This is to certify that the

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PALEOMAGNETISM AND SHEAR HISTORY

OF PRECAMBRIAN X DIKES

presented by

MARK ALLEN FORTUNA

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of the requirements for

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F. W. Cambray
Major professor

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PALEOMAGNETISM AND SHEAR HISTORY
OF PRECAMBRIAN X DIKES

By

Mark Allen Fortuna

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ABSTRACT

PALEOMAGNETISM AND SHEAR HISTORY
OF PRECAMBRIAN X DIKES

By

Mark Allen Fortuna

A paleomagnetic study was conducted on the Archean gneisses and Lower Proterozoic metadiabase dikes intruded into the Archean Granite-Greenstone terrain north of the Marquette Trough, Upper Michigan. From the standard thermal and A.C. (alternating current) demagnetization techniques used to date the rocks, four different thermal events were determined to have effected this area. The Compeau Creek Gneiss thermal event yielded poles which fell on Irving's Apparent Polar Wander Path at approximately the 2.5 G.a. position ± .06 G.a., closely corresponding to dates given for the Algoman Orogeny. Metadiabase intruded the gneiss in what appears to be a period of tension that effected the area about 2.18 G.a. ± .04 G.a. Following this extensional phase came the compression and metamorphism of the Penokean Orogeny which partially reset the paleopoles in the gneiss and metadiabase and was dated by such at 1.88 G.a. ± .03 G.a.

Lastly, another series of diabase dikes, the Keweenawan Series, intruded the region at about 1.11 G.a. ± .02 G.a. in what is thought to be a failed attempt at continental rifting.

ACKNOWLEDGMENTS

To God goes my greatest thanks for the personal strength given me to pursue this goal to its conclusion and for a creation in which this study could succeed.

The author wishes to express appreciation to Dr. F. W. Cambray, Chairman of the Department of Geology, Michigan State University, under whose counseling this study was undertaken, for his assistance and many suggestions.

Gratitude is expressed to Dr. James Trow, Dr. John Wilband, and Dr. Hugh Bennett, other members of my committee, for their time and help at critical times.

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Many thanks are given to Dan Jensen, Tom Urban, Rick Hamrick, Al Trippel, Dave Shanabrook, and Doyle Watts, good friends who offered their time and assistance when it was needed.

Fondest thanks are expressed to my parents, Mr. and Mrs. H. S. Fortuna and my sister, Susan, for their encouragement and help, not only during this study but for everything.

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INTRODUCTION

This study was undertaken to ascertain whether, in the absence of isotope dates, the paleomagentically determined age and magnetic history of certain Precambrian metadiabase dikes could be determined through the analysis of their paleomagnetic pole positions. In order to do this it must be demonstrated that the magnetism held within the rocks has remained stable since the acquisition of remanence. This requirement can be satisfied in a number of ways but the method of choice when working with igneous rocks is the "baked contact test" (Irving, 1964). This test utilizes the field relationships at contacts between igneous rocks which were intruded and cooled at different times. In this study it must be shown that unintruded country rock, the Compeau Creek Gneiss, carries an Archean palopole (Figure 1), and that in areas reheated by intrusion of metadiabase the gneiss has acquired the same younger pole as the metadiabase. A third pole should also be discernable due to the metamorphism of the Penokean Orogeny.

Age		Events	Orogenies
570 M.a. . .	Cambrian		
Precambrian Z	Upper Proterozoic	Jacobsville	
800 M.a. . .			Post Keweenawan Tilting
Precambrian Y	Middle Proterozoic	Intrusion Keweenawan Diabase	
1.6 G.a. . .			1.85-1.9 G.a. . . Penokean
Precambrian X	Lower Proterozoic	Huronian, Animikie, Marquette Supergroup, Mafic Dikes and Sills	
2.5 G.a.			2.5 G.a. . . Algoman = (Kenoran)
		Algoman Granite	
Precambrian W			

Figure 1. Precambrian Chronology and Sequence of Events.

