# "A RESETTING OF PALEOREMANENCE IN LOW-GRADE METAVOLCANICS"

by

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on Graduate Students

# TABLE OF CONTENTS

# TABLE OF CONTENTS

(CONT)

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## ABSTRACT

Until recently metamorphic rocks have rarely been used in paleomagnetic studies, although understanding of the geological history of metamorphic regions would be greatly enhanced if reliable paleomagnetic data could be extracted from them. In this study, it is shown that useful information can be retrieved from the volcanics in areas of low-grade regional metamorphism.

The samples studied were taken from outcrops of three metavolcanic formations in the Boston, Massachusetts area. The age of the Marlboro metabasalts has been determined as late pre-Cambrian, while that of the Mattapan and Lynn metarhyolites seems to be Silurian. Progressive demagnetization cleaning in an alternating field has shown that the samples acquired a secondary chemical magnetization, which completely replaced the primary thermal remanent magnetization. The chemical remanence appears to have been acquired during the Devonian Acadian Orogeny. The average of the completely cleaned directions of those samples which have the highest probability of being "in situ" was found to coincide closely with the best available value for the Devonian pole position for North America.

The secondary magnetite appeared to have been produced by the low-grade metamorphic transition of pyroxene to chlorite and magnetite. The resulting magnetite seemed to contain a sizeable percentage of multidomain grains, as implied by generally low median destructive fields. Investigation of the anisotropic nature of the samples indicated that they were virtually magnetically isotropic.

It is concluded that low-grade metavolcanics which have been tectonically deformed during metamorphism may still be used for the calculation of paleomagnetic pole positions, if those pole positions are referred to the time of metamorphism rather than to the time of eruption. This investigation has indicated this fact by finding consistant orientations in samples taken over several miles despite metamorphic folding, and by finding a mean paleopole position appropriate for the time of metamorphism.

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# GEOLOGICAL SETTING AND PETROLOGY

## GENERAL STATEMENT

The first geologic survey of the Boston, Massachusetts area was conducted at the turn of the century by Crosby (1900) and has since been followed by studies of increasing complexity (Emerson, 1917), (Billings, 1929), (LaForge, 1932), and (Bell, 1948). These studies indicated that all of the formations may be considered to fall into five groups, based on lithology and age.

The first of these groups consists of metamorphosed igneous and sedimentary rocks regarded as probably of late pre-Cambrian to Middle Cambrian age. Included in this group are the pre-Cambrian Waltham Gneiss, the Westboro Quartzite, the Marlboro basaltic flows, the Woburn Volcanics, the Lower Cambrian Weymouth argillites, and the Middle Cambrian Braintree shales. The second group is comprised of three sub-alkaline batholiths and their apophysal offshoots and include the pre-Devonian (probably Ordovician) Salem Gabbro-diorite, Nahant Gabbro, and Dedham Granodiorite.

Rocks of the third group form the Middle Paleozoic alkaline intrusive bodies of the Peabody Granite, the Quincy Granite, and the Blue Hills Granite Porphyry. Apparently associated with the emplacement of these intrusives are the flows of the Lynn and Mattapan Volcanic Complexes. The stratified Roxbury Conglomerate, Cambridge Siltstone, Brighton Volcanics, and Squantum Tillite comprise the fourth group, all having been deposited as post

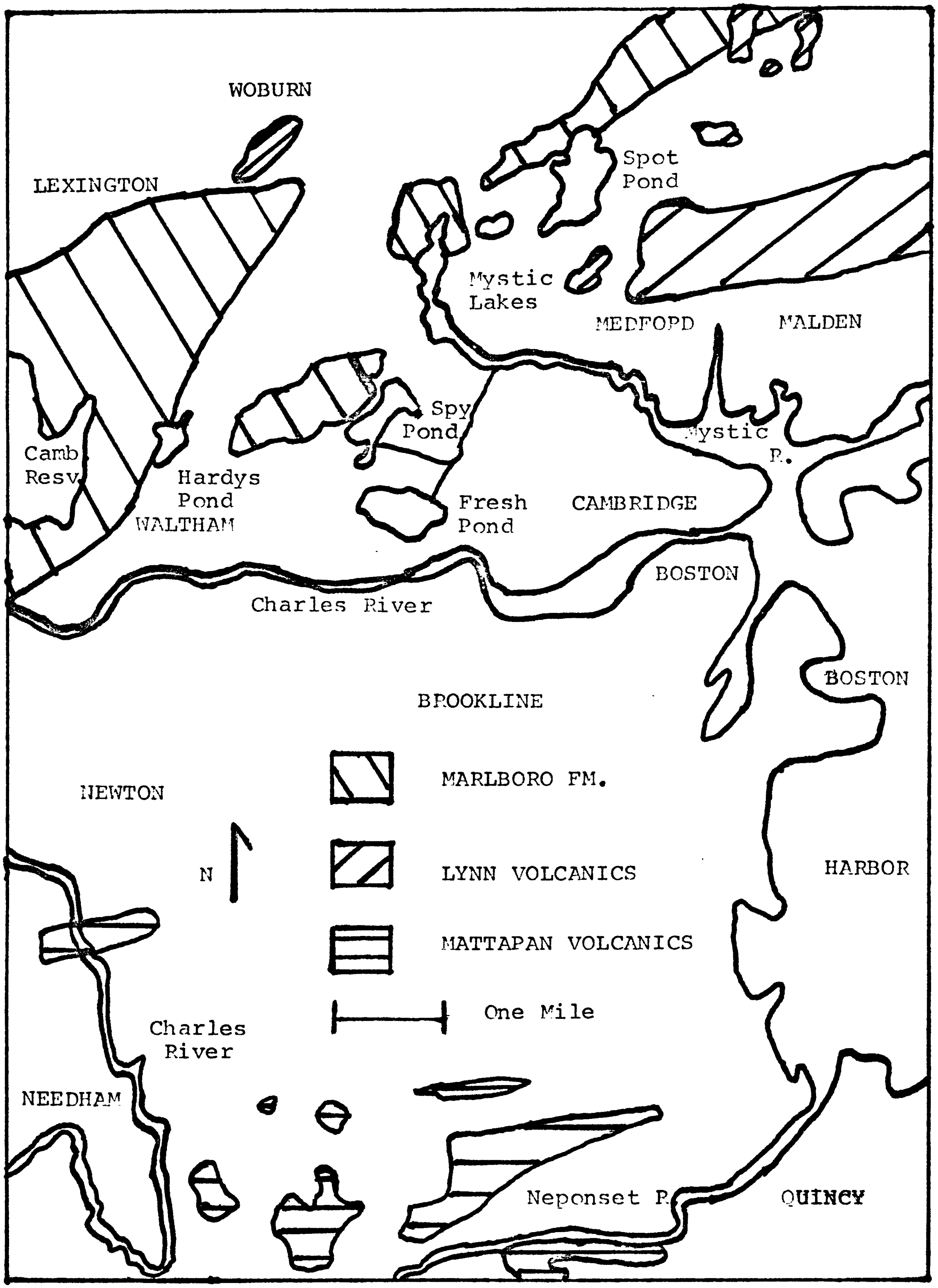
Acadian glacial outwash sediments in the Boston Basin. The fifth and final group consists of a large number of post Paleozoic diabase dikes and sills which were injected into all of the formations of the area, presumably during the Triassic period. Rock samples from three of the above mentioned formations, the Marlboro Formation, the Mattapan Volcanic Complex, and the Lynn Volcanics have been investigated in this study. (See maps for sample locations). The following several pages describe the natures of these formations as they are understood at this time.

## MARLBORO FORMATION

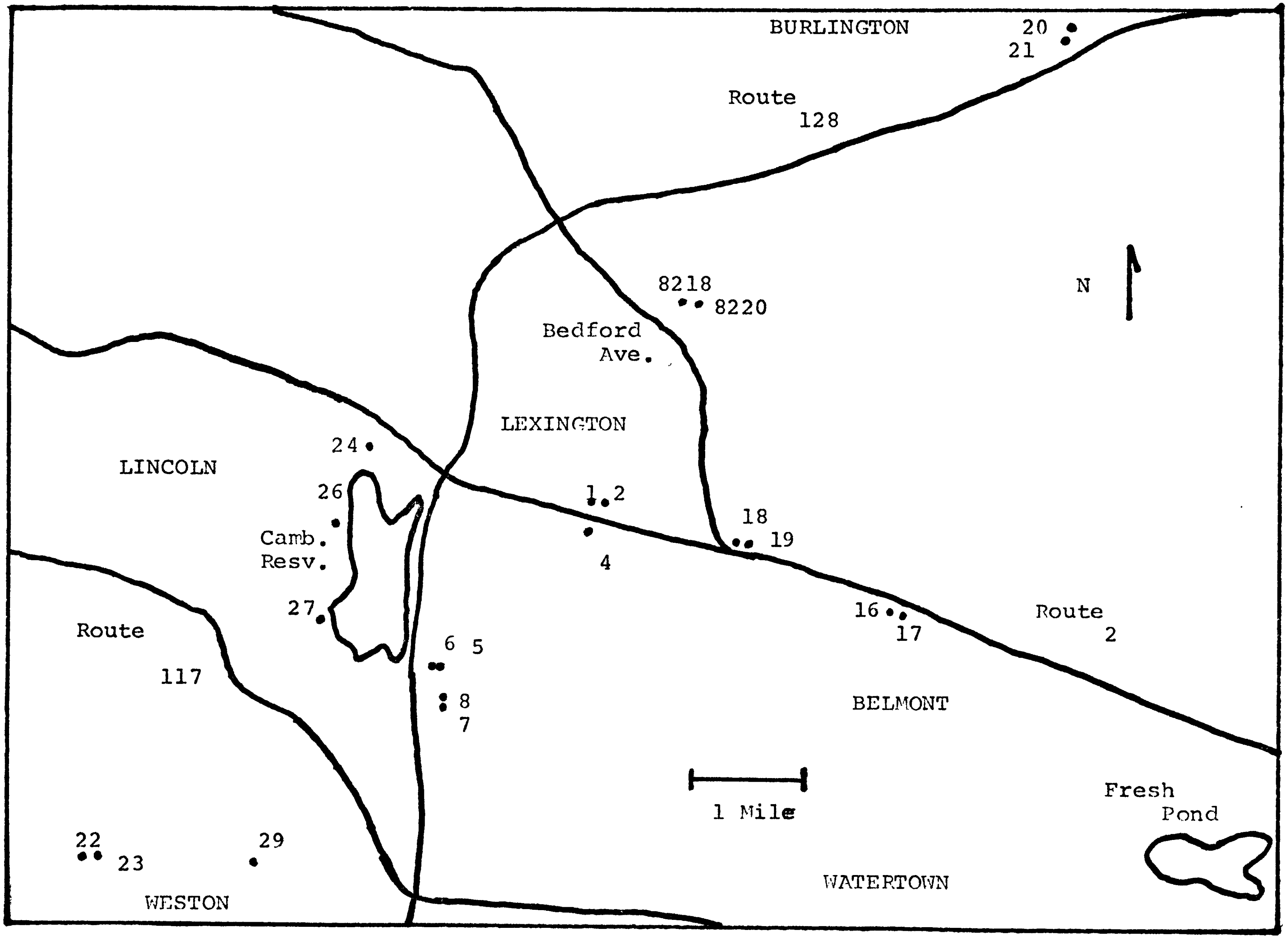
The term "Marlboro Formation", originally applied by Emerson at the type locality of Marlboro, Massachusetts, is a catch-all designation applied in the Boston area to two NE-SW trending belts of dark colored stratified and metamorphic rocks which have been grouped together regardless of type or origin. The first belt begins at the northern edge of the Lynn Quadrangle and can be traced southwestward, through North Saugus, Wakefield, Stoneham, Winchester, and Arlington, ending against the north boundry fault of the Boston Basin. The second belt, from which twenty-one of the study's thirty-one samples were taken, lies further to the northwest, beginning at the northern edge of the Lexington Quadrangle in Woburn and passing southwestward through Burlington, Lexington, and Waltham.

The age of the Marlboro rocks has been described in the literature as either pre-Cambrian or Cambrian. LaForge (1932) favored a pre-Cambrian age due to the characteristics the Marlboro

