54	0.335
500	3	60	0.278	342	59	0.263	313	72	0.315	326	53	0.391	333	49	0.553	324	53	0.305
525	355	61	0.210	345	60	0.236	320	69	0.251	321	54	0.357	335	46	0.442	322	53	0.279
550	353	59	0.143	345	60	0.195	317	66	0.163	324	55	0.260	340	52	0.193	319	53	0.264
575	317	62	0.023	49	78	0.026	126	35	0.005	200	38	0.010	356	61	0.008	305	31	0.030
Jn(A/m)	2.921			2.836			2.205			2.047			2.157			1.578		

TABLE 4 (Continued)

Specimens Temperature (^{o}C)	LD 17C (Dike 4)			LD 20B (Dike 5)			LD 26A (Dike 6)			LD 30B (Dike 7)			LD 35A (Dike 8)			LD 36B (Dike 8)		
	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn
0	321	72	1.00	209	73	1.00	224	42	1.00	22	24	1.00	47	63	1.00	352	60	1.00
100	322	72	0.836	215	60	0.716	224	78	0.620	27	16	0.819	44	63	0.931	346	58	0.884
150	324	70	0.802	219	62	0.60	234	78	0.540	29	8	0.688	42	63	0.867	346	57	0.817
200	325	70	0.764	240	59	0.487	261	79	0.495	33	-10	0.573	40	63	0.794	343	57	0.777
250	329	67	0.699	232	64	0.384	282	75	0.410	50	-40	0.596	35	63	0.746	342	58	0.721
300	332	65	0.643	240	56	0.319	308	74	0.370	67	-56	0.714	34	64	0.674	341	57	0.662
350	331	63	0.603	260	73	0.297	304	70	0.319	87	-65	0.810	32	64	0.611	341	57	0.615
400	335	62	0.560	222	62	0.228	301	67	0.288	98	-61	0.730	31	64	0.551	341	58	0.529
450	337	61	0.503	267	65	0.185	311	62	0.239	119	-66	0.745	28	65	0.471	341	59	0.442
500	336	60	0.458	333	86	0.144	314	57	0.214	102	-62	0.336	27	67	0.335	340	59	0.343
525	339	59	0.414	24	85	0.108	306	45	0.079	84	-54	0.225	36	67	0.283	337	59	0.286
550	337	59	0.360	74	56	0.053	280	13	0.025	103	-40	0.132	34	67	0.199	336	58	0.175
575	354	69	0.026	86	17	0.015	128	32	0.011	106	-17	0.047	107	-28	0.005	100	-15	0.006
Jn(A/m)	1.873			1.007			1.594			0.558			3.200			3.921		

TABLE 4 (Continued)

Specimens Temperature (°C)	LD40C (Dike 9)			LD45A (Dike 10)			LD49B (Dike 11)			LD53B (Dike 12)			LD57B (Dike 13)			LD62A (Dike 14)		
	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn
0	297	54	1.00	70	64	1.00	75	84	1.00	320	60	1.00	342	78	1.00	156	65	1.00
100	296	53	0.880	76	60	0.844	67	86	0.787	318	52	0.633	329	77	0.823	154	63	0.868
150	299	52	0.734	80	57	0.697	88	87	0.614	318	46	0.426	324	76	0.714	154	61	0.790
200	302	53	0.680	76	56	0.613	32	88	0.517	317	43	0.289	321	75	0.639	152	58	0.745
250	315	57	0.785	66	66	0.631	330	81	0.556	318	31	0.200	322	74	0.537	146	55	0.738
300	323	60	0.719	53	68	0.493	326	76	0.485	305	-16	0.112	328	78	0.274	141	53	0.590
350	319	57	0.409	149	-6	0.268	227	89	0.268	324	-36	0.068	116	69	0.073	138	52	0.332
400	322	54	0.214	37	-7	0.975	234	72	0.195	6	22	0.033	128	-4	0.066	138	46	0.216
450	294	35	0.086	185	-7	0.310	283	24	0.110	110	9	0.067	137	-39	0.052	134	49	0.114
500	349	5	0.051	189	-24	0.019	165	22	0.058	122	20	0.063	140	-35	0.046	121	24	0.025
525	10	27	0.032	71	1	0.020	189	13	0.050	115	9	0.053	141	-10	0.029	168	84	0.031
550	16	61	0.015	102	-18	0.018	195	24	0.034	98	-1	0.037	134	-6	0.006	103	1	0.009
575	358	15	0.026	356	0	0.007	208	3	0.027	64	25	0.012	214	56	0.005	94	11	0.012
Jn(A/m)	5.885			3.517			3.154			1.785			4.082			6.044		

TABLE 4 (Continued)

Specimens Tempera-ture (^{o}C)	LD 73A (Dike 15)			LD 75A (Dike 16)			LD 78B (Dike 17)			LD 86B (Dike 18)		
	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn	D	I	J/Jn
0	20	63	1.00	16	50	1.00	62	85	1.00	72	72	1.00
100	12	56	0.772	12	45	0.743	40	82	0.757	71	71	0.726
150	12	54	0.694	11	45	0.641	16	78	0.588	76	71	0.601
200	10	50	0.629	3	41	0.523	3	64	0.360	24	75	0.637
250	2	52	0.558	356	46	0.503	80	79	0.461	343	66	0.918
300	1	55	0.489	349	48	0.406	21	69	0.194	344	68	0.609
350	3	57	0.292	358	48	0.189	329	-33	0.259	28	79	0.251
400	1	59	0.218	358	48	0.138	71	82	0.174	25	77	0.218
450	353	67	0.096	12	43	0.055	137	78	0.224	86	63	0.092
500	352	63	0.044	60	67	0.021	32	81	0.053	61	76	0.060
525	40	63	0.025	151	14	0.007	272	53	0.055	43	72	0.033
550	125	-11	0.004	147	15	0.005	284	49	0.055	109	-4	0.006
575		*			*		258	34	0.099	159	-44	0.006
Jn(A/m)	3.738			3.932			2.035			3.275		

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