General Geology

The major elements of the Superior Structural Province can be readily observed in and about the region of the Marquette Trough, Michigan. The province is divided into two contrasting terrains, an older Archean gneiss sequence south of the Trough and extending into Wisconsin that may be greater than 3.1 billion years old (Sims, 1976) and a granite-greenstone terrain north of the Trough, also of Archean age but younger than the gneiss (2.7-2.6 G.a.). Besides differing in age and geographic location these two terrains reflect differences in rock assemblage, structural style and metamorphic grade (Morey and Sims, 1976). The greenstone sequences were originally deposited primarily underwater along with shales, cherts, and volcanoclastics possibly offshore of the protocratonic gneisses to which they are now joined (Morey and Sims, 1976). This sequence was then folded and metamorphosed concurrently with the emplacement of the granitic plutons (Compeau Creek Gneiss) during the Algoman Orogeny at the end of the Archean. The span of time following the Algoman Orogeny and extending through the next major metamorphic event, the Penokean Orogeny, is known as the Lower Proterozoic (Precambrian X). The approximately 800 million years between these two events saw the formation, subsidence of, and sedimentation in a series of basins, including the Marquette Trough, situated at the juncture of the two Archean terrains. Sedimentation of the Marquette Supergroup within the basin is cyclic and records a complete transition from stable shelf to deep water eugeosynclinal environments (the Chocolay, Menominee, and Baraga groups respectively). Emplacement of the series of mafic dikes and sills in the Marquette Trough area (the objective of this study) is thought to have occurred prior to, or synchronously with the sedimentation of the Menominee Group (Sims, 1976). The trough sequence, but apparently not the basement rocks, were then folded and metamorphosed during the Penokean (Canon, 1973). Although a correlation with other mafic dikes, such as the Nipissing Diabase, has been suggested (Sims, 1976), the lack of isotopic dates for these rocks makes correlation at present just speculation. With the entire timing of subsidence and sedimentation in the Marquette Trough dependent on dates determined to an accuracy no better than 800 million years, the need to date these rocks paleomagnetically becomes apparent. The methods of dating formations by their paleomagnetic pole positions are not new, nor is the separation of several poles from one site (due to igneous cooling, metamorphism, viscous effects, and others). However, these techniques have never been tried in this area on rocks as old or as metamorphosed as these. During the Middle Proterozoic (Precambrian Y--about 1.1 G.a.) another series of diabase dikes and lavas were emplaced in the Superior Province. Known as the Keweenawan Series, these rocks are believed to be a failed attempt at continental rifting (Chase and Gilmer, 1973). Minor uplift and sedimentation then followed during the Upper

Proterozoic (Precambrian Z). The study area itself consisted of seven collecting sites spaced over some 20 square miles north and northwest of Marquette, Michigan. Sites chosen reflect the varying Archean and Proterozoic rock types and crosscutting relationships that occur in the Granite-Greenstone terrain north of the Marquette Trough.

Location and Topography

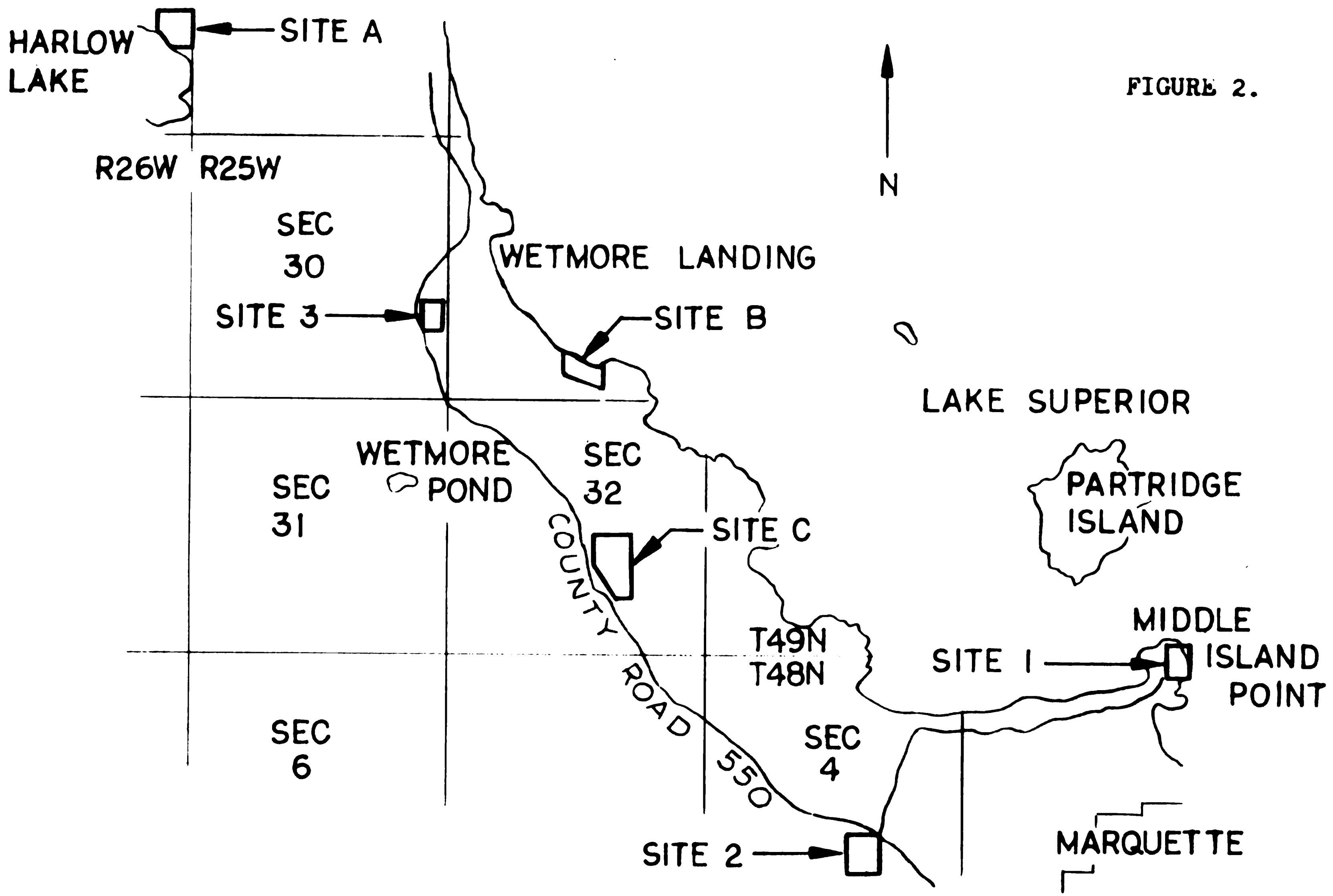
Originally the study was planned to investigate the relationships between the X age metadiabase and the W age gneiss at 5 to 10 locations. Seven sites were finally chosen and collected at, six of them shown in Figure 2.