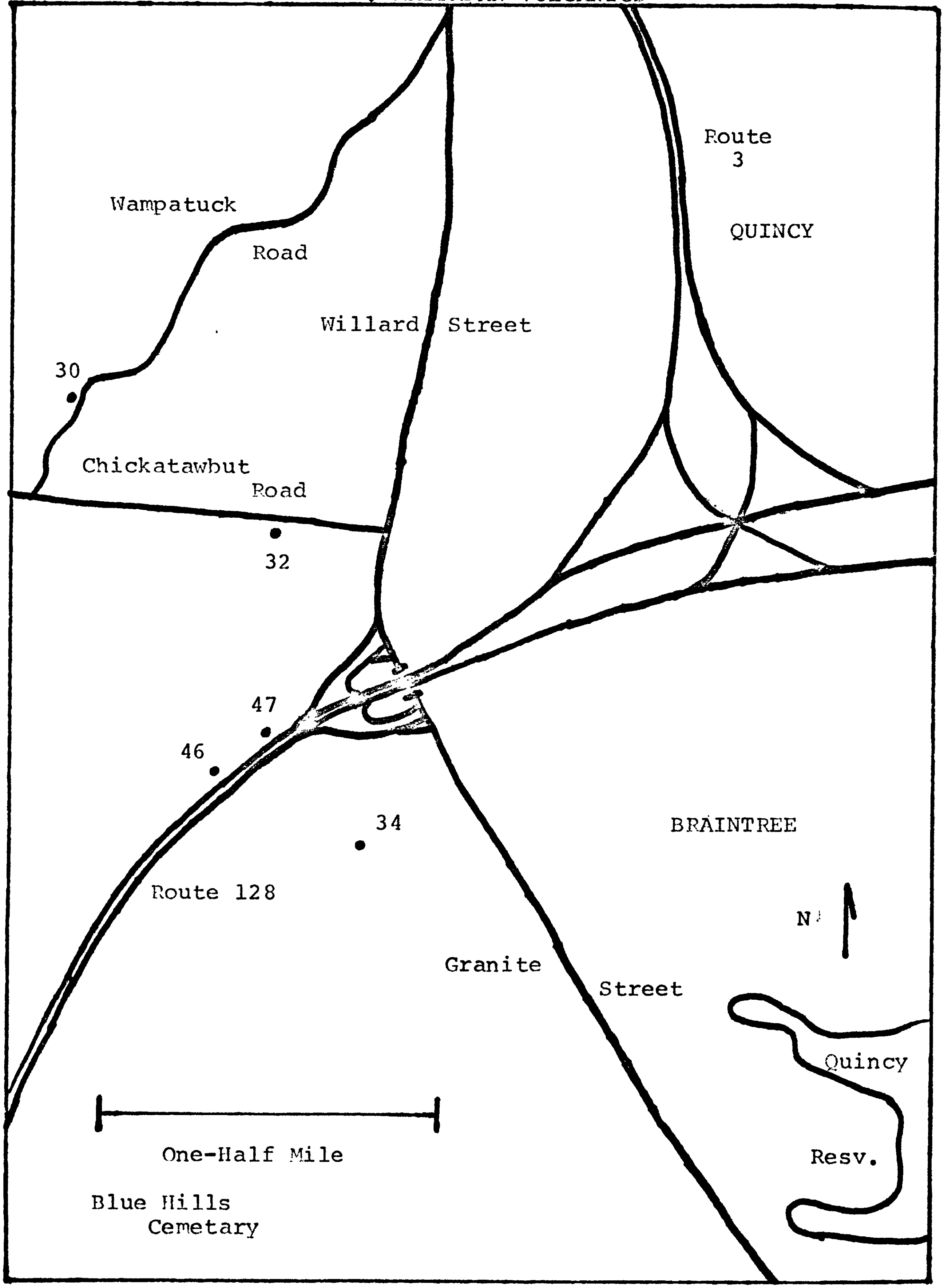
MAP 1. BOSTON AREA



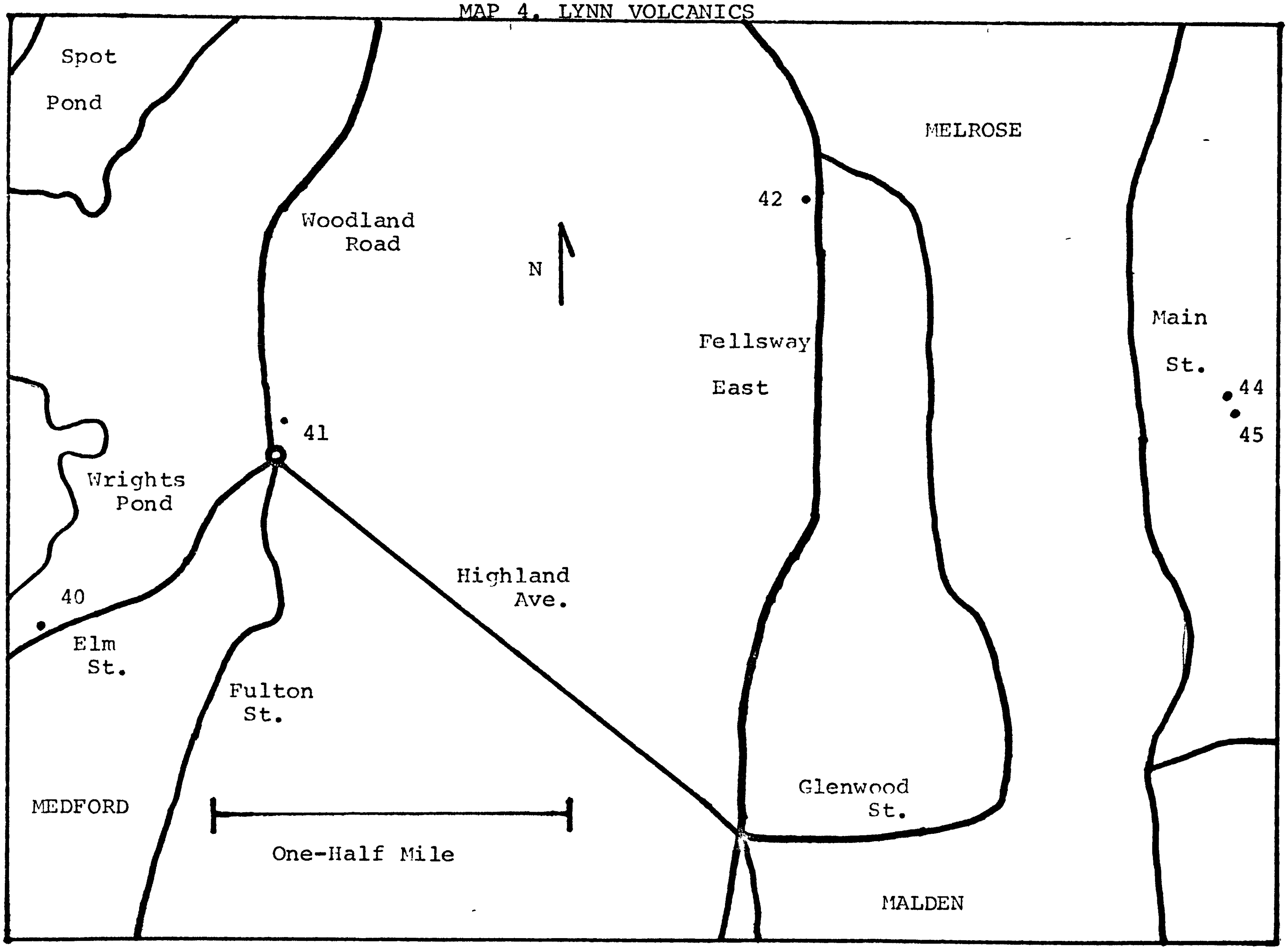
MAP 2. MARLBORO VOLCANICS



MAP 3. MATTAPAN VOLCANICS



MAP 4. LYNN VOLCANICS



shares with formations elsewhere classed as Algonkian. Bell(1948) assigned the Marlboro a Lower Cambrian age based on its stratigraphic contacts and assumptions as to the ages of the contacted formations. Recent radiometric dating on the Milford Granite, which cuts the Marlboro southwest of Boston, implies a pre-Cambrian age for both (R.E. Zartman and R.S. Naylor - personal communication). Rubidium-strontium dating on the granite gives a 614 m.y. age, while zircon dating suggests a slightly older 630 m.y. age.

LaForge (1932) and Bell (1948) generally describe the Marlboro rocks just west of Boston as dark colored chloritic, biotitic, and amphibolite schists which were originally basaltic volcanics. Recent U.S.G.S. mapping in the Waltham-Lexington area has variously described the locations from which samples were taken as foliated amphibolites, massive basalts, and massive stock gabbros (D.C. Alvord of the Boston U.S.G.S. - personal Communication). Petrographic examination of the samples revealed that all but one sample were originally basalts which have been metamorphosed to the low to medium greenschist level. Sample number five appears to be an original granitic dike rock which has been metamorphosed to the same level. Texturally, all samples but number 23 are reasonably massive. Number 23 exhibits a rather pronounced schistocity. Appendix One contains a listing of the various samples' mineralogies.

## MATTAPAN VOLCANICS

The Mattapan Volcanic Complex, named by LaForge after the type locality Mattapan section of Boston, comprises the volcanic rocks in and adjoining the southern part of the Boston Basin. The largest outcrops in size and number exist in a belt about one and one-half miles wide which begins in the east in Quincy and extends westward to the southernmost part of west Roxbury. Another belt of smaller exposures runs from Newton westward through Needham. The five Mattapan samples used in this study came from the former belt in an area of the Blue Hills Quadrangle mapped by Chute (1969).

The three major formations in this part of the Blue Hills Quadrangle are the Mattapan rocks, the Qunicy Granite, and the Blue Hills Granite Porphyry. While field relations indicate the Mattapan rocks are older that the porphyry and perhaps the Quincy Granite as well, exact ages of these formations are difficult to ascertain, as recent radiometric dating has given somewhat ambiguous results. Chute (1966) saw inclusions of the granite in the porphyry and Warren (1913) discovered xenoliths of the volcanics in the porphyry, indicating that both the Mattapan and the Quincy rocks are older than those of the Blue Hills formation. LaForge (1932) cites evidence from outside the Blue Hills area indicating the volcanics are older than either of the two intrusive rocks. Whatever the exact age relationships, LaForge (1932), Bell (1948), and Kaktins (1974), all state that the granite and the porphyry seem to belong to the same magmatic suite.

Radiometric dating work on the Quincy Granite has produced ambiguous results (Bottino and others - 1970, Zartman and Marvin - 1971). However, Kaktins (1974) cites a Lyons and Kreuger interpretation of a 400 to 420 m.y. age for the granite. The Bottino paper indicates the porphyry acted as an open system with respect to rubidium and strontium and Rb-Sr dating on the porphyry in inconclusive. Bottino and others (1970) also tried Rb-Sr dating on the volcanics, but a wide scatter of points did not allow an accurate isocron to be drawn for these rocks, either. Kaktins (1974), however, points out that the greater the induration and degree of welding within the various Mattapan flows, the older the apparent age. The oldest apparent age of 420 m.y. comes from the Pine Hill rhyolite flows. This oldest age might very well imply that the Pine Hill rocks acted more as a closed Rb-Sr system than the other Mattapan rocks, and that the 420 m.y. age might be a reasonably accurate figure for the volcanics.

One final piece of evidence seems also to imply a Silurian age for the Mattapan Formation. LaForge (1932) and Bell (1948) cite field evidence which implies the Mattapan and Lynn Volcanics are either contemporaneous flows or parts of the same set of flows. Dos Santos (1960) and M.P. Billings and R.S. Naylor (personal communication) state that the Newbury Volcanic eruptions were contemporaneous with the Mattapan and Lynn eruptions. A Silurian age has been indicated for all three formations with the discovery of Silurian fossils in parts of the Newbury strata (Dos Santos-1960).

One of the most comprehensive discussion of the chemistry and mineralogy of the Mattapan Volcanics is given by Kaktins (1974). He has divided the Mattapan complex into six rhyolite flow types by means of textural variations, compositional variations, and stratigraphic position. Four of the six types have been sampled for this study. The oldest is the Wampatuck Hill ash flow, followed in age by the Chickatawbut Road ash flow, and the pyritic volcanics. The relative age of the Pine Hill flow has not yet been determined.

Sample 30 comes from the Wampatuck Hill densely welded zone, characterized by a low phenocryst content and a cryptocrystalline K-feldspar matrix. Number 32, from the Chickatawbut Road flow, most closely resembles Kaktin's upper zone with quartz and microperthite phenocrysts and a quartz and sanadine matrix. The pyritic volcanics are represented by sample 34, which closely resembles number 32. Samples 46 and 47 come from the Pine Hill lava flow. Both resemble the other Mattapan samples with quartz and K-feldspar phenocrysts and quartz and sanadine matricies. Samples 30, 32, and 34 exhibit a low grade greenschist type metamorphism, with the existence of chlorite and what appears to be secondary magnetite. Samples 46 and 47 also appear to have been metamorphosed to the same level, but they contain a considerably smaller percentage of magnetite and chlorite. No pronounced schistocity exists in any of the samples.

## LYNN VOLCANICS

The Lynn Volcanics, first named by Clapp (1921), consist predominately of fyholitic lava flows, with some flows of a more ferromagnesian character (andesitic-basaltic) also having been noticed (LaForge - 1932). Outcrops of the Lynn rocks lie in two belts which run in a general east-west direction just north of the Boston Basin. The first belt, from which the five Lynn samples investigated in this study were taken, varies in width from two to three miles and extends from the eastern part of Lynn through Saugus and Malden to Medford. A narrower belt runs through North Saugus and southern Wakefield and Stoneham. Presumably also part of the Lynn Complex are rocks forming the north half of Marblehead Neck. That the age of the Lynn rocks is probably Silurian is indicated in the age discussion of the Mattapan Formation.

General discussions of the Lynn mineralogies are included in LaForge (1932) and Bell (1948). The more felsic varieties are described as conspicuously porphoritic in texture and thoroughly massive to fine banded in structure. The groundmasses consist predominantlyof K-feldspar, quartz, and sodic plagioclase, while the phenocrysts are chiefly sodic plagioclase and K-feldspar. Samples number 41,44, and 45 come from felsic outcrops and mineralogically correspond to the above description. Texturally they tend to be reasonably massive.

The more ferromagnesian varities are more coarsely crystalline than the felsites and in the cases of samples 40 and 42 exhibit intergranular basaltic textures and nearly original basaltic compositions. The groundmasses are predominantly sodic plagioclase replaced to varying degrees by sericite and include chlorite, epidote, and sometimes hornblende. The phenocrysts are either sodic plagioclase, clinopyroxene, or sometimes quartz. The mineralogies of numbers 40 and 42 agree with the above descriptions, except for the absence of quartz phenocrysts. The existence of what appears to be secondary chlorite and magnetite in all the Lynn samples implies, once again, a low grade greenschist metamorphism.

## METAMORPHIC REACTIONS

As has been noted, what appears to be secondary magnetite occurs in each of the thirty-one samples investigated. A few additional words concerning the nature of this and the small amount of primary magnetite remaining in some of the samples are now in order. The great percentage of magnetite seen in the samples is intimately associated with chlorite. This magnetite occurs as small irregular bodies (blebs) at chlorite grain boundries and as dusty magnetite disseminated throughout the chlorite.

Such magnetite occurring in a metamorphosed volcanic is quite probably secondary, having formed as the result of the metamorphic transition of pyroxene to chlorite and magnetite. This theory is substantiated by the observation in several samples of that very transition arrested in mid-process by cooling. Most of the magnetite in the samples, therefore, appears to be secondary and to have been developed during the metamorphism.

Very little magnetite appeared to be primary: that which was observed occurred as large, partially resorbed crystals associated with such minerals as chlorite, actinolite, and sphene. Eventually, the growth of such minerals consumes the primary opaques. Small primary magnetite grains would be the first to go, the only primary grains possibly remaining being those too large to be completely resorbed under the prevailing metamorphic conditions.

## REGIONAL METAMORPHISM

In order to understand the nature and the meaning of the Marlboro, Mattapan, and Lynn paleoremanence, it is first necessary to understand the nature of the geologic events which might have overprinted or completely replaced the primary remanence. Of course, thermal resetting of remanence is always a possibility in contact metamorphic areas (i.e.-the local Taconic Ordovician batholiths (Bell-1948)), but there is no evidence of contact effects in the vicinity of the sample sites. The only local events which might possibly have been extensive and intensive enough to have caused a resetting of the magnetic remanences are the so-called Acadian Orogeny and a thermal disturbance during the Permain. If resetting occurred, a comparison of the measured pole positions with the polar wandering path for North America should show it.

The pertinent facts in the question of local orogeny are now listed. Thompson and Norton (1968) have mapped the various Paleozoic pelitic metamorphic zones in New England. Their map indicates that the most intense (sillimanite - K-feldspar zone) metamorphism occurred in south central New Hampshire and central Massachusetts, with generally decreasing grade to the chlorite level eastward by Boston and westward by Albany. The Acadian Orogeny has long been recognized as a period which saw the most intense deformation and regional metamorphism affecting the northern Appalachians. No doubt much, if not all of the low grade metamorphism in the Boston area came about as a result of this orogeny. The regional motion was comprised mainly of a broad upwarping belt localized in central New England. This upwarping probably produced a metamorphic isograd pattern very similar to the one mapped by Thompson and Norton (1968). Naylor (1971) has used Rb-Sr dating on eastern Vertmont granites and field evidence to date the Acadian Orogeny in New England as between 380 and 410 m.y. old. K-Ar age values related to this orogeny are closer to 360 m.y. (P.M. Hurley-personal communication). Superimposed on the regional dispersion of Acadian age values is a broad belt in central Massachusetts and southern New Hampshire in which K-Ar ages are reset to values in the range 200-260 m.y. This belt coincides fairly closely with the area within the sillimanite isograd of Thompson and Norton (Zartman and others-1970).

The question of great importance to this study is whether either of these age resetting events affected the paleoremanence of the rocks studied in this report. Local field evidence seems to support a theory of Permian deformation for the Boston area, but not metamorphism. Bell observed that the local post Acadian formations appear to be reasonably fresh and unmetamorphosed. He discussed the northeast trending folds in Boston Basin sediments and attributed the cause of these folds to Permian deformation, (1948). Of possible importance to this study, though, is his observation that many of the rigid igneous masses outside the Basin were involved in the motion of Permian fault blocks. Any Permian faulting may, of course, have rotated the primary or secondary magnetic directions.

Looking ahead to the results of this study; namely that the average reset pole position of "in situ" samples is found to be close to that of the Devonian pole for North America, it is tentatively concluded that the reset remanence reflects an Acadian (360 m.y.) age rather than a later overprint of Permian (260 m.y.) age. However, even if this conclusion is wrong, the Permian pole position for North America is close to the Devonian position and both are far removed from the late pre-Cambrian position. Therefore, resetting has clearly occurred for the Marlboro rocks. As the Silurian pole is near the Devonian pole, though, resetting for the Mattapan and Lynn rocks is not quite so evident.

# EXPERIMENTAL PROCEDURE

## SAMPLE COLLECTION AND SPECIMEN PREPARATION

In this investigation, in keeping with paleomagnetic study tradition, oriented pieces of rock called "samples" were collected from a number of different physical localities called "sites" and then several "specimens" were extracted from each sample. In paleomagnetic terms, the word "site" refers to a geological unit, the entire paleomagnetic remanence of which was acquired at the same time. The vertical thickness of only a few feet in a sedimentary column might, therefore, represent several sites, while a lateral extent of several miles in a single igneous lava flow probably represents only a single site. Samples are usually studied from several (eight or more seems to be standard procedure) sites whose rocks gained their remanence at about the same geologic time in order to calculate an average paleopole for that general time. That this be done is necessary because only over a period of several thousands of years does the ever-moving magnetic pole position average out to be the earth's rotational axis pole. The single site "virtual geomagnetic pole" (V.G.P.) may be of little use in this study as V.G.P.s of about the same age but different localities do not generally correlate. The averaged paleomagnetic poles of the same rocks (those poles which are averages of V.G.P.s) do correlate, however, and this fact forms the basis of this paleomagnetic remanent direction study. For a more complete treatment of this effect, the reader is referred to basic studies (Doell and Cox-1961; Irving-

1964; McElhinny-1973; Strangway-1970).