Outcrop terrain varied, but as sites were chosen mainly for easy road accessability, gneiss and metadiabase generally appeared as low rounded domes or low steep sided ridges rising above a forest canopy rooted in Pleistocene outwash and till. The following is a list of site locations and lithologies sampled.

Site 1	T48N	R25W	sec 3	765'N.L.	765'E.L.	Metadiabase
Site 2	T48N	R25W	sec 4	3960'N.L.	1795'E.L.	Metadiabase & Gneiss
Site 3	T49N	R25W	sec 30	3696'N.L.	396'E.L.	Metadiabase & Gneiss
Site A	T49N	R26W	sec 24	3009'N.L.	122'E.L.	Gneiss
Site B	T49N	R25W	sec 29	3764'N.L.	2587'E.L.	Diabase & Gneiss
Site C	T49N	R25W	sec 32	3748'N.L.	2100'E.L.	Metadiabase & Gneiss
Site F	T48N	R27W	sec 15	1478'N.L.	792'E.L.	Metadiabase

Figure 2. Location of Study Areas, Sites 1, 2, 3, A, B, C.

FIGURE 2.


HARLOW LAKE
SITE A
R26W R25W
SEC 30
SITE 3
WETMORE LANDING
SITE B
N
LAKE SUPERIOR
SEC 31
WETMORE POND
SEC 32
SITE C
PARTRIDGE ISLAND
COUNTY ROAD 550
T49N
T48N
MIDDLE ISLAND POINT
SITE 1
SEC 6
SEC 4
SITE 2
MARQUETTE

Field and Laboratory Methods

The geologic maps used in this investigation were prepared by the U.S.G.S. and appeared in Professional Papers #788 (Puffet, 1974) and #397 (Glair and Thaden, 1968).

At each site chosen an attempt was made to collect at least five oriented blocks for each lithology observed (Irving, 1964) i.e., Site C--five blocks of gneiss, five blocks of metadiabase.

In the laboratory the blocks were then reoriented, cut and cored to produce samples that could be analyzed at the University of Michigan's Paleomagnetic Laboratory. Standard A.C. and thermal demagnetization techniques were employed during the work.

GEOLOGY AND MINERALOGY

Four different igneous rock types are recognized in the literature as outcropping in the study area. These are the Mona Schist, the Compeau Creek Gneiss, the Lower Proterozoic Metadiabase bodies, and the Middle Proterozoic Keweenawan Diabases (Glair and Thaden, 1968). Of these, the only rocks not sampled or studied were those of the Mona Schist. Thin sections were used for mineralogic identification and compositions were determined optically.