The fact that samples for this study were collected from various physical "sites" has been stated. The fact that these physical sites might not represent paleomagnetic sites and are not considered as such is now explained. As will be discussed later, it is believed that the primary remanence of the samples investigated was destroyed and replaced with a secondary chemical remanence. The secondary remanence was acquired as a result of the growth of secondary magnetite under low to medium grade metamorphic conditions. As the Curie Temperature of magnetite was not approached, therefore, paleomagnetic theory implies that the growing nucleii each became magnetically stable once they reached the magnetite critical blocking diameter. The growth of secondary magnetite over the volume of a collected sample is quite probably a uniform process, most of the magnetite reaching the critical diameter at the same "paleomagnetic" time. The difficulty in interpreting sites under these conditions derives from the fact that the secondary magnetite in samples only several hundred feet apart might very well have grown to the critical size at two distinct "paleomagnetic" times. The term "paleomagnetic" time in the two preceeding sentences is meant to imply a period during which the V.G.P.'s position did not change appreciably.

Therefore, in low grade regional metamorphic terrain, samples from approximately the same physical locality cannot be assumed to necessarily be of the same site. In order to assume that any number of samples are of the same site, they would have to be of such close proximity that between sample statistics would amount to little more than between specimen statistics. The desirability of attempting to employ site statistics in this study is decreased even more by the strong suspicion that several of the samples come from outcrops the positions of which have been moved since the secondary remanence was acquired.

The various methods of field sample collection are given in Collinson and others (1967). In this study, a Brunton compass, a sun compass, a felt tipped pen, and a crow bar were employed. Samples were sought at jointed outcrops and pried loose after orientation and carried back to the laboratory whole. The method of orientation employed is described in McElhinny (1973), with the exception that the orientation azimuth was determined with a Brunton compass instead of a sun compass shadow. The three legs of the sun compass were placed on a prospective sample's flat surface and the compass' upper plate was rotated along the hinge in such a manner that the upper plate became horizontal. The positions of the three legs were then marked, a line being drawn between the two legs on the hinge side of the lower plate for identification purposes. A Brunton compass was then placed on the upper plate parallel with the plate's side and pointing in the direction of the hinge. The Brunton's reading, along with the angle between the sun compass' upper and lower plates, were then recorded as azimuth and dip in a field notebook, which also contained a short geological description of each outcrop.

Once back in the laboratory, the sample was viced into a core drilling device, the plane of the three spots parallel with the floor. Vertical cores were then drilled, but not broken off at the base. For orientation purposes, a vector was drawn across the diameters of the tops of each core perpendicular to the "hinge legs line". The sense of this vector was the same direction as the Brunton pointed during collection. The cores were then extracted and lines were drawn vertically down their sides so that these lines connected with the ones on the core tops at the vector heads.

The next step in the specimen preparation process involved cutting the cores into small cylinders whose height to diameter ratio was 0.865. That this is the optimum ratio to ensure that the resulting cylinders will have negligible shape anisotropy during remanence measurement is explained by Noltimier (1971). A dot was then placed on the bottom (with respect to the drilling direction) face of each specimen so that its cylindrical axis orientation would be known. A sticker containing pertainent specimen data was placed on top. The field orientation so prepared is exactly known, as the line on its side faces the field determined azimuth and plunges at an angle determined by subtracting the sample field dip frim ninety degrees.

## SPECIMEN SPINNING AND DEMAGNETIZATION

Once prepared as described above, the specimens, which numbered between ten and sixteen per sample, were ready for spinning and demagnetization. The spinner magnetometer employed throughout the study was the Schonstedt Instrument Company SSM-1A, which provided for the measurement of remanence (1-$10^{-7}$ emu) and induced anisotropic moments. The moments measured were all greater than $10^{-5}$ emu, the accuracy being better than 10% on the $10^{-5}$ scale and better than 1% on the larger scales. The SSM-1A works at a 5 rps spin rate and contains two complete signal processing channels so that the X and Y components of magnetic moment are simultaneously measured with the sample spinning about the Z axis. The magnetometer sensor and the spinning sample are located in a large multi-layered magnetic shield where sufficient attenuation is provided so that variations in the ambient field make no measureable contribution to system noise.

The magnetic cleaning method used in the study consisted of tumbling specimens simultaneously about three orthogonal axes in a continuously decreasing alternating field. The demagnetizing device was designed by Doctor Aviva Brecher of M.I.T. and provided for a rapid mechanical tumbling in fields up to 1300 oersteds, with a decrease rate of eighty oersteds per minute.

In order to determine the nature of the remanence in each sample, the following procedure was employed. The natural remanent magnetization vector of each specimen was determined by spinning in the SSM-1A, using the six spin method outlined in Doell and Cox (1965). Once this was completed, two specimens from each sample were demagnetized to first the 50, then the 100, 150, 300, and finally, the 500 oersted level. This completed, the direction (declination and inclination) and intensity associated with each spin was calculated on a Wang 500 calculator employing a program similar to the one in Doell and Cox (1965).

The magnetic vector directions of the NRM and demagnetization levels were plotted on individual Schmidt nets and their behaviors with increasing level observed. For each sample, the specimen directions changed and converged and the remanent intensities decreased as the magnetization level increased. After a certain level, however, the specimen directions diverged and changed in an apparently random manner. The cause of this behavior will be discussed in the conclusions section of this paper as will be the idea that the level just before divergence was the best one to which to demagnetize all the sample's specimens. The remanence at this best level probably represents the last magnetization the sample acquired in the direction of the earth's field (either primary or secondary replacing or overprinting the primary) other than a viscous component. For some of the samples, the best level was not reached by 500 gauss and further demagnetizations were necessary. In any event, however, once the best level was discovered, all the sample's specimens were reduced to that level and the resulting group of directions, along with the NRM group, was statistically treated as described in the next section.

## STATISTICAL TREATMENT

In the hierarchical statistical study of paleomagnetic directions of magnetization, the directions of specimens are first combined to give a sample mean. Sample means are then combined to give site means and site means to give formation or unit. means. The direction averaging at each level has required the development of a method of analysing a set of vectors. Such a method, in which each direction is represented by a unit vector and no weighting in favor of directions with greater intensities is allowed, was developed by Fisher (1953).

According to Fisher, when regarding the vectors as points on a unit sphere, they will be distributed with probability density P', where

$$P' = K/(4\pi \sinh K) \exp (K \cos F)$$

where F is the angle between the direction of a specimen, sample, etc., and the true direction at which F=0 and density is a maximum. The parameter K, the "precision parameter", determines the dispersion of the points. When K is large, the points cluster about a true mean direction and when K=0 the points are uniformly distributed.

Given a set of paleomagnetic directions, the best estimate of the mean direction is the vector sum of the unit vectors having the directions of the several observations. In this study, a magnetic direction is specified by its declination, D, measured clockwise from true north, and its inclination, I, measured positively downwards from the horizontal. This direction may be expressed in terms of its three direction cosines

| | |
|---|---|
| North Component | $l=\cos D \cos I$ |
| East Component | $m=\sin D \cos I$ |
| Down Component | $n=\sin I.$ |

Now, as the direction cosines of the vector sum of N such directions are proportional to the sum of the separate direction cosines, the vector sum will have length R given by

$$R^2 = (\Sigma l_i)^2 + (\Sigma m_i)^2 + (\Sigma n_i)^2$$

where R is less than or equal to N. The mean direction declination and inclination are expressed as

$$D_R = \tan^{-1} (\Sigma m_i/\Sigma l_i) \text{ and } I_R = \sin^{-1} (1/R(\Sigma n_i),$$

while the best estimate k of the precision parameter is given by Fisher (1953) as $k = (N-1)/(N-R)$, for k greater than 3.

This study has employed one other parameter, also attributable to Fisher (1953). Fisher showed that the true mean of N directions lies within a circular cone about R with semi-angle a at probability level (1-P'), for k greater than 3, where

$$\cos a_{(1-P')} = 1 - ((N-R/R) \left[(1/P')^{1/N-1} - 1\right] .$$

In comparing a paleomagnetically determined direction with a known direction, it is recognized that the two are significantly different at the x confidence level if the angle between them is greater than $a_x$. Two paleomagnetically determined directions are significantly different at the x confidence level if their $a_x$ cones of confidence do not intersect. In this study, the value of P' employed was 0.05, implying that all cones of confidence cited refer to the 95 per cent probability level.

## ANISOTROPY DETERMINATIONS

Since individual grains of magnetite are magnetically isotropic intrinsically (unless they are shape-anisotropic), a collection of such grains randomly dispersed throughout an inert matrix will behave isotropically with respect to an applied field. In particular, this applies to single domain grains, which are the most important ones to the paleomagnetist, as they carry the hardest remanence. If the grains are somehow preferentially oriented as in foliated metamorphic rocks, or are aligned crystallographically, then the rock will be magnetically anisotropic.

If rocks have a textural anisotropy, the remanence may be deflected away from the direction of the applied field toward the direction of easy magnetization. As metamorphic rocks are being considered in this study, the question of anisotropy is an important one and the most important anisotropy question concerns the degree of anisotropy which can be tolerated before a specimen's remanence is deflected through a significant angle (Uyeda and others-1963; Fuller and Uyeda-1962). Anisotropy is measured by the variation of such values as bulk susceptibility, saturation magnetization, and the IRM or TRM in different directions in a specimen. Anisotrpoy of susceptibility is considered in this study because of the ease with which it is measured with a spinner magnetometer.

When the SSM-1A is set to determine anisotropy, the six spin quadrature output corresponds to:

$$E_1 = (H(X_2-X_1)/2) \quad E_2 = (H(X_1-X_3)/2) \quad E_3 = (H(X_2-X_3)/2),$$

where the E values are the quadrature readings, H is the machine applied field (0.5 oersteds), and $X_1$, $X_2$, and $X_3$ are the maximum, intermediate, and minimum specimen susceptibilities. Each E value is determined twice in six spins and average values are used. Any two of the above equations, when used in conjunction with the approximation

$$\overline{X} = (X_1 + X_2 + X_3)/3$$

will give $X_1$, $X_2$, and $X_3$ by way of solving the simultaneous equations. The value $\overline{X}$, the bulk susceptibility, was determined for each sample by using a Bison Instruments Model 3101 susceptibility meter. The approximation has been made throughout that the sample coordinates are also the principal susceptibility axes, and therefore, the off-diagonal terms, read on the "in phase" meter are (almost) zero. This approximation, made for simplicity, is considered appropriate for this study, as little metamorphic fabric could be visually resolved.

The angle through which a specimen's remanence is deflected is determined by

$$\tan W = (P-1)/2(P)^{1/2},$$

where W is the maximum angle of deflection and $P = X_1/X_3$ (McElhinny-1973). For an anisotropy of ten per cent (P = 1.10), then, the maximum deflection is 2.7 degrees, and for 20 per cent anisotropy, it is 5.2 degrees. These figures indicate that large anisotropies can be tolerated without significantly deflecting the specimen remanence. This is particularly so since $a_{95}$ = 10 degrees has been adopted as the tolerance level for "good" clustering of NRM directions in a sample.

In addition to P values, which represent the general degree of anisotropy, three other anisotropy values were calculated for each sample. (Hrouda and others-1971). $E = X_2^2/X_1X_3$ was used to determine the type of preferred orientation. If E be greater than one, foliation or planar-parallel orientation is predominant. If E be less than one, lineation or linear-parallel orientation is the principal cause of anisotropy. $K_{rl} = X_1/X_2$ indicates the degree of lineation (stringing of grains) in the maximum susceptibility plane defined by $(X_1,X_2)$. $K_p = (X_1 + X_2)/2X_3$ is used to determine the degree of foliation in the rock as a whole. Values of P, E, $K_{rl}$, and $K_p$ are listed in Appendix Five for each sample. Sample means for these parameters and for bulk susceptibility were calculated by averaging the results of two specimens.

## INDIVIDUAL SAMPLE DISCUSSION

In the interest of brevity, the following discussions of the natures of individual samples have been cast in a semi-outline form. The general nature of this outline is now illustrated.

SAMPLE X:

a) The nature of the magnetic phase as determined by petrographic investigation is discussed.

b) Values of bulk susceptibility measured directly with the Bison Instrument are compared with values calculated using formulas from Mooney and Bleifuss (1953) and Balsley and Buddington (1958). The Mooney and Bleifuss formula,

$$\bar{X} = 2.89\times10^{-3}\ V^{1.01}$$

is based on the volume percentage of actual magnetite in a sample. The Balsley and Buddington formula,

$$\bar{X} = 2.6\times10^{-3}\ V^{1.33}$$

is based on the volume percentageof what appears to be magnetite during petrographic examination, but which may be any combination of Fe-Ti oxide minerals of spinel structure.

The fact that a number of calculated susceptibilities are larger than the measured values may be explained by the likely occurance of titano-magnetites of lower susceptibility. Percentages in samples with more than one per cent opaques were estimated to the half per cent. This probably explains minor dicrepancies between calculated and measured values for the samples with high opaque mineral content. Samples with less than 0.1 per cent opaques were listed as having exactly 0.1 per cent. This probably explains discrepancies for the samples with low contents of opaque minerals.

Appendix Four tabulates calculated and measured susceptibilities.

c) The nature of directional and intensity changes of the remanent vector with progressive demagnetization are discussed.

d) The meanings of the calculated anisotropy parameters are discussed.

e) General comments are made.

Throughout the sample discussions, references will be made to NRM and demagnetization level remanence directions. Figure One graphically compiles the average sample NRM directions as plotted on a Schmidt net in terms of the sample site declination and inclination. Figure Two likewise displays the average sample directions measured after magnetically cleaning (demagnetization) softer (possibly viscous in multidomain magnetite) components. Also plotted on Figure are normal and reversed paleopoles for the periods from the pre-Cambrian to the present. The pre-Cambrian normal pole is McElhinny's (1973) NA 1.49, the Cambrian, his NA 2.4, and the Devonian, his NA 5.1. All other poles come from the averages of Strangway (1970). All reverse poles are 180 degree reversals of the above mention ed normal poles with the exception of the Devonian pole, which is an average of McElhinny's (1973) NA 5.2 through NA 5.5. Paleopole to sample site D-I transformations were accomplished by way of equations in Mc Elhinny (1973). Positive inclinations were plotted as filled circles, while negative inclinations were plotted as open circles.