Precambrian W--Gneiss

The gneiss is best exposed in clean patches on the shores of Lake Superior and Harlow Lake but typically outcrops throughout the area is massive, poorly jointed, domes or low rounded hills rising above intervening forested valleys. Although often encrusted with lichen and moss the gneiss is easily identifiable when well exposed by its characteristic light grey to pale salmon weathering colors and by its predominant west-northwest to east-southeast foliation.

Based on the classification scheme found in Moorhouse (1959), the composition of the gneiss ranged from some rare granitic forms (Site A) to granodiorite (Sites 1 and 2), quartz monzonite (Site 3), and quartz diorite (Sites B and C). This variability is almost never discernable in the field due to weathering and the compositional description almost always given is "granitic" (Glair and Thaden, 1968).

The dominant minerals, quartz, microcline, and plagioclase account for 90% to over 95% of the rock. Depending on the variety of gneiss examined, compositions ranged from 20-40% quartz, 2-40% microcline, 30-50% plagioclase, 1-14% hornblende, chlorite, and chloritoid, and 1-5% opaques and accessory minerals. The opaques and common accessory minerals consisted of hematite, magnetite, pyrite, pyrrhotite, leucoxene, illmenite, sphene, epidote, and zircon. Euhedral to anhedral plagioclase grains, although extensively saussuritized, were determined to be in the compositional range An_{10}-An_{30} by the Michel Levy method. In the granite, clear unaltered microcline occurred mostly as anhedral grains whereas up to 20% have quite pronounced vein microperthite. Minor amounts of granophyre micropegmatite were found in samples of quartz diorite grouped about plagioclases. Effects of strain could be readily seen in aggregates of quartz grains showing strain lamellae. Hornblende occasionally retained euhedral twinned crystals but was most often found as ragged pleochroic fragments difficult to distinguish from chlorite. In all cases any original igneous texture has been replaced during metamorphism by a granoblastic arrangement of lobed decussate grains.

Although of uncertain origins and with often unclear field relationships, it is suggested that the gneiss probably acquired its foliation when it was deformed during the Algoman Orogeny, perhaps being intruded contemporaneously with the deformation (Sims, 1976).

Precambrian X--Metadiabase

X age metadiabase dikes and sills intrude all earlier Precambrian units in the study area and some of the metasediments within the Marquette Trough.

Weathering dark grey to grey-green, often lichen and moss covered, the poorly jointed, massive metadiabase can be found to outcrop individually or within the gneiss. In the former case the dikes appear as low steep sided elongate hills surrounded by valleys filled with Pleistocene glacial deposits. In the latter case their appearance is best seen in cleared gneiss domes on the shores of the lakes or exposed in railroad and highway cuts.

While some of the thinner dikes are distinctly chloritized and display an internal foliation, the larger metamorphosed bodies still retain recognizable traces of igneous fabric. Textures are fine grained intragranular and diabasic although these have been altered by metamorphic recrystalization. Dominant minerals are chlorite and amphibole, plagioclase, and opaques. Amphibole with compositions in the actinolite-tremolite group varies in appearance from relatively well preserved crystals, often pseudomorphic after pyroxene, to shred-like pleochroic fragments. Except for extinction angle, these fragments are often difficult to distinguish from chlorite which also makes up a significant portion of the rock. Amphibole and chlorite together account for between 30 and 40% of the identifiable minerals. Sodic plagioclase (An_{10-20}) is the common feldspar making up about 35 to 45% of the rock. It occurs as twinned and untwinned laths pseudomorphic after calcic plagioclase which is commonly sericitized and/or extensively saussuritized. Opaques and accessories constitute the remaining fraction of minerals. The opaques identified under reflected light, include in decreasing amounts hematite, pyrite, magnetite, leuxocene, pyrrhotite, and illmenite. These can be found disseminated throughout the sample or isolated in skeletal bodies about relic pyroxenes and amphiboles. Common accessory minerals encountered are epidote, sphene, and zircon. These mineral assemblages along with the alignment of chlorite and amphibole are taken as indicating metamorphism in the chlorite zone or Greenschist facies.

Precambrian Y--Diabase

The predominantly east-west trending unmetamorphosed Keweenawan dikes are the youngest rocks in the area and are seen to cut all previous units except the X age metadiabase. The larger X age dikes are unfoliated and are often mistaken for these diabases due to their similar fresh appearance and grey-green color. The only certain methods of distinguishing between the two are the existence of sheared margins on the X dikes, the mineralogy, and the differences in remanent magnetism.

Composition of the diabase is dominated by plagioclase feldspar, 40-60%, of the andesine-labradorite family. Among the remaining minerals, pyroxenes comprise between 30 and 40%, followed by hornblende and chlorite 5 to 15%, opaques 5 to 10%, and minor amounts of serpentine and accessories. Over 95% of the opaques are magnetite, occurring as disseminated grains and irregularly shaped bodies near pyroxenes and serpentine, the remaining 5% being hematite and pyrite. Dewatering of the diabase probably accounts for the remaining alteration minerals chlorite and serpentine. Textures among the plagioclase and pyroxene grains are intergranular and subophitic, typical of diabases.

Structure--Foliation Study

Besides the primary paleomagnetic objective of this study, a secondary structural objective was to obtain a statistical number of internal shear foliation orientation within the X age metadiabase dikes. It was hoped that this foliation could be used to define a direction of final applied stress during the Penokean Orogeny (Berger, 1971). Unfortunately during the study the lack of fresh exposures plus the need to visit larger dikes to acquire the oriented blocks meant that fewer than a statistical sampling of dike orientations were recorded. This objective therefore had to be abandoned.

GEOPHYSICS

Paleomagnetic Theory

Physicists have described several states of magnetism, only one of which is of importance in carrying natural remanence in rocks, that being ferrimagnetism. There are very few ferromagnetic rock forming minerals, therefore those few have been studied in great depth; they are magnetite--maghemite--ulvospinel solid solution, hematite-illmenite solid solution, and pyrrhotite-pyrite solid solution. The first end-member of each solid solution is ferrimagnetic while the other is either paramagnetic or antiferromagnetic. Fortunately there is great difficulty in forming and/or maintaining a solution between any two end members except at high temperatures. This means that the magnetism measured in normal rocks is essentially pure ferrimagnetism (McElhinny, 1973).

Two magnetic mineral properties that are especially important in paleomagnetic considerations are the Curie temperature and grain size. Normally the Curie temperature can vary with the percent solid solution but since the minerals are almost pure end members the values are essentially constant. The Curie point, the temperature above which ferromagnetic materials become paramagnetic, is distinctive for each mineral: magnetite 578°C, hematite 680°C, and pyrrhotite 320°C. The grain size, on the other hand, varies considerably and controls the number and size of the magnetic domains. Since each domain carries its own individually oriented magnetic vector, the number of domains per magnetic grain controls the orientation of the total remanence vector and the ease with which it can be broken into its original components. The situation of one domain per grain being the least complex both physically and mathematically to handle. In hematite the grain size threshold, above which grains are multidomain, is about .15 centimeters while in magnetite the threshold is 3 to 30 microns (depending on the grain shape). From these sizes Stacy (1967) has concluded that virtually all rocks of interest paleomagnetically contain enough magnetic minerals below this threshold size for single domains to dominate the remanence.

Paleomagnetism in igneous and metamorphic rocks is founded on the important assumption that the domains in rock forming magnetic minerals are aligned in a direction parallel to the direction of the Earth's magnetic field at the time the rock cools through its Curie point(s) (Irving, 1964). Although this assumption can never be proven, its constant use and production of coherent results appears to make it valid. If these domains were aligned parallel to the field lines of some ancient pole then the position of this ancient pole can be located by measuring the direction and intensity of the magnetism left in the minerals. Studies which compare the isotopic ages and associated paleopole position give consistent groupings of poles for each geologic period; connecting these groupings creates the so-called "Apparent Polar Wander (A.P.W.)" paths (Irving, 1964), which are thought to be more a reflection of plate motions than of the wanderings of the North Pole (Irving and McGlyn, 1976). Therefore, if the age of a rock is known only to the accuracy of an era but its paleopole is well defined, then it can be compared to the appropriate A.P.W. path and its age approximated. Moreover, if the rocks are metamorphosed then often more than one pole can be determined, one for the metamorphism and one for the original igneous thermal event (Buchan and Dunlop, 1976).

Techniques

Two methods that are commonly applied in paleomagnetic investigations of igneous rocks are stepped thermal and A.C. (alternating current) cleaning techniques (McElhinny, 1973), both of which were used in this study. As the word cleaning implies, the original magnetism of the rock is cleaned out in successively larger amounts by each increase in thermal or A.C. intensity. The aim in removing the magnetism by steps is to sample, in a short period of time, the spectrum of variation in strength and orientation of the magnetic vectors contained within the domains of the magnetic minerals. The pattern of variation can then be used to determine the stability of the magnetism and whether the sample contained one or several superimposed magnetizations.