FIGURE 1. NRM DIRECTIONS

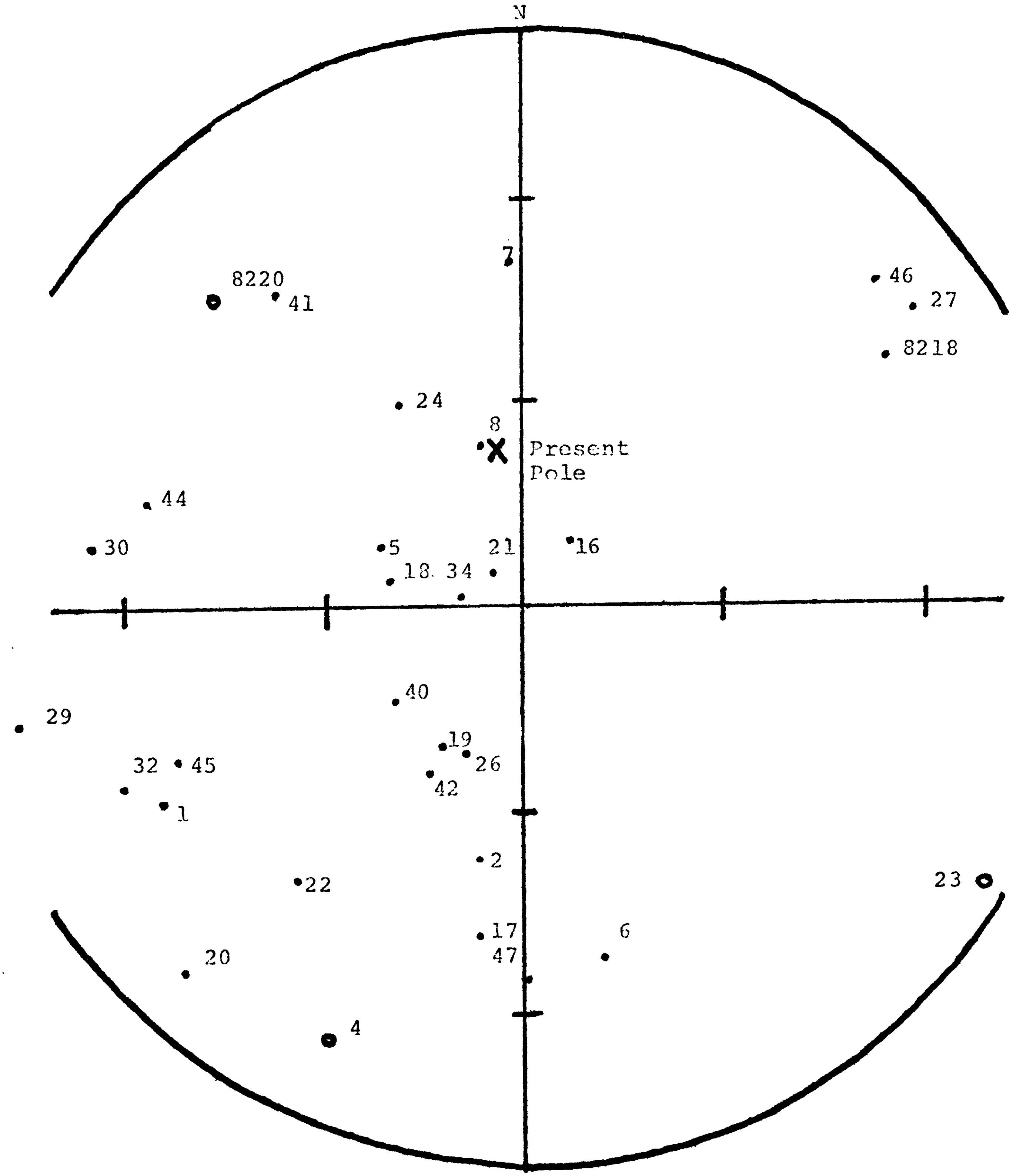
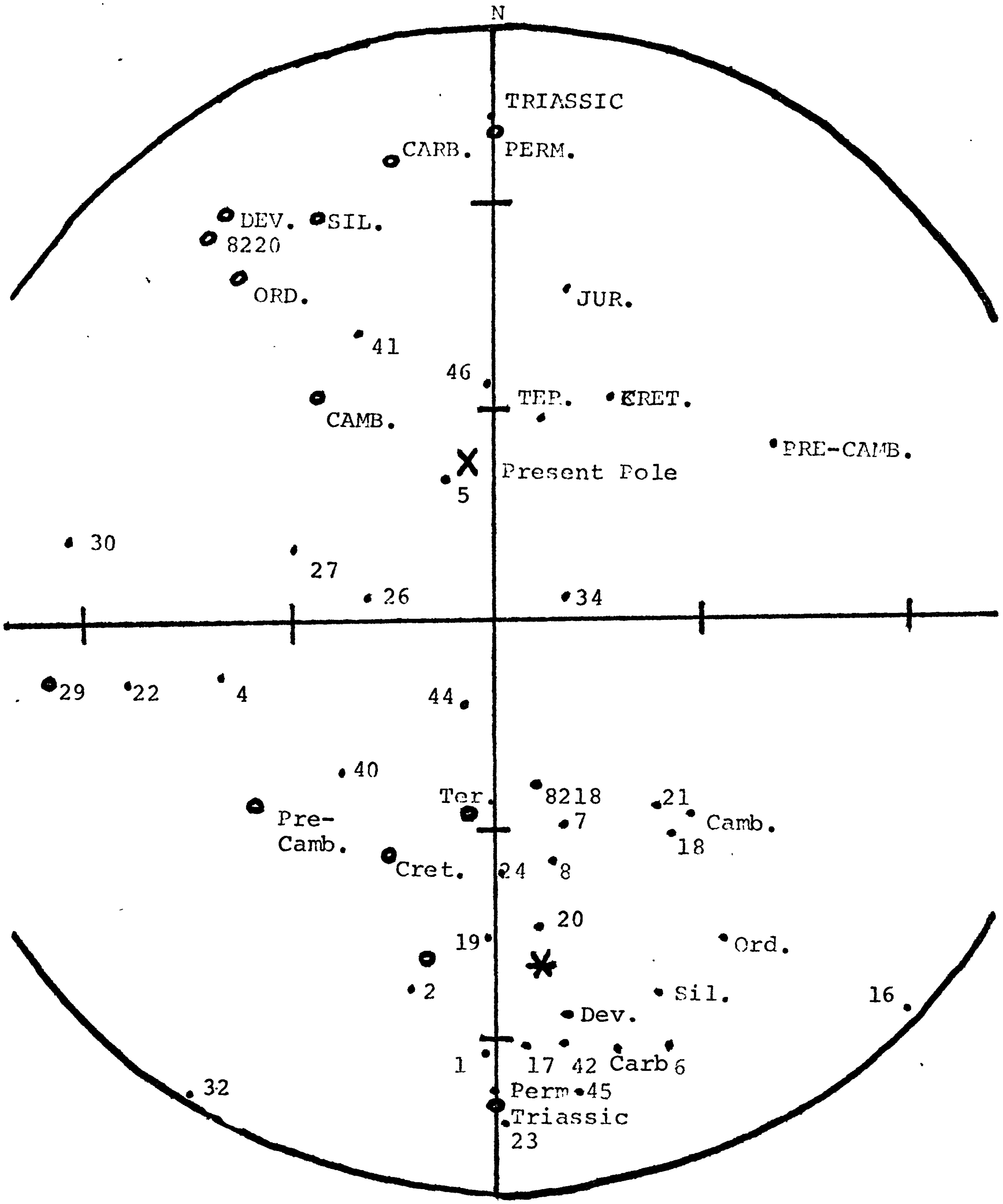


FIGURE 2. CLEANED DIRECTIONS



"TRIASSIC"-Normal Period Pole
"Triassic"-Reversed Period Pole

✱ -Average of "In Situ" Samples

MARLBORO FORMATION SAMPLES

SAMPLE 1:

a) A few primary, euhedral, partial resorbed magnetite crystals exist, but the magnetite occurs primarily as blebs and as dusty particles. Both the blebs and the dusty magnetite are associated with secondary chlorite.

b) The calculated susceptibilities agree well with the measured value. The value calculated using the Balsley and Buddington formula (hereafter referred to as the "magnetite" value) is closer to the measured figure than the value calculated using the Mooney and Bleifuss formula (hereafter referred to as the magnetite value), implying the existence of an Fe-Ti spinel other than magnetite.

c) Hereafter, the progressive demagnetization sequence will be referred to as starting or beginning at the NRM directional value and as stopping or ending at the directional value at which the soft, possibly secondary or viscous components are conventionally interpreted as being erased; i.e.-at the level at which directions have stopped changing and/or have converged (the "cleaned" level). The position of any given direction on the Schmidt net may be designated by the quadrant in which that direction falls.

Number one started in the southwest quadrant and demagnetized toward the southeast quadrant, ending by 150 oersteds demagnetization level within a few degrees of the Permian pole. Its directions remained stationary until 700 oersteds demagnetization, beyond which specimen directions diverged. The low median destructive field (demagnetization field at which one-half the NRM intensity is lost) of 45 oersteds implied that a considerable fraction of the NRM was carried in multidomain grains and was viscous in nature. Intensity levels decreased monotonically with increasing demagnetization level. The divergence occurred at a level where only three per cent of the NRM intensity remained, implying that demagnetization by this level had randomized the remanence of all but the highest coercive force domains.

The divergence in specimen directions could be due to the fact that so few domains are left unrandomized that the statistical randomness of domain magnetization orientation no longer holds. Another factor which might contribute to the diverging behavior is connected with the possible existence of a small percentage of very low coercivity grains in the sample. Such grains would have a very short relaxation time and could be affected by the earth's field in the time between demagnetization and spinning. Any magnetization acquired by these grains would be random in nature and would not be noticed until nearly all other domain magnetisms had been randomized, if the percentage of such grains were low. Of course, the acquisition of random anhysteritic remanent magnetic directions is always a possibility. The divergence phenomenon was noted in all the samples studied at different levels of demagnetization.

d) The anisotropy parameters are all near unity and imply that number one is nearly magnetically isotropic.

e) Due to its cleaned direction lying near the Permian reversed pole, this sample apparently acquired a secondary magnetization during the Permian.

SAMPLE 2:

a) The nature of the magnetite in number two is the same as in number one.

b) Both calculated values of suseptibility are very close to the measured value. There probably is a non-magnetite Fe-Ti oxide, but this cannot be stated definitely from the calculated result.

c) Number two started near the middle of the SW-SE quadrant intersection, but only moved a few degrees. The movement brought it closer to both the reversed Permian and Devonian poles. The movement was directed away from the present pole along a great circle connecting the two directions, indicating a viscous component directed toward the present pole.

This sample's intensity behavior during demagnetization was similar to that exhibited by number one, with divergence occurring at $M/M_o$ (fraction of original intensity left) = 0.06 (300 oersted demag. level) and with a median destructive field (M.D.F.)=45 oersteds.

d) The anisotropy values are all close to one implying an isotropic behavior.

e) Number two apparently derived a secondary magnetization during either the Devonian or the Permian.

SAMPLE 4:

a) The magnetite in number four is similar in nature and association to that in number one. There is direct evidence of pyroxene altering to chlorite and magnetite.

b) The calculated suseptibility values are virtually the same, both being reasonably close to the measured value.

c) Number four starts as a negative inclination direction in the SW quadrant, moved in the general direction of the present pole, and ended near the NW-SW quadrant intersection with a positive inclination.

Number four's intensity behavior during demagnetization was similar to number one's with divergence occurring at $M/M_o=0.03$ (300 oersted demag. level) and with an M.D.F.=45 oersteds.

d) Number four exhibited a 16 per cent anisotropy (a little over three degrees in deflection) and a 13 per cent foliation. Both are tolerable within the bounds of experimental error.

e) The cleaned remanent direction of this sample pointed nowhere near any of the period poles. The outcrop was small and could be a sizeable, but dislodged piece which was rotated out of position during the last glaciation. It could also have been rotated during the Permian deformation.

SAMPLE 5:

a) Most of the magnetite appears to be primary. Virtually no dusty magnetite appears in chlorite grains.

b) Both calculated suseptibility values are very close to the measured value.

c) Number five started within twenty degrees of the present pole and moved to within five degrees by 150 gauss. The general intensity behavior with demagnetization was similar to that exhibited by number one with an M.D.F. of 40 oersteds and an $M/M_o$ value of 0.03 at divergence (300 oersted level).

d) The anisotropy parameters all were near one, implying an isotropic behavior.

e) Number five appeared to be a granodioritic dike rock intruding

Marlboro volcanics. A whole rock Rb-Sr age value from a similar dike in the area indicates a late pre-Cambrian age similar to the volcanics. The existence of a bit of secondary chlorite in five suggests it underwent regional metamorphism at the same time as the volcanics. Considerations of the nature of the magnetite (probably nearly all multidomain), the rock's probable age, and its demagnetization behavior imply that number five's magnetization is virtually all viscous and that its magnetization has followed the pole from period to period.

SAMPLE 6:

a) The magnetite occurs either as blebs on the boundries or as dusty particles within chlorite grains.

b) The calculated suseptibility values are considerably larger than the measured value implying an overestimation of the volume percentage of magnetite.

c) Number six started near the Devonian reversed pole and moved less than twenty degrees by 500 oersteds, which was the M.D.F. The intensity decreased monotonically with increasing demagnetization, no divergence being observed by 1100 oersteds.

d) The anisotropy parameters were all very near one implying an isotropic nature for number six.

e) The exceptional hardness of this sample's magnetization implies a very high percentage of high coercivity single domain magnetite and a very stable remanence with nearly no viscous component. Its cleaned direction lies near the reversed Devonian, Silurian, and Carboniferouspoles, but it is difficult to say to which it belongs, as they are all very close.

SAMPLE 7:

a) A very large percentage (more than 50 per cent) of the magnetite in seven appears to be primary, only some of the pyroxene having been changed to chlorite and secondary, bleb-like magnetite.

b) The calculated suseptibility values are considerably greater than the measured value, implying an overestimation of the magnetite volume percentage.

c) Number seven started in the northwest quadrant and ended about thirty degrees away from the Devonian reversed pole, having moved nearly eighty degrees along the great circle connecting the present and Devonian poles.

This sample's intensity behavior was similar to that of number one with divergence occurring at $M/M_o=0.07$ (700 oersted level) and with an M.D.F.=100 oersteds.

d) As the anisotropy parameters are all very near one, a magnetically isotropic nature is implied.

e) Number seven appears to have acquired a stable secondary remanence during the Devonian with the large (primary multidomain?) magnetite crystals carrying a viscous component directed toward the present pole.

SAMPLE 8:

a) The magnetite occurrs as highly irregular blebsand dusty particles associated with the chlorite.

b) Both calculated suseptibilities agree well with the measured value, the "magnetite" value coming closer.

c) The directional behavior of eight is similar to that of seven as is the intensity behavior. The only difference is that number eight does not diverge until 900 oersteds ($M/M_o$=0.07). The M.D.F.=100 oersteds.

d) The anisotropy parameters imply a very slight general foliation with the magnetic vector directional deviation being little more than one degree.

e) Number eight probably acquired a secondary remanence during the Devonian. It also possesses what appears to be a multidomain viscous component directed toward the present pole.

SAMPLE 8218:

a) The magnetite occurs primarily as blebs associated with the chlorite. Some dusty magnetite dispersed in chlorite grains also occurs.

b) The calculated suseptibility data are greater than the measured value, implying an overestimation of the opaque mineral content.

c) This sample started in the NE quadrant and moved toward the Devonian reversed pole, ending about thirty degrees short of it before divergence at 600 oersteds ($M/M_o$=0.04). An M.D.F. of 40 oersteds was calculated. The intensity behavior of number 8218 with increasing demagnetizing field was similar to that of number one.

d) The anisotropy parameters are nearly one, implying an almost isotropic behavior.

e) This sample might have acquired a secondary remanence during the Acadian and viscous components thereafter, but its cleaned direction lies at a pronounced angle to the Devonian pole direction. Perhaps this outcrop was slightly rotated during glaciation or the Permian deformation. This is difficult to determine in the field.

SAMPLE 8220:

a) The magnetite occurs as blebs and dusty particles associated with chlorite.

b) Once again, the calculated suseptibility values exceeded the measured value implying a slight (one per cent) overestimation of the magnetite content.

c) The direction of this sample started twelve degrees away from the Devonian normal pole and ended within five degrees of it.

This sample's intensity behavior with increasing demagnetizing field was similar to that exhibited by number one, with divergence occurring at $M/M_O$=0.07 (300 oersted level) and with an M.D.F.=40 oersteds.

d) The anisotropy parameters imply a slight foliation, but the magnetic vector deflection is only about two degrees.

e) This sample seems to have acquired a secondary magnetization during the Devonian period.

SAMPLE 16:

a) The magnetite occurs primarily as dusty and bleb particles, with some larger subhedral grains.

b) The calculated suseptibility values both are very similar to the measured value, the "magnetite" value being virtually the same.

c) This sample's direction starts near the present pole and demagnetized toward the early Paleozoic pole positions, ending some forty degrees away from the Siluro-Devonian direction.

This sample's intensity behavior with increasing demagnetizing field was similar to that exhibited by number one, with divergence occurring at $M/M_o$=0.06 (700 oersted demag. level) and with and M.D.F.=40 oersteds.

d) The anisotropy parameters are all close to one, implying a virtually isotropic nature.

e) The proximity of the NRM direction to the present pole implies a viscous component in this direction. The directional demagnetization behavior implies that a secondary magnetization was acquired sometime during the early Paleozoic.

SAMPLE 17:

a) The magnetite occurs almost exclusively as secondary dusty particles in the chlorite grains. A few bleb particles exist.

b) The calculated suseptibility values are somewhat larger than the measured value, the "magnetite" value being somewhat more accurate.

c) The direction of this sample starts within 18 degrees of the Devonian reversed pole and ended within eight degrees of it. As expected, only a small percentage of the NRM intensity (eight per cent) was left by divergence (700 oersteds). The intensity decreased monotonically with increasing demagnetizing field. A high M.D.F. of 150 oersteds was noted.

d) All the anisotropic parameters are very near to one, implying an isotropic nature.

e) The reasonably high M.D.F. implies a high percentage of high coercivity domains. It seems likely, therefore, that a relatively high percentage of the dusty magnetite is single or pseudo-single domain. This fact is in agreement with the small observed viscous component.

The directional evidence implies that this sample acquired a secondary remanence during the Devonian.

SAMPLE 18:

a) The magnetite occurs primarily as large blebs and dusty material associated with chlorite. A few evidently partially resorbed primary crystals also exist.

b) The calculated suseptibility values are just slightly larger than the measured value, better aggreement being noted between the measured value and the "magnetite" value.

c) This sample's direction began near the four quadrant intersection and moved toward the early Paleozoic polar wandering path, ending very near the Cambrian reversed pole.

This sample's general intensity behavior with increasing demagnetizing field was similar to that exhibited by number one with divergence occurring at 150 oersteds ($M/M_o=0.04$) and with an M.D.F.=30 oersteds.

d) The minor anisotropy deviations from unity imply a nearly isotropic nature.

e) This sample's directional convergence pattern seems to imply that it derived a secondary remanence during the Cambrian.

SAMPLE 19:

a) The magnetite occurs almost exclusively as blebs associated with chlorite.

b) The calculated suseptibility values are close to the measured values, the "magnetite" value being closer.

c) This sample's direction started in the SW quadrant and moved directly toward the Devonian reversed pole, ending within 14 degrees of it.

This sample's intensity behavior with increasing demagnetizing field was similar to that exhibited by number one, with divergence occurring at $M/M_o=0.07$ (900 oersted demag. level) and with an M.D.F.=125 oersteds. The implications of these facts are a relatively high percentage of high coercivity (single or pseudo-single domain) domains.

d) The anisotropy parameters indicate a slight general foliation. The calculated maximum deflection, however, is only between one and two degrees.

e) The directional evidence implies that this sample acquired a secondary remanence during the Devonian.

SAMPLE 20:

a) The magnetite occurs primarily as blebs associated with chlorite. Some magnetite of the dusty variety occurs and has similar associations.

b) Both calculated suseptibilities are very close to the measured value, the "magnetite" value being almost exactly the same.

c) This sample's direction started in the SW quadrant and moved toward the Devonian reversed pole, ending 13 degrees away from it.

This sample's intensity behavior with increasing demagnetizing field was similar to that exhibited by number one with divergence occurring at $M/M_o=0.05$ (600 oersted demag. level) and with an M.D.F. of 30 oersteds. The low M.D.F. implies a sizeable percentage of low coercivity magnetite.

d) The anisotropy parameters imply a large general foliation giving a four degree maximum deflection of the magnetic vector.

e) This sample appears to have acquired a secondary magnetization during the Devonian period.

SAMPLE 21 :

a) Some magnetite occurs as dusty particles in the chlorite, but a greater percentage occurs as subhedral to euhedral crystals which appear to be primary.

b) Both of the calculated suseptibility values agree well with the measured value, the "magnetite" value coming closer.

c) Directionally, this sample starts near the present pole and cleans toward the early Paleozoic reversed polar wandering path, ending very near the Cambrian pole.

This sample's general intensity behavior with increasing demagnetizing field resembles that of sample number one with divergence at $M/M_o=0.03$ (300 oersted demag. level) and with an M.D.F.=30 oersteds. The low M.D.F. implies a sizeable of low coercivity magnetite.

d) The anisotropy paramters imply a slight general foliation with a maximum deflection in magnetic vector direction of less than three degrees.

e) The directional convergence of this sample implies that it acquired a secondary magnetization during the early Paleozoic (in this case, the Cambrian).

SAMPLE 22:

a) The magnetite in this sample occurs primarily as blebs associated with the chlorite. Some dusty particles are also seen inside chlorite grains.

b) The calculated bulk suseptibilities are considerably larger than the measured value implying that either an overestimation of the percentage of magnetite was made, an error was made in the direct measurement, or both.

c) This sample's direction starts near the middle of the SW quadrant and increases in declination with increased demagnetization to a point near the NW-SW quadrant boundry.

This sample's general intensity behavior with increasing demagnetization level was similar to that of number one with divergence occurring at the 700 oersted level ($M/M_o$=0.07) and with an M.D.F.=100 oersteds. The relatively high M.D.F. and high level at divergence imply a relatively high percentage of high coercivity single domain-like magnetite.

d) The anisotropy parameters are all near unity, the implication being a nearly isotropic behavior for this sample.

e) This sample's demagnetization path comes at no point near a period pole. As the outcrop from which this sample comes is quite small and isolated, it seems entirely possible that the sample acquired a Paleozoic secondary magnetization and was subsequently rotated out of its "in situ" position.

SAMPLE 23:

a) The magnetite in this sample occurs primarily as blebs and subhedral (possibly primary) grains with some dusty particles in evidence in chlorite grains.

b) Both calculated suseptibilities are close to the measured value, the magnetite value being closer. The implication, of course, is that most of the opaques in number 23 are actual magnetite.

c) The magnetic vector direction of this sample starts near the periphery of the SE quadrant and moves toward the upper Paleozoic portion of the reversed polar wandering path, ending near the Permian pole.

This sample's general intensity behavior with increasing demagnetizing field is similar to the exhibited by number one with an M.D.F.=30 oersteds and with divergence occurring at $M/M_O$=0.02 (700 oersted demag. level). The low M.D.F. implies a sizeable percentage of low coecivity multidomain-like magnetite. The divergence at 700 oersteds implies the existence of a relatively high coercivity fraction of grains.

d) This sample's anisotropy parameters imply the most pronounced general foliation and magnetic anisotropy encountered in this study. Petrographic examination of number 23 revealed the only clearly demonstrable foliation. The calculated maximum deviation of the magnetic vector is between seven and eight degrees.

e) This sample's anisotropic direction deviation notwithstanding, the directional change with increasing demagnetization field implies that number 23 acquired a secondary magnetization during the Permian.

SAMPLE 24:

a) Most of the magnetite in this sample is of the dusty variety, with some occurring as blebs. All the magnetite is associated with secondary chlorite grains.

b) Both of this sample's calculated suseptibilities are somewhat larger than the measured value implying an overestimation of the magnetite value.

c) Number 24 started near the present pole, moved along a great circle toward the Devonian reversed pole, and stopped less than twenty degrees short of it.

This sample's general intensity behavior with increasing demagnetization field was similar to that exhibited by number one with an M.D.F.=40 oersteds and with divergence occurring at $M/M_o$=0.07 (900 oersteds demag. level). The low M.D.F. and high divergence level have the same significance they did for number 23.

d) The anisotropy parameters are close to one, implying a nearly isotropic nature for this sample.

e) The nature of the directional convergence implies that 24 acquired a secondary remanence during the Devonian. It also possesses what appears to be a multidomain viscous component directed tpward the present pole.

SAMPLE 26:

a) The magnetite occurrs as blebs closely associated with chlorite grains.

b) Both calculated suseptibility values are close to the measured value, the "magnetite" value being virtually the same.

c) Number 26 started in the SW quadrant and moved into the NW quadrant in the general direction of the present pole. It stopped some twenty degrees short of the pole.

This sample's general intensity behavior with increasing demagnetizing field was similar to that exhibited by number one, with an M.D.F.=30 oersteds and with divergence occurring at $M/M_o$=0.04 (900 oersted demag. level). The low M.D.F. and high divergence level have the same significance they did for number 23.

d) The anisotropy parameters are all very near to one, implying an isotropic nature.

e) It does not seem likely that this sample's magnetization could be nearly all viscous, as was the case with number five, even though it does demagnetize in the vacinity of the present pole as five did. The high divergence level implies a significant fraction of high coercivity grains, which seems to preclude this possibility. It seems entirely likely that this sample was rotated out of position. The field evidence supports this view, as the area from which number 26 came is quite jointed and fractured.

SAMPLE 27:

a) The magnetite occurs primarily as blebs associated with chlorite grains. Some dusty particles are dispersed throughout the chlorite grains.

b) Both calculated suseptibilities are close to the measured value, the "magnetite" value being virtually the same.

c) This sample started near the middle of the outer periphery of the NE quadrant and moved in the general direction of the present pole, ending quite near the direction that number 26 ended.

This sample's general intensity behavior with increasing demagnetizing field was similar to that exhibited by number one, with an M.D.F.=30 oersteds and with divergence occurring at $M/M_o$= 0.04 (700 oersteds demag. level). The low M.D.F. and high divergence level have the same significance they did for number 23.

d) As all the anisotropy parameters lie close to one, a reasonably isotropic nature is implied.

e) This sample's cleaned direction lies nowhere near any of the period poles. The implication is that it was rotated out of position. The field evidence supports this view, as the area from which 27 came is quite jointed and fractured.

SAMPLE 29:

a) The magnetite occurrs as blebs associated with chlorite grains.

b) Both calculated suseptibilities are reasonably close to the measured value, the "magnetite" value being closer.

c) Number 29 started near the outer edge of the SW quadrant periphery with a virtually horizontal inclination. The declination remained virtually the same with increasing demagnetization, while the inclination increased in a negative sense by some 25 degrees.

This sample's general intensity behavior with increasing demagnetizing field was similar to that exhibited by number one, with an M.D.F.=40 oersteds and with divergence occurring at $M/M_o$=0.07 (1100 oersted demag. level). The low M.D.F. and high divergence level have the same significance they did for number 23.

d) The anisotropy parameters are all near one, implying an isotropic nature for this sample.

e) This sample's cleaned direction lies nowhere near any of the period poles. This fact, and the jointed and fractured nature of the small outcrop, imply that number 29 was rotated out of position.

MATTAPAN VOLCANICS SAMPLES

SAMPLE 30:

a) The magnetite occurs primarily as dusty particles dispersed throughout chlorite grains. A few blebs also occur.

b) Both calculated suseptibilities are close in value to the measured value, the "magnetite" value being closer.

c) This sample started near the periphery of the NW quadrant and through 900 oersteds of progressive demagnetization moved very little, ending only about five degrees from its NRM direction.

This sample's general intensity behavior with increasing demagnetizing field was similar to that exhibited by number one, with an M.D.F.=30 oersteds and with divergence occurring at $M/M_o =$ 0.02 (1100 oersted demag. level). The low M.D.F. and high divergence level carry the same significance they did for number 23.

d) The anisotropy parameters imply a slight general folaition with the calculated maximum deviation being less than 2.5 degrees.

e) This sample's cleaned direction lies nowhere near any of the period poles, implying that it was rotated out of position.

SAMPLE 32:

a) The magnetite occurs primarily as dusty particles dispersed throughout chlorite grains. A few blebs also occur.

b) Both calculated suseptibilities are close to the measured value., the magnetite value being closer.

c) This sample's NRM direction lay in the SW quadrant. Erasing the viscous component caused the delination to decrease by 25 degrees and the inclination by 20 degrees. The movement was in the general direction of the reversed Paleozoic pole positions.

This sample's general intensity behavior with increasing demagnetizing field was similar to that exhibited by number one, with an M.D.F.=50 oersteds and with divergence occurring at the 600 oersted level ($M/M_o$=0.03). The low M.D.F. implies a sizeable percentage of low coercivity grains , while the 600 oersted divergence level implies a high coercivity fraction of grains which are probably single domain.

d) This sample's anisotropy parameters are all very near to one, implying a virtually isotropic nature.

e) Although the sample's direction moved toward the late Paleozoic pole positions with demagnetization, its cleaned direction still lies at a reasonably large angle to these poles. It is difficult to say whether this sample's direction is a late Paleozoic direction or the direction of a rotated outcrop.

SAMPLE 34:

a) The magnetite occurs as dusty particles dispersed throughout chlorite grains and blebs associated with chlorite.

b) The calculated suseptibility values are larger than the measured value, the "magnetite" value being somewhat more accurate.

c) This sample's direction started near the center of the Schmidt net (nearly vertical inclination) and ended only a few degrees away from the NRM position.

This sample's general intensity behavior with increasing demagnetizing field was similar to that exhibited by number one, with an M.D.F.=100 oersteds and with divergence occurring at $M/M_o$=0.06 (500 oersted level). The relatively high M.D.F. indicates a relatively low percentage of low coercivity grains.

The 500 oersted divergence level implies that the coercivity of the high coercivity fraction is not so great as that of samples like number 30.

d) The anisotropy paramters are all near one and imply a nearly isotropic nature.

e) The position of this sample's cleaned direction and the intensely fractured nature of its outcrop indicate that it has been rotated out of position.

SAMPLE 46:

a) The magnetite occurs as blebs and subhedral to euhedral crystals.

b) Both calculated suseptibilities are somewhat larger than the measured value, the "magnetite" value being somewhat more accurate.

c) This sample started in the NE quadrant and began moving in the general direction of the present pole with increasing demagnetizing field. A convergence was noted at 50 oersteds, but divergence increased with increasing field thereafter. Fifty oersteds was therefore used as the cleaning field. The direction at this level was within ten degrees of the normal Tertiary pole.

Divergence was noted at 100 oersteds ($M/M_o$=0.05) and, as might be expected, a low M.D.F. of 25 oersteds was noted.

d) The anisotropy parameters imply a slight general foliation, the maximum directional deflection being about 1.5 degrees.

e) A very high percentage of this sample's magnetite must have been grains of low coercivity. The position of the cleaned direction implies that the sample has been rotated.

SAMPLE 47:

This sample's intensity behavior with increasing demagnetization field precludes its use in this study. The intensities of individual specimens behaved in a most irregular manner with increasing field, increasing and decreasing at random. The implication is that the magnetite in this sample was of such a short relaxation time that it was able to equilibrate with the earth's field on the laboratory experiment time scale.

LYNN VOLCANIC SAMPLES

SAMPLE 40:

a) The magnetite occurs almost exclusively as dusty particles dispersed throughout chlorite crystals. A few blebs and what appear to be primary magnetite crystals exist.

b) Both calculated suseptibility values are close to the measured value, the "magnetite" figure being closer.

c) Number 40 started in the SW quadrant with a large positive inclination. It cleaned direction lay only a few degrees away, having moved to its position by 300 oersteds in a direction away from the present pole. The sample probably contained a viscous component directed toward the present pole.

The sample's general intensity behavior with increasing demagnetizing field was similar to that exhibited by number one, with an M.D.F.=50 oersteds and with divergence occurring at $M/M_o=0.02$ (500 oersted level).

d) The anisotropy parameters imply a very slight foliation, the maximum magnetic vector deflection being about one degree.

e) The angular distance of this sample's direction (cleaned) from the Paleozoic pole path is a little too large to attribute to secular variation. A bit of rotation has also probably occurred.

SAMPLE 41:

a) The magnetite occurs as blebs and dusty particles associated with the chlorite.

b) The calculated suseptibilities are larger than the measured value, the "magnetite" value being closer.

c) This sample's direction started near the center of the NW quadrant, moving in the general direction of the present pole with increasing demagnetization. Its cleaned direction lay less than ten degrees away from its NRM direction.

This sample's general intensity behavior with increasing demagnetizing field was similar to that exhibited by number one, with an M.D.F.=30 oersteds and with divergence occurring at $M/M_o=0.03$ (100 oersted level). This behavior implies a high percentage of low coercivity grains.

d) The anisotropy parameters are all close to one, implying an essentially isotropic nature.

e) This sample's cleaned direction implies that it has been rotated since acquiring a stable remanence.

SAMPLE 42:

a) The magnetite occurs as blebs associated with chlorite crystals.

b) Both calculated suseptibilities are close to the measured value, the "magnetite" value being closer.

c) This sample's direction started in the SW quadrant with a reasonably large positive inclination and moved toward the reversed Devonian pole with increasing demagnetization. The cleaned direction lay only five degrees from the Devonian pole.