In A.C. demagnetization, the specimen is placed within a shielded container and is subjected to a peak A.C. field which then decays exponentially. This has the effect of randomizing domains by imposing an exponentially decreasing hysteresis loop on those whose coercive force is less than the peak field generated. By increasing the field by discrete steps, one samples the pole contribution of domains with increasingly high coercive energies (Figures 3 and 4). Note this is not always equivalent to the highest temperature T.R.M. (thermal remanent magnetism) pole (McElhinny, 1973). The magnetic intensity values for each step were eventually normalized to a ratio of the original N.R.M. (natural remanent magnetism) value, J_o, for presentation in the figures. The amount by which the step is incremented reflects a compromise between the time available for study and the amount of data needed for a pattern of variation to develop. In this study the step increments varied anywhere between 50 oe and 150 oe (oersteds) and 75° and 200°C.

At this point the data could then be analysed and paleopoles determined, either by the use of sophisticated computer programs (Stupavsky and Symons, 1978) or through the traditional method of vector subtraction by the use of Zijderveld diagrams (Zijderveld, 1967) Figures 5, 6, 7, 8, and 9). Computer programs, as opposed to graphical methods, have the advantages of being quick, accurate, and relatively

Figure 3. Thermal Intensity Spectra for Gneiss Samples.

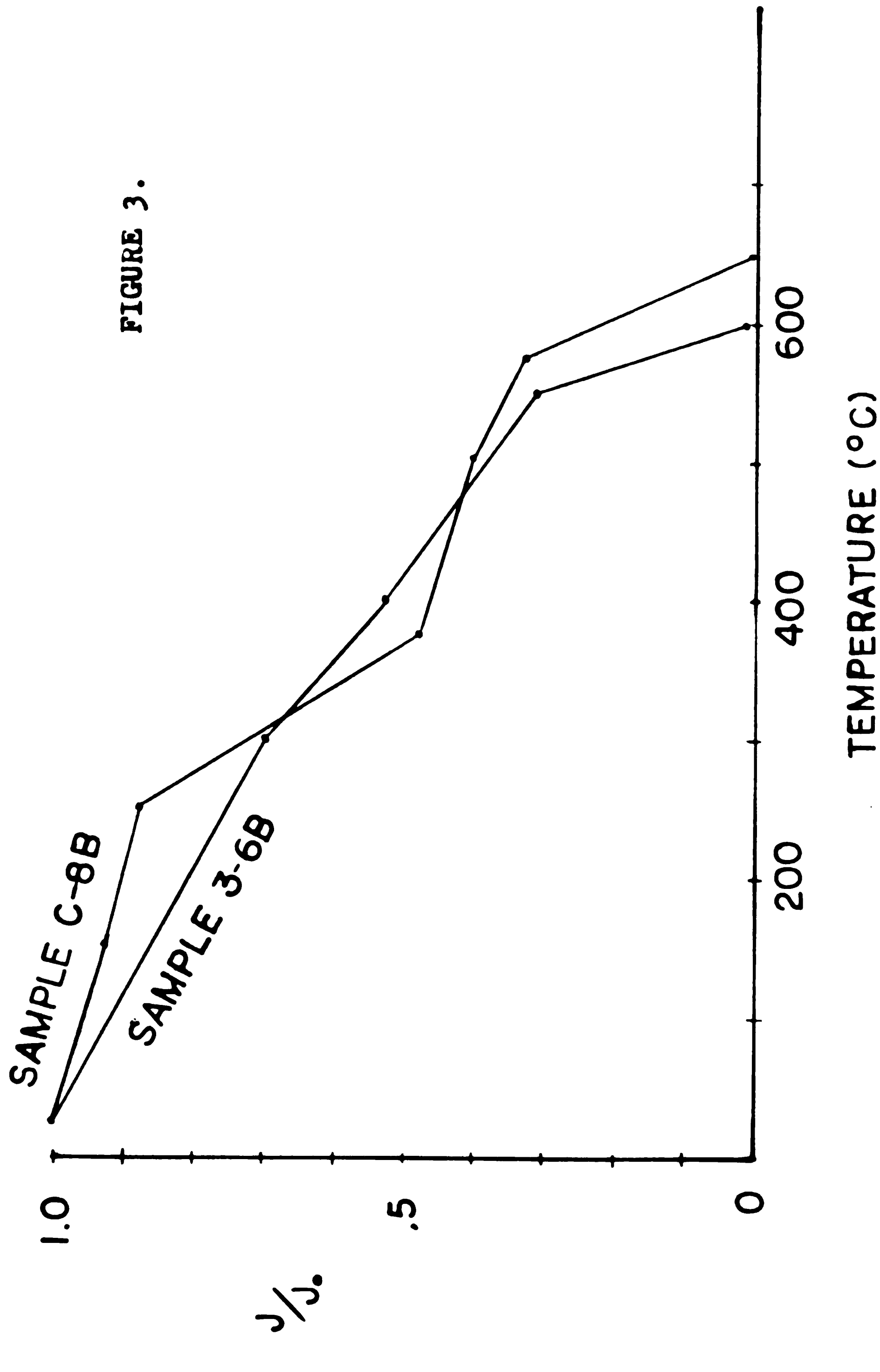


FIGURE 3.

Figure 4. Thermal Intensity for Metadiabase Samples.

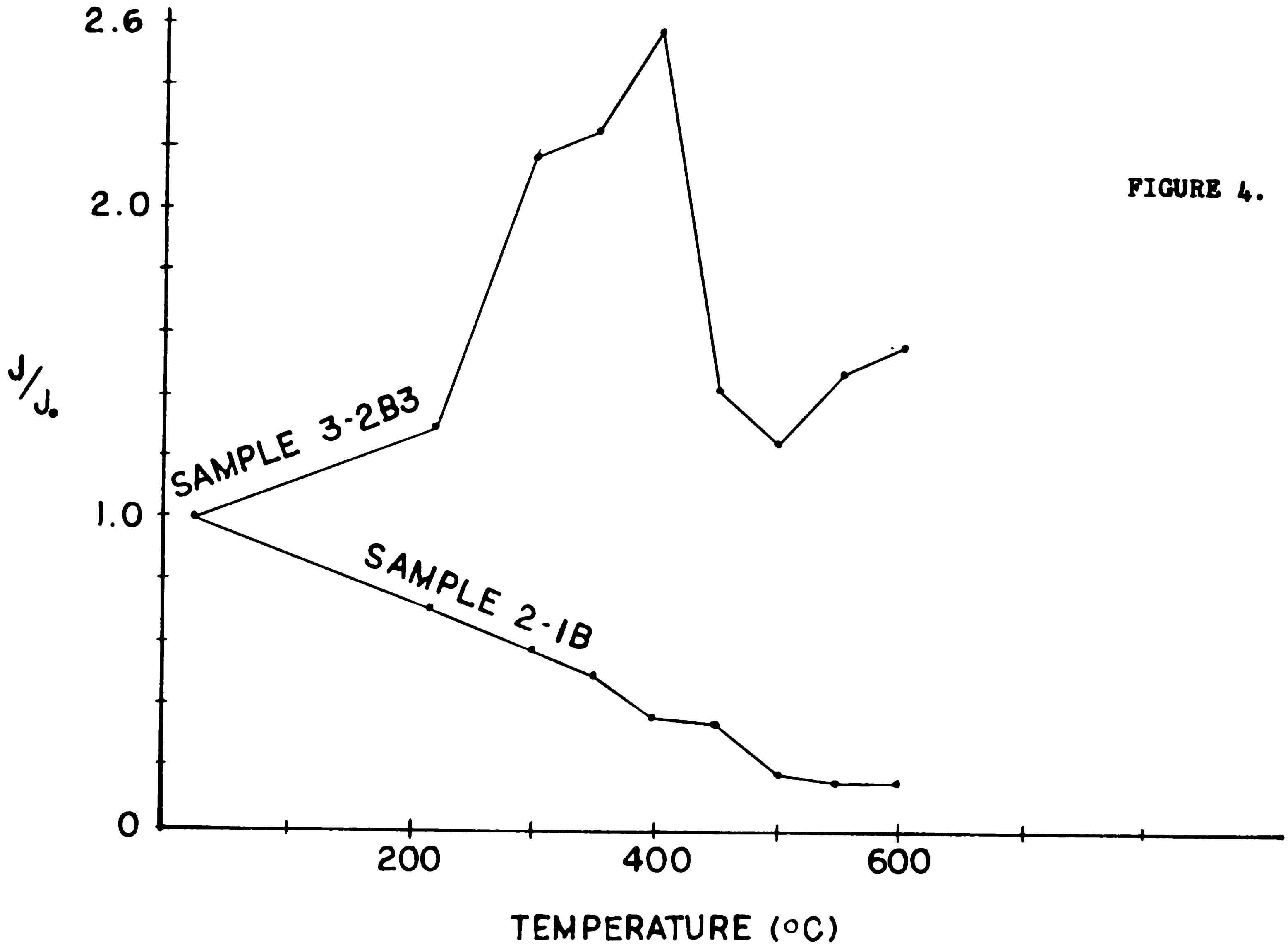

2.6
2.0
1.0
0
J/J₀
SAMPLE 3-2B3
SAMPLE 2-1B
200
400
600
TEMPERATURE (°C)

FIGURE 4.