This sample's general intensity behavior with increasing demagnetizing field was similar to that exhibited by number one, with an M.D.F.=100 oersteds and with divergence occuring at $M/M_o=0.05$ (300 oersted demag. level).

d) The anisotropy parameter values are all near one, implying a nearly isotropic nature for the sample.

e) The sample evidently acquired a secondary magnetization during the Devonian.

SAMPLE 44:

a) The magnetite occurs primarily as blebs associated with chlorite. Some dusty particles also exist.

b) The calculated suseptibilities are both very close to the measured value, the "magnetite" value being a bit closer.

c) This sample's direction started in the NW quadrant, moving toward the early Paleozoic poles with increasing demagnetization- Its cleaned direction lay at a considerable angle to the poles, however, coming closest to the Cambrian reversed pole.

This sample's general intensity behavior with increasing demagnetizing field was similar to that exhibited by number one, with an M.D.F.=30 oersteds and with divergence occurring at the

300 oersted level ($M/M_o$=0.02). The implication is a sizeable percentage of low coercivity grains.

d) The anisotropy parameters imply a very slight general foliation, the maximum deflection being less than one degree.

e) The angular distance of number 42 from the Paleozoic pole path is a little too large to attribute to secular variation. A bit of rotation has also probably occurred.

SAMPLE 45:

a) The magnetite occurs primarily as blebs associated with chlorite. Some dusty particles also exist.

b) Both calculated suseptibilities are close to the measured value, the "magnetite" value being almost the same.

c) This sample's direction started in the SW quadrant and moved toward the middle to upper Paleozoic polar wandering path with increasing demagnetization. The cleaned direction was equidistant from the reversed Deonian, Carboniferous, and Permian poles.

This sample's general intensity behavior with increasing demagnetization was similar to that exhibited by number one, with an M.D.F. of 80 oersteds and with divergence occurring at the 300 oersted level ($M/M_o$=0.06). The implication is a less sizeable proportion of relatively low coercivity grains than most of the other samples.

d) The anisotropy parameters are all near one, implying a nearly isotropic nature for this sample.

e) The directional evidence implies that number 45 acquired a secondary remanence sometime during the middle to upper Paleozoic.

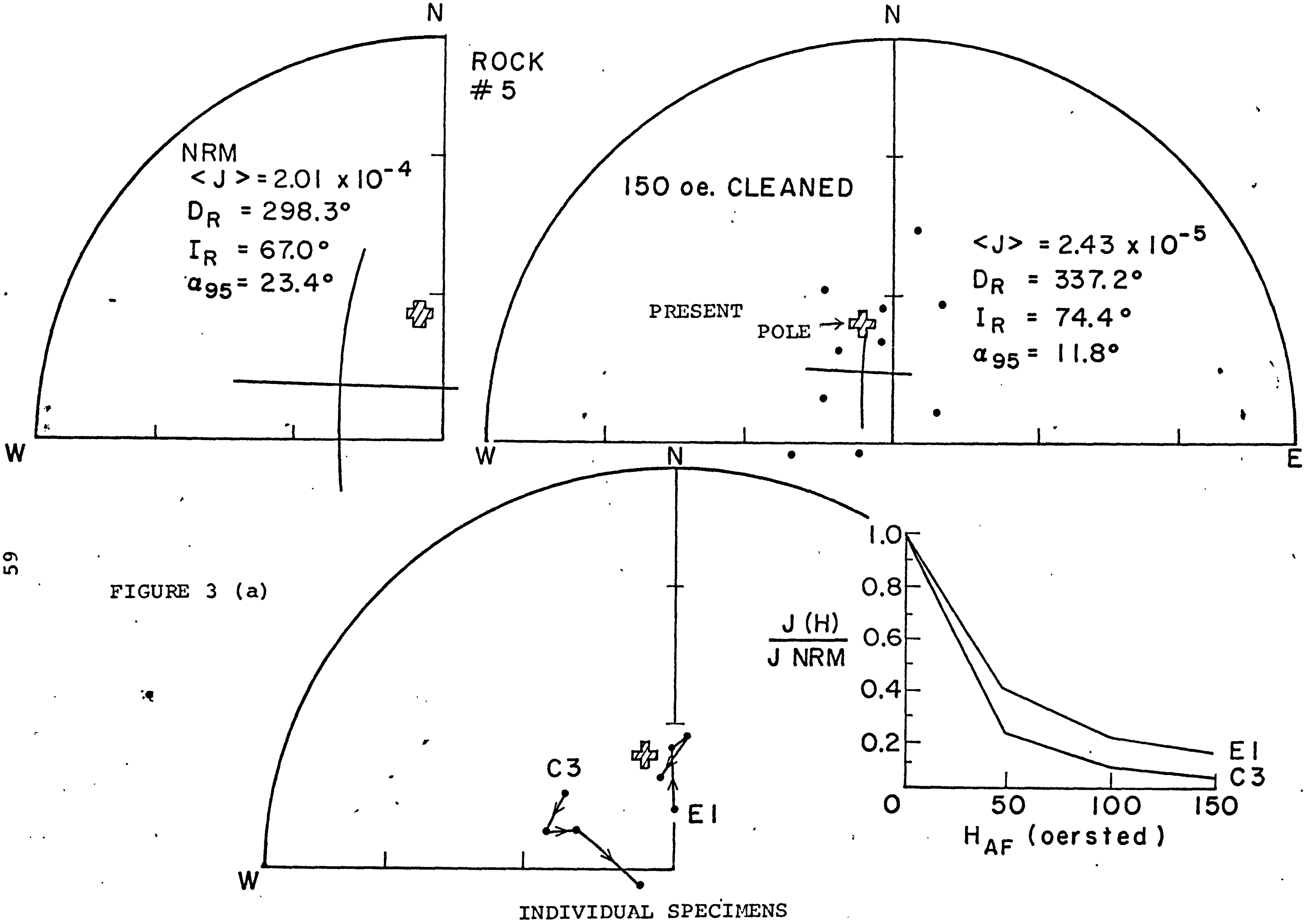

ROCK #5
N
W
NRM
$\langle J \rangle = 2.01 \times 10^{-4}$
$D_R = 298.3°$
$I_R = 67.0°$
$\alpha_{95} = 23.4°$
N
150 oe. CLEANED
PRESENT POLE
$\langle J \rangle = 2.43 \times 10^{-5}$
$D_R = 337.2°$
$I_R = 74.4°$
$\alpha_{95} = 11.8°$
W
E
N
C3
E1
W
INDIVIDUAL SPECIMENS
$\frac{J(H)}{J\ NRM}$
1.0
0.8
0.6
0.4
0.2
0
50
100
150
$H_{AF}$ (oersted)
E1
C3

FIGURE 3 (a)

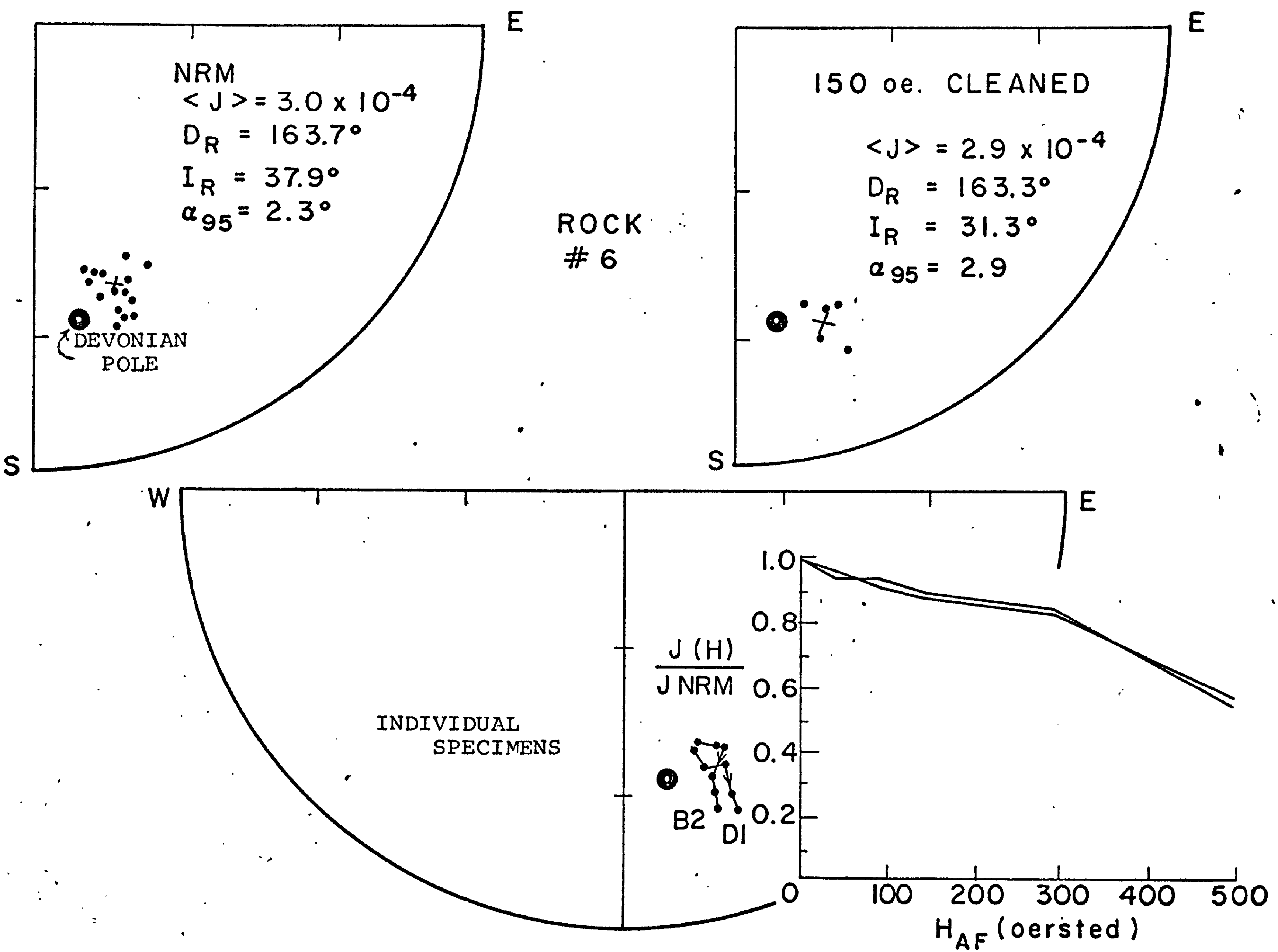

NRM
< J > = 3.0 x 10-4
DR = 163.7°
IR = 37.9°
α95 = 2.3°
DEVONIAN POLE
E
S
ROCK # 6
150 oe. CLEANED
<J> = 2.9 x 10-4
DR = 163.3°
IR = 31.3°
α95 = 2.9
E
S
W
E
INDIVIDUAL SPECIMENS
B2
DI
J (H) / J NRM
1.0
0.8
0.6
0.4
0.2
0
100
200
300
400
500
HAF (oersted)

FIGURE 3(b.)

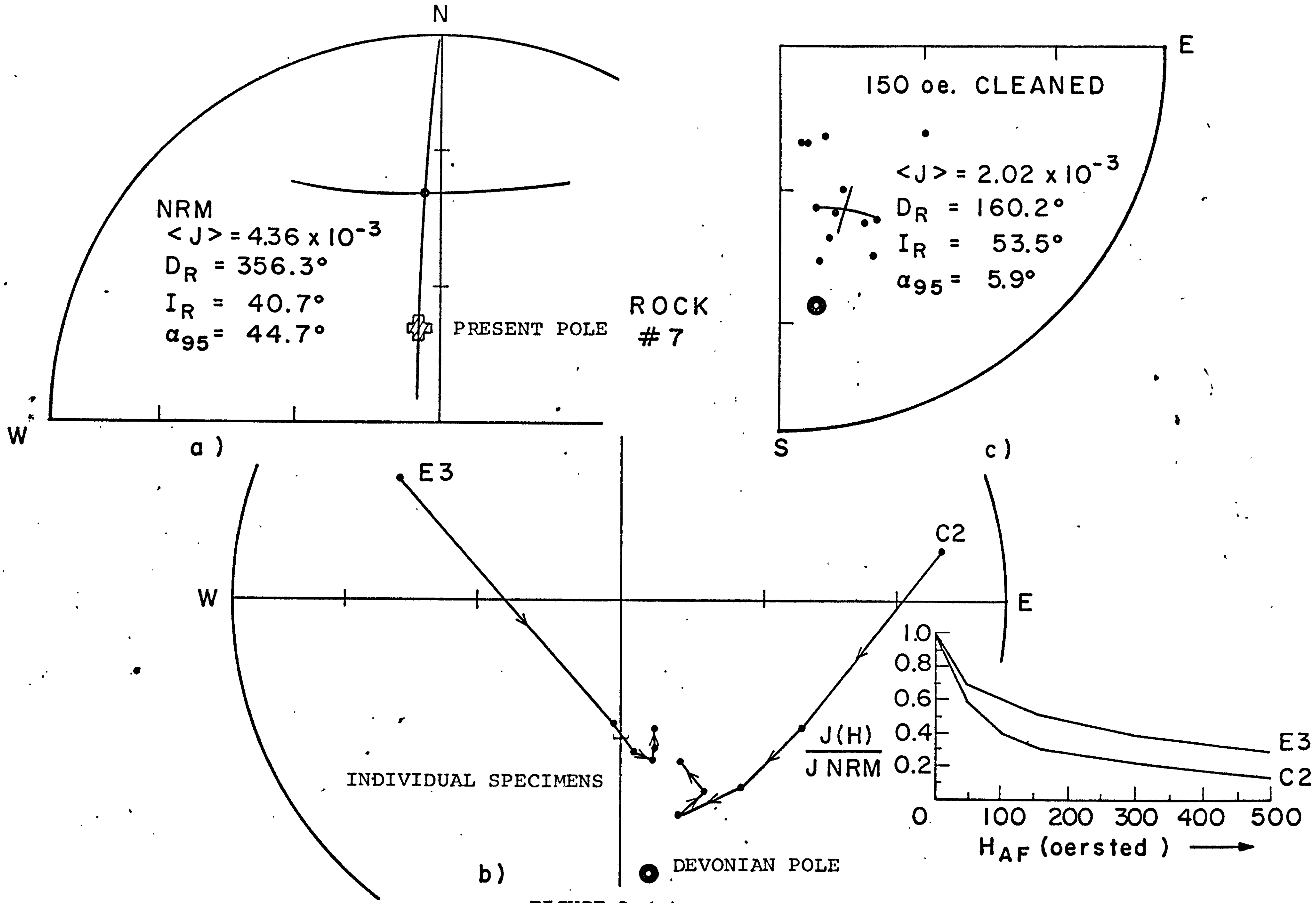

N
NRM
< J > = 4.36 x 10^-3
D_R = 356.3°
I_R = 40.7°
α_95 = 44.7°
PRESENT POLE
ROCK
# 7
W
a )
E
150 oe. CLEANED
< J > = 2.02 x 10^-3
D_R = 160.2°
I_R = 53.5°
α_95 = 5.9°
S
c )
E3
C2
W
E
INDIVIDUAL SPECIMENS
J(H) / J NRM
1.0
0.8
0.6
0.4
0.2
0
100
200
300
400
500
E3
C2
H_AF (oersted) →
b )
DEVONIAN POLE

FIGURE 3 (c)

ROCK # 19

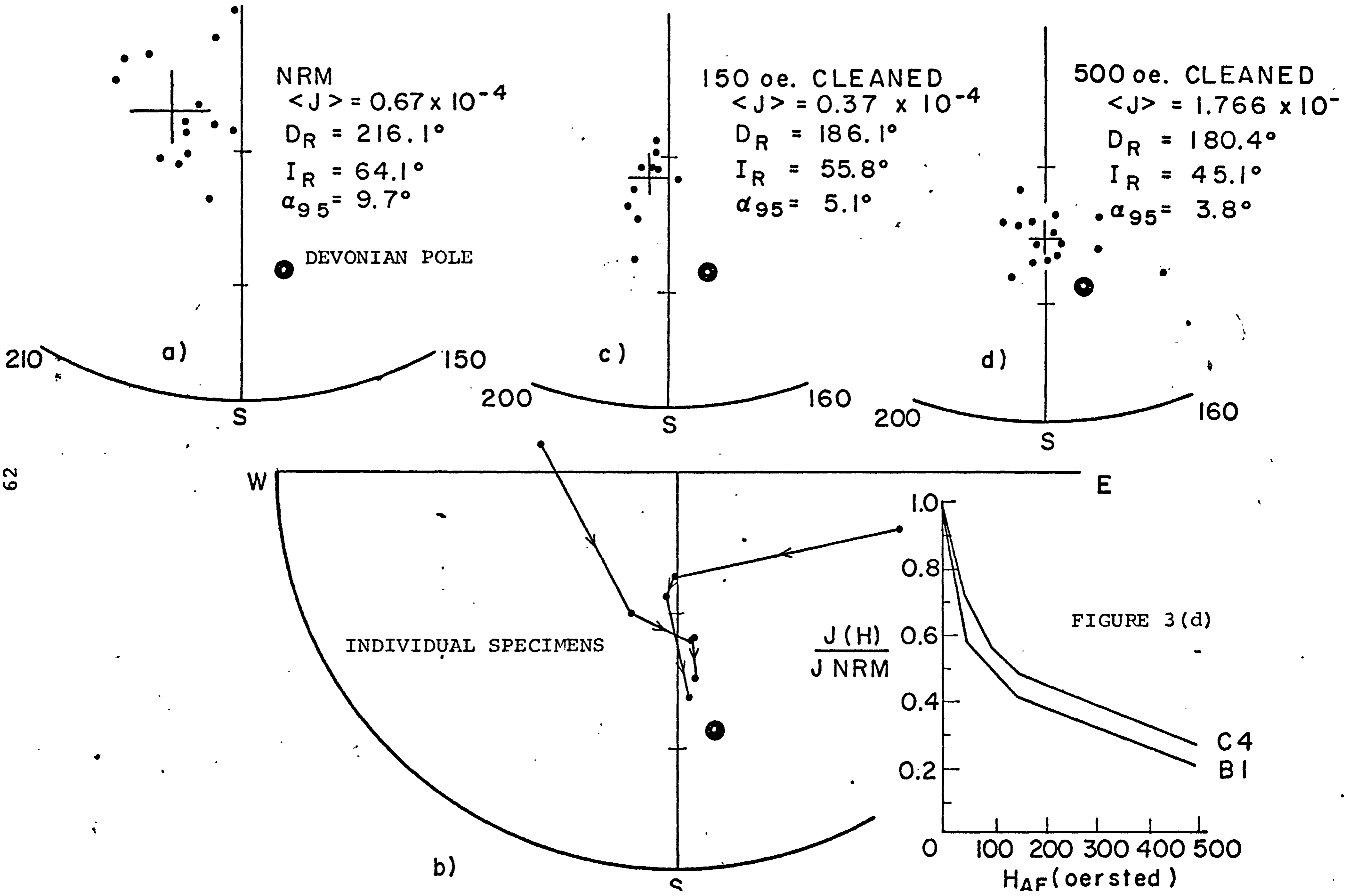


FIGURE 3(d)

# DISCUSSION AND CONCLUSIONS

The main features of the geology, mineralogy, and paleomagnetic behavior of the thirty-one samples investigated in this study are summarized in the following comments.

Samples were chosen from three Boston area effusive-hypabyssal volcanic formations, the ages of which all pre-date the Acadian Orogeny. Field relations imply that the local Marlboro Formation rocks, while probably not all of the same episode, may be considered as a group to be late pre-Cambrian in age. Field relations, fossil evidence, and attempts at radiometric dating have indicated a pre-Devonian, quite possibly Silurian age for the Mattapan and Lynn Volcanic Complexes.

The only local events which might possibly have caused a resetting of the samples' paleoremanences appear to be the Acadian Orogeny and a thermal-deformational disturbance during the Permian. The Acadian Orogeny, dated as Early Devonian, has long been recognized as a period which saw the most intensive deformation and regional metamorphism affecting the northern Appalachians. No doubt, much, if not all, of the Boston area low grade regional metamorphism came about as a result of this orogeny. The possibility that a Permian event, which reset K-Ar radiometric ages in central New England, significantly affected the Boston area metamorphically seems to be less likely. Most local samples do not give anomalously low K-Ar ages and the post-Acadian formations appear to be reasonably fresh and unmetamorphosed. There is evidence, though, of at least local Permian deformation.

The probability of a paleoremanence resetting at some time seems very high, considering the petrographic evidence. Nearly all of the magnetite in the samples studied appears as small, irregularly shaped bodies and dusty particles associated with the mineral chlorite. Such magnetite is probably secondary, having formed as the result of the metamorphic transition of pyroxene to chlorite and magnetite. Very little magnetite which appeared to be primary was seen: that observed occurring as large, partially resorbed crystals associated with such minerals as chlorite, actinolite, and sphene. The metamorphic growth of such minerals consumes primary opaques.

The mineralogies indicate a low to medium-grade greenschist metamorphism. Observation of the above-mentioned reactions, plus observation of the occasional growth of secondary biotite and the albitic nature of the plagioclase imply that the samples are of the "quartz-albite-muscovite-chlorite" or the "quartz-albite-epidote-biotite" greenschist subfacies (Turner and Verhoogen-1960). The metamorphic temperatures reached, therefore, could not have been high enough to have caused a thermal resetting of remanence. This fact, combined with the knowledge of the nature of the magnetite, suggest that a secondary chemical remanent magnetization was acquired by the samples. In order to determine when this occurred, an investigation of the remanent magnetic directions must be made.

As has been discussed, the concept of paleomagnetic sites probably has little applicability in this study. For the same reasons that this is true, and because of the possibility of several samples being from ice-rotated blocks, the concept of formation means is not employed, either. Calculation of a formation mean from the Mattapan data, for instance, would be ridiculous. Each sample studied has, therefore, been assigned a probability of being "in situ" and those with high probabilities are treated rather like individual specimens in that their averaged cleaned directions are averaged to give a mean "Boston area volcanics" pole.

Those samples which seem clearly to have been rotated from "in situ" positions due to the fact that their cleaned directions lie nowhere near a period pole include numbers 4, 22, 26, 27, 29, 30, 34, 41, and 46. Although number 46 lies near the normal Tertiary pole, it probably does so due to a rotation, as there seems little chance of its having acquired a secondary remanence during the Cenozoic.

There are two samples which are considered as separate cases. Number five's direction corresponds with the present pole, probably having followed the polar wandering path throughout its existence due to a low coercivity, multidomain character of its magnetite. The Devonian normal pole falls within the $a_{95}$ confidence circle of 8220, implying that the sample did, indeed, acquire a secondary remanence during the Devonian.

The remaining samples to be considered all seem to be associated with the Paleozoic polar wandering path. Samples 16, 32, 40, and 44 all seem to lie at too great an angle to the Paleozoic poles to have these great angles explained by secular variation. They, too, were probably rotated. The average pole position of the remaining 15 "in situ" samples was found to be D=171 degrees and I=40 degrees (21N,100E), with an $a_{95}$ of 9 degrees. The averaged Devonian reversed pole falls within this $a_{95}$. The $a_{95}$ circles of the Silurian, Carboniferous, and Permian reversed poles quite likely intersect that of the "Boston Volcanics", but the Devonian pole is closer than any of these. The implication is that the volcanic samples did acquire a secondary chemical remanence during the Devonian period. The rotated samples quite likely acquired a secondary remanence at the same time, suffering movement from their "in situ" positions either during the Permian deformation or during a period of glaciation.

The idea that each sample lost its primary remanence while acquiring a secondary remanence is supported by the fact that no sample exhibited a stable direction other than the one listed for it. Even though a few pole directions might be construed as falling near pre-Cambrian or Silurian poles, it is likely that these phenomena are caused by Devonian secular variation or by rotations.

In progressive AF demagnetization of rock specimens, domains with the lowest coercive force are those which randomize earliest. For any given grain volume, these grains are also the ones with the shortest relaxation times and, therefore, the greatest susceptibility to viscous effects. Stacey (1961) has pointed out that the coercive force of multidomain grains is quite low. These grains are, therefore, most susceptible to viscous effects. (Given the high content of multidomain magnetite in the samples studied, the soft NRM component is probably viscous in nature.) The fact that most of the samples studied have very low median destructive fields (less than 50 oersteds), implies that they have a high percentage of low coercivity, multidomain grains.

The coercive force of multidomain grains is unlikely to exceed a few hundred oersteds. The remanence after fields of about 400 oersteds, then, is likely to be the result of the magnetization of single domain (and pseudo single domain) grains. The cleaned remanence of samples with cleaning field levels in excess of 400 oersteds is probably single domain in nature, while the cleaned remanence of samples with cleaning fields less than 400 oersteds is probably single and multidomain in nature.

Single domain grains have a much higher coercivity than multidomain grains and are probably responsible for the samples' demagnetization behavior at high fields. The level of divergence is probably determined by the nature of these grains. Single domain grains of magnetite are very shape anisotropy dependent, their coercivity being increased with increased elongation. The samples with high demagnetization level divergences probably have a higher percentage of lamellar single domain-like material.

One might be tempted to look for a direct correlation between the median destructive field and divergence level based on the relative amounts of single and multidomain material in a sample, but the correlation is probably considerably more complex, if it exists. This is due to the fact that the median destructive field depends on the <u>amount</u> of multidomain material, whereas the divergence level depends on the <u>nature</u> of the single domain material. As is obvious from the individual sample data, the correlation does not exist for the samples studied.

Other correlations, or lack of correlations have been noted. A good correlation exists between the percentage of magnetite in a sample and its NRM intensity. This is understandable, since the greater the percentage of magnetite in a sample, the greater will be that sample's susceptibility and thus its induced magnetization. No correlations were observed, however, between the amount of magnetite and parameters which depend on the nature of the magnetite such as median destructive field and divergence level. Even felsic rocks, which contain less magnetite than mafic varieties, should be good for paleomagnetic studies, provided the nature of their magnetite is conducive to retaining the direction of an applied field (high coercivity grains, etc.).

A word about the nature of the anisotropy of the rocks studied is now in order. As has been noted, the anisotropy parameters of each sample were all near the isotropic value of one. Even the maximum possible magnetic vector deflection of about seven degrees (sample 23) did not cause its sample's direction to be unacceptable. All other sample anisotropies were considerable less than this, though, and for the purposes of determining an average paleopole, the average sample directions were entirely acceptable. The implication is that low grade metavolcanics may be used in paleomagnetic studies without fear of great errors from high anisotropies. This conclusion is in basically good agreement with results from recent literature (Park-1973; Irving and Park-1973). The interest in the paleomagnetic record preserved in metamorphic rocks has been recounted in recent years, in spite of the belief that most metamorphic rocks are paleomagnetically unreliable (Hargraves and Banerjee-1973).

# APPENDIX ONE

Listed are the mineralogies of the thirty-one samples investigated as determined by petrographic study. With the exception of magnetite, any mineral with a volume percentage less than one per cent is not listed. Notable amoung the minerals which quite often fall into this category are quartz, actinolite, calcite, sphene, and epidote.

Sample 1: 65% plagioclase (up to 90% of some grains sericitized), 30% chlorite, 3.5% quartz, 1.5% opaques.

Sample 2: 70% plagioclase (80% sericitized), 15% chlorite, 10% stilpnomelane, 4% opaques, 1% quartz.

Sample 4: 40% (10% sericitized), 25% biotite, 25% chlorite, 4% hypersthene, 3% augite, 3% opaques.

Sample 5: 48% quartz, 47% feldspar (mostly microcline with some orthoclase and sodic plagioclase), 4.5% chlorite, 0.5% biotite, traces of opaques.

Sample 6: 63% chlorite, 32% sericitized plagioclase, 3% stilpnomelane, 2% opaques.

Sample 7: 40% plagioclase, 40% pyroxene (mostly augite-some hypersthene), 15% chlorite, 5% opaques.

Sample 8: 43% microcline, 41% plagioclase, 10% stilpnomelane, 5% chlorite, 1% quartz, 0.3% opaques.

Sample 8218: 50% chlorite 35% plagioclase (50% sericitized), 7% quartz, 5% actinolite, 3 % opaques.

## APPENDIX ONE

## (Continued)

Sample 8220: 55% chlorite, 37% plagioclase, 5% quartz, 3% opaques.

Sample 16: 60% plagioclase, 15% olivine, 14% pyroxene, 8% chlorite, 2% stilpnomelane, 0.7% opaques.

Sample 17: 50% plagioclase, 25% biotite, 25% chlorite, 0.1% opaques.

Sample 18: 75% plagioclase (75% sericitized), 13% chlorite, 5% olivine, 4% clinopyroxene, 2% opaques, 1% hornblende.

Sample 19: 65% plagioclase (5% sericitized), 20% chlorite, 10% stilpnomelane, 5% microcline, 0.1% opaques.

Sample 20: 90% plagioclase, 5% chlorite, 3% microcline, 1% olivine, 1% clinopyroxene.

Sample 21:50% plagioclase (50% sericitized), 47% chlorite, 2.5% opaques.

Sample 22: 85% plagioclase (75% sericitized), 7% chlorite, 5% opaques, 2% clinopyroxene, 1% olivine.

Sample 23: 83% plagioclase, 5% microcline, 5% muscovite, 3% chlorite, 3% stilpnomelane, 3% opaques.

Sample 24: 40% plagioclase, 45% chlorite, 2% quartz, 10% muscovite, 1% olivine, 1% clinopyroxene, 1% opaques.

Sample 26: 50% plagioclase, 47% chlorite, 2% opaques, 1% biotite.

Sample 27: 60% chlorite, 37% plagioclase (30% sericitized), 2% clinopyroxene, 0.4% opaques.

Sample 29: 70% chlorite, 29% plagioclase, 0.4% opaques.

Sample 30: 30% sanadine, 30% orthoclase, 15% microcline, 15% plagioclase, 7% quartz, 1% chlorite, 1% biotite, 1% opaques.

## APPENDIX ONE

(continued)

Sample 32: 40% sanadine, 30% orthoclase, 18% quartz, 5% microcline, 4% plagioclase, 1% muscovite, 1% chlorite, 0.5% opaques, (30% of the feldspars are sericitized).

Sample 34: 25% sanadine, 25% orthoclase, 10% microcline, 10% plagioclase (50% of all feldspars are sericitized), 22% quartz, 8% chlorite, 0.1 % opaques.

Sample 40: 63% plagioclase, 5% chlorite, 27% clinopyroxene, 2% orthoclase, 1.5% opaques, 1% epidote, (fld. 40% seric.).

Sample 41: 30% orthoclase, 25% quartz, 35% plagioclase, 8% microcline, 2% chlorite, 0.1% opaques (feldspars 50% sericitized).

Sample 42: 65% plagioclase, 17% clinopyroxene, 11% chlorite, 5% orthopyroxene, 1.5% opaques, (20% of plag. sericitized).

Sample 44: 30% orthoclase, 30% plagioclase, 25% quartz, 10% microcline, 4% chlorite, 0.5% stilpnomelane, 0.5% opaques, ((feldspars 40% sericitized).

Sample 45: 40% orthoclase, 25% quartz, 30% plagioclase, 4% chlorite, 1% stilpnomelane, 0.2% opaques, (Feldspars 40% sericitized).

Sample 46: 36% sanadine, 34% quartz, 20% orthoclase, 8% microcline, 1% plagioclase, 1% chlorite, 0.1% opaques, (feldspars 30% sericitized).

Sample 47: 35% sanadine, 33% quartz, 22% orthoclase, 5% microcline, 4% plag., 1% chlorite, 0.1% opaques, (30% felds. sericite).

# APPENDIX TWO

## SAMPLE LOCATION

Sample 1: On north side of Route 2, about one-quarter mile east of the Route 2-Waltham Street intersection, Lexington, Ma.

Sample 2: Same outcrop as Sample 1, about 150 feet to the east.

Sample 4: On opposite side of Route 2 from samples 1 and 2, about 100 yards into Piper Road.

Sample 5: On Toten Pond Road, 1/3 of a mile east of the Route 128 intersection, in Waltham, Ma.

Sample 6: Taken from the same outcrop (1.5 feet west) as Sample 5.