Figure 5. Typical Zijderveld Diagram for A.C. Demagnetized Metabiabase (Sample 2-10).

Open circles are in vertical plane; solid circles are in the horizontal plane; units are 10^{-5} emu/sample.

FIGURE 5.

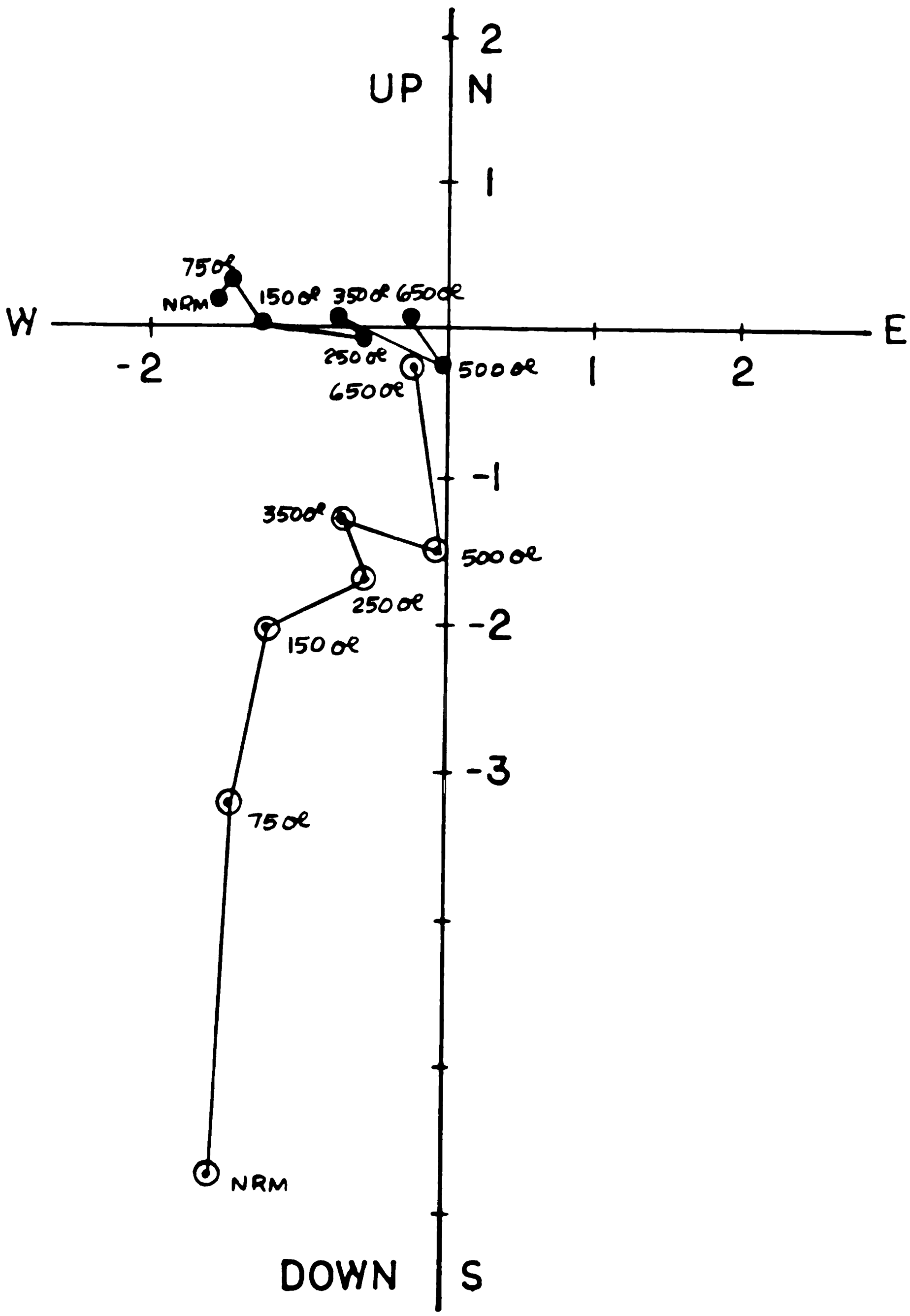