Sample 7: North of the fire tower (3/10 of a mile) in Prospect Hill Park, Waltham, Ma.

Sample 8: Taken from an outcrop 100 feet north of Sample 7.

Sample 8218: On Oakmont Circle on west side of Granny Pond, Lexington, Ma.

Sample 8220: On east side of Granny Pond, Lexington, Ma.

Sample 16: On road parallel to and south of Route 2, opposite the Saint Paul Church, 0.15 miles west of Park Avenue, Watertown, Ma.

Sample 17: Taken from an outcrop 70 feet east of the sample 16 outcrop.

Sample 18: North of Route 2 and east of Route 4 (at the intersection), Lexington, Ma.

Sample 19: Taken from an outcrop 50 feet east of the sample 18 outcrop.

## APPENDIX TWO

(Continued)

Sample 20: The Winn Street, going northeast off of Route 128, in Burlington, Ma.

Sample 21: The Winn Street enterance, going southwest onto Route 128, Burlington, Ma.

Sample 22: On road connecting Draper Road and Sudbury Road, 1/4 mile east of Draper Road, Weston, Ma.

Sample 23: Taken from an outcrop 60 east of the sample 22 outcrop.

Sample 24: On Old Country Road, 0.5 miles north of Trapelo Road, Lincoln, Ma.

Sample 26: On Winter Road 1.2 miles south of Trapelo Road, Waltham, Ma.

Sample 27: On Winter Road 1.9 miles south of Trapelo Road, Waltham, Ma.

Sample 29: At dead end of Fairview Road 0.8 miles south of the Conant Road-Route 117 intersection, Weston, Ma.

Sample 30: At east end of Wampatuck Hill on west side of Wampatuck Road, 2/10 of a mile north of the Wampatuck Road-Chickatawbut Road intersection, Quincy, Ma.

Sample 32: On south side of Chickatawbut Road, 2/10 of a mile west of the Chickatawbut Road-Granite Street intersection, in Quincy, Ma.

Sample 34: Three-tenths of a mile south of the Granite Road-Route 3 intersection, Braintree, Ma.

## APPENDIX TWO

(Continued)

Sample 40: On the west side of Elm Street, 3/10 of a mile west northeast of the Felsway West-Elm Street intersection, Medford, Ma.

Sample 41: On the east side of Woodland Road, 300 feet north of the Woodland-Elm-Highland traffic circle, in Medford, Ma.

Sample 42: At the intersection of Pebble Road and Felsway East, on the west side of Felsway East, in Melrose, Ma.

Sample 44: North side of Sylvan Street, 1/5 of a mile east of the Sylvan Street-Main Street intersection, Melrose, Ma.

Sample 45: Taken from outcrop 100 feet southeast of the sample 44 outcrop.

Sample 46: On the north side of Route 128, 350 yards west of the Route 128-Route 37 intersection, Braintree, Ma.

Sample 47: Taken from an outcrop 100 yards east of the sample 46 outcrop.

## APPENDIX 3

## SAMPLE DATA

PART ONE - NRM DATA

| SAMPLE NO. | DEGREES DECLINATION | DEGREES INCLINATION | $a_{95}$ | k | R | N | INTENSITY GAUSSx$10^4$ |
|---|---|---|---|---|---|---|---|
| 1 | 239.8 | 22.4 | 5.10 | 62.1 | 13.79 | 14 | 19.9 |
| 2 | 192.8 | 51.5 | 15.17 | 7.3 | 13.09 | 15 | 30.8 |
| 4 | 208.1 | -19.5 | 31.70 | 2.3 | 9.55 | 16 | 8.6 |
| 5 | 298.3 | 67.0 | 23.40 | 4.4 | 9.50 | 12 | 0.3 |
| 6 | 163.7 | 37.9 | 2.30 | 241.9 | 16.93 | 17 | 0.4 |
| 7 | 356.3 | 40.7 | 44.70 | 1.9 | 6.23 | 12 | 5.9 |
| 8 | 344.6 | 64.0 | 14.67 | 11.8 | 9.24 | 10 | 4.0 |
| 8218 | 51.9 | 34.5 | 13.27 | 10.7 | 11.88 | 13 | 5.8 |
| 8220 | 314.8 | -27.2 | 8.05 | 23.5 | 14.40 | 15 | 21.4 |
| 16 | 35.6 | 78.6 | 4.96 | 77.6 | 11.86 | 12 | 43.3 |
| 17 | 189.4 | 39.2 | 6.90 | 29.6 | 15.49 | 16 | 0.2 |
| 18 | 279.5 | 69.4 | 6.22 | 49.7 | 11.78 | 12 | 17.3 |
| 19 | 216.1 | 64.1 | 9.69 | 25.8 | 9.65 | 10 | 0.1 |
| 20 | 228.0 | 11.0 | 20.03 | 5.3 | 10.70 | 13 | 1.9 |
| 21 | 309.8 | 82.5 | 19.68 | 4.5 | 12.66 | 16 | 19.3 |

## APPENDIX 3

(Cont)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 22 | 227.6 | 35.2 | 15.34 | 10.8 | 9.17 | 10 | 16.6 |
| 23 | 122.6 | -4.5 | 32.58 | 3.5 | 6.68 | 9 | 71.4 |
| 24 | 329.4 | 54.2 | 23.70 | 6.4 | 6.91 | 8 | 1.1 |
| 26 | 210.7 | 65.7 | 18.49 | 7.8 | 8.84 | 10 | 7.9 |
| 27 | 50.2 | 23.7 | 7.42 | 35.2 | 11.69 | 12 | 1.5 |
| 29 | 252.9 | 1.8 | 7.44 | 35.0 | 11.69 | 12 | 2.4 |
| 30 | 278.7 | 22.6 | 5.20 | 59.5 | 13.78 | 14 | 53.5 |
| 32 | 242.3 | 19.7 | 6.19 | 42.1 | 13.69 | 14 | 0.8 |
| 34 | 274.1 | 81.0 | 3.55 | 166.2 | 10.94 | 11 | 0.05 |
| 40 | 237.7 | 65.6 | 1.43 | 771.4 | 13.98 | 14 | 148.0 |
| 41 | 324.1 | 37.3 | 7.09 | 38.4 | 11.71 | 12 | 0.1 |
| 42 | 218.2 | 60.3 | 6.48 | 41.9 | 12.71 | 13 | 12.0 |
| 44 | 284.5 | 29.7 | 4.05 | 128.2 | 10.92 | 11 | 11.2 |
| 45 | 243.5 | 25.8 | 16.02 | 9.1 | 9.90 | 11 | 0.6 |
| 46 | 44.7 | 23.7 | 22.33 | 4.4 | 10.28 | 13 | 1.6 |
| 47 | 180.0 | 36.2 | 55.4 | 1.7 | 4.77 | 10 | 0.01 |

# APPENDIX 3

(Cont)

PART TWO - CLEANED SAMPLE DATA

| SAMPLE NO. | DEGREES DECLINATION | DEGREES INCLINATION | OERSTEDS DMG. LEVEL | $a_{95}$ | k | R | N | INTENSITY GAUSSx$10^5$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 181.8 | 27.2 | 150 | 3.78 | 121.1 | 12.90 | 13 | 31.1 |
| 2 | 193.9 | 35.4 | 150 | 3.93 | 103.2 | 13.87 | 14 | 44.8 |
| 4 | 257.5 | 46.7 | 150 | 7.00 | 36.0 | 12.67 | 13 | 5.2 |
| 5 | 337.2 | 74.4 | 150 | 11.80 | 16.0 | 10.38 | 11 | 0.3 |
| 6 | 160.0 | 24.4 | 500 | 4.20 | 133.1 | 9.93 | 10 | 2.1 |
| 7 | 161.0 | 58.9 | 500 | 10.02 | 24.2 | 9.63 | 10 | 11.0 |
| 8 | 168.2 | 54.2 | 700 | 11.00 | 38.1 | 5.87 | 6 | 3.9 |
| 8218 | 167.1 | 66.1 | 500 | 6.76 | 58.9 | 8.86 | 9 | 4.1 |
| 8220 | 321.1 | -23.4 | 150 | 5.38 | 51.5 | 14.73 | 15 | 58.9 |
| 16 | 137.5 | 4.3 | 500 | 9.82 | 25.2 | 9.64 | 10 | 5.5 |
| 17 | 176.9 | 28.5 | 300 | 4.31 | 126.5 | 9.93 | 10 | 1.1 |
| 18 | 143.6 | 52.9 | 100 | 8.73 | 59.9 | 5.92 | 6 | 23.9 |
| 19 | 180.4 | 45.1 | 500 | 3.78 | 111.6 | 13.88 | 14 | 0.3 |
| 20 | 170.0 | 46.0 | 500 | 3.02 | 77.3 | 5.94 | 6 | 1.1 |
| 21 | 141.8 | 55.1 | 150 | 10.08 | 23.9 | 9.62 | 10 | 3.5 |

# APPENDIX 3

(Cont)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 22 | 258.1 | 33.5 | 500 | 9.32 | 36.3 | 7.81 | 8 | 19.8 |
| 23 | 178.9 | 14.6 | 500 | 10.98 | 26.4 | 7.73 | 8 | 3.3 |
| 24 | 175.2 | 55.6 | 700 | 15.52 | 16.1 | 6.63 | 7 | 0.9 |
| 26 | 290.1 | 70.6 | 500 | 11.38 | 35.6 | 5.86 | 6 | 3.0 |
| 27 | 303.9 | 58.0 | 500 | 15.89 | 18.7 | 5.73 | 6 | 0.2 |
| 29 | 261.3 | -23.0 | 500 | 9.37 | 52.1 | 5.90 | 6 | 4.7 |
| 30 | 285.4 | 26.1 | 300 | 7.94 | 38.0 | 9.76 | 10 | 1.9 |
| 32 | 217.6 | 0.1 | 500 | 9.93 | 46.5 | 5.89 | 6 | 0.4 |
| 34 | 78.5 | 81.2 | 300 | 13.77 | 17.1 | 7.59 | 8 | 0.1 |
| 40 | 226.2 | 55.7 | 300 | 8.19 | 35.8 | 9.75 | 10 | 46.5 |
| 41 | 332.0 | 48.0 | 50 | 6.27 | 60.4 | 9.85 | 10 | 0.6 |
| 42 | 174.2 | 28.2 | 150 | 4.31 | 166.0 | 7.96 | 8 | 42.3 |
| 44 | 195.8 | 78.2 | 150 | 6.54 | 72.6 | 7.90 | 8 | 2.2 |
| 45 | 172.7 | 20.3 | 150 | 6.77 | 67.9 | 7.90 | 8 | 1.3 |
| 46 | 358.6 | 58.3 | 50 | 8.02 | 45.21 | 6.92 | 7 | 4.9 |
| 47------------------------------------------------------------------------ | | | | | | | | |

# APPENDIX FOUR

## BULK SUSEPTIBILITY DATA

| SAMPLE NO. | Vol. Mag. Microscope % | $X_{zz}$ Measured $\overline{X}x10^3$ (C.G.S.) Bison | $\overline{X}x10^3$ from $\overline{X}=2.89x10^{-3}V^{1.01}$ (C.G.S.) | $\overline{X}x10^3$ from $\overline{X}=2.6x10^{-3}V^{1.33}$ (C.G.S.) |
|---|---|---|---|---|
| 1 | 1.5 | 3.87 | 4.7 | 4.1 |
| 2 | 4.0 | 12.50 | 12.0 | 13.0 |
| 4 | 3.0 | 7.27 | 9.0 | 9.0 |
| 5 | 0.1 | 0.26 | 0.3 | 0.2 |
| 6 | 2.0 | 0.12 | 6.0 | 5.0 |
| 7 | 5.0 | 4.83 | 15.0 | 15.0 |
| 8 | 0.3 | 0.63 | 0.8 | 0.7 |
| 8218 | 3.0 | 5.72 | 9.0 | 9.0 |
| 8220 | 3.0 | 4.77 | 9.0 | 9.0 |
| 16 | 0.7 | 1.67 | 2.0 | 1.6 |
| 17 | 0.1 | 0.08 | 0.3 | 0.2 |
| 18 | 2.0 | 3.20 | 6.0 | 5.0 |
| 19 | 0.1 | 0.10 | 0.3 | 0.2 |
| 20 | 0.2 | 0.39 | 0.6 | 0.4 |
| 21 | 2.5 | 6.11 | 7.5 | 7.0 |
| 22 | 5.0 | 6.45 | 15.0 | 15.0 |
| 23 | 1.0 | 2.96 | 2.9 | 2.6 |
| 24 | 1.0 | 1.20 | 2.9 | 2.6 |
| 26 | 2.0 | 4.86 | 6.0 | 5.0 |
| 27 | 0.4 | 0.84 | 1.1 | 0.9 |
| 29 | 0.4 | 0.72 | 1.1 | 0.9 |

## APPENDIX FOUR

(Continued)

| | | | | |
|---|---|---|---|---|
| 30 | 0.8 | 1.97 | 2.6 | 2.2 |
| 32 | 0.5 | 1.39 | 1.4 | 1.2 |
| 34 | 0.1 | 0.03 | 0.3 | 0.2 |
| 40 | 1.5 | 3.56 | 4.7 | 4.1 |
| 41 | 0.1 | 0.05 | 0.3 | 0.2 |
| 42 | 1.5 | 3.24 | 4.7 | 4.1 |
| 44 | 0.5 | 1.09 | 1.4 | 1.2 |
| 45 | 0.2 | 0.38 | 0.6 | 0.4 |
| 46 | 0.1 | 0.05 | 0.3 | 0.2 |
| 47 | 0.1 | 0.02 | 0.3 | 0.2 |

# APPENDIX FIVE

## ANISOTROPY DATA

| SAMPLE NO. | P | E | $K_{rl}$ | $K_p$ |
|---|---|---|---|---|
| 1 | 1.039 | 0.983 | 1.028 | 1.024 |
| 2 | 1.016 | 1.000 | 1.008 | 1.012 |
| 4 | 1.160 | 1.046 | 1.053 | 1.131 |
| 5 | 1.086 | 0.935 | 1.078 | 1.047 |
| 6 | 1.008 | 1.008 | 1.000 | 1.008 |
| 7 | 1.013 | 1.013 | 1.000 | 1.013 |
| 8 | 1.057 | 1.050 | 1.003 | 1.055 |
| 8218 | 1.027 | 1.005 | 1.010 | 1.021 |
| 8220 | 1.068 | 1.024 | 1.021 | 1.057 |
| 16 | 1.018 | 1.010 | 1.004 | 1.016 |
| 17 | 1.024 | 0.986 | 1.019 | 1.015 |
| 18 | 1.024 | 0.980 | 1.022 | 1.013 |
| 19 | 1.062 | 1.028 | 1.017 | 1.053 |
| 20 | 1.149 | 1.086 | 1.028 | 1.133 |
| 21 | 1.105 | 1.021 | 1.041 | 1.084 |
| 22 | 1.013 | 0.992 | 1.011 | 1.007 |
| 23 | 1.274 | 1.008 | 1.125 | 1.204 |
| 24 | 1.029 | 1.005 | 1.012 | 1.023 |
| 26 | 1.008 | 1.003 | 1.002 | 1.007 |
| 27 | 1.033 | 1.006 | 1.013 | 1.026 |
| 29 | 1.026 | 1.017 | 1.004 | 1.023 |
| 30 | 1.087 | 1.062 | 1.011 | 1.081 |

## APPENDIX FIVE

(Continued)

| SAMPLE NO. | P | E | $K_{r1}$ | $K_p$ |
|---|---|---|---|---|
| 32 | 1.004 | 1.004 | 1.000 | 1.004 |
| 34 | 1.010 | 0.997 | 1.006 | 1.007 |
| 40 | 1.043 | 1.008 | 1.017 | 1.034 |
| 41 | 1.014 | 1.011 | 1.001 | 1.013 |
| 42 | 1.018 | 0.994 | 1.012 | 1.012 |
| 44 | 1.037 | 0.975 | 1.031 | 1.021 |
| 45 | 1.023 | 0.997 | 1.013 | 1.017 |
| 46 | 1.063 | 1.047 | 1.007 | 1.059 |
| 47 | 1.012 | 1.005 | 1.003 | 1.010 |

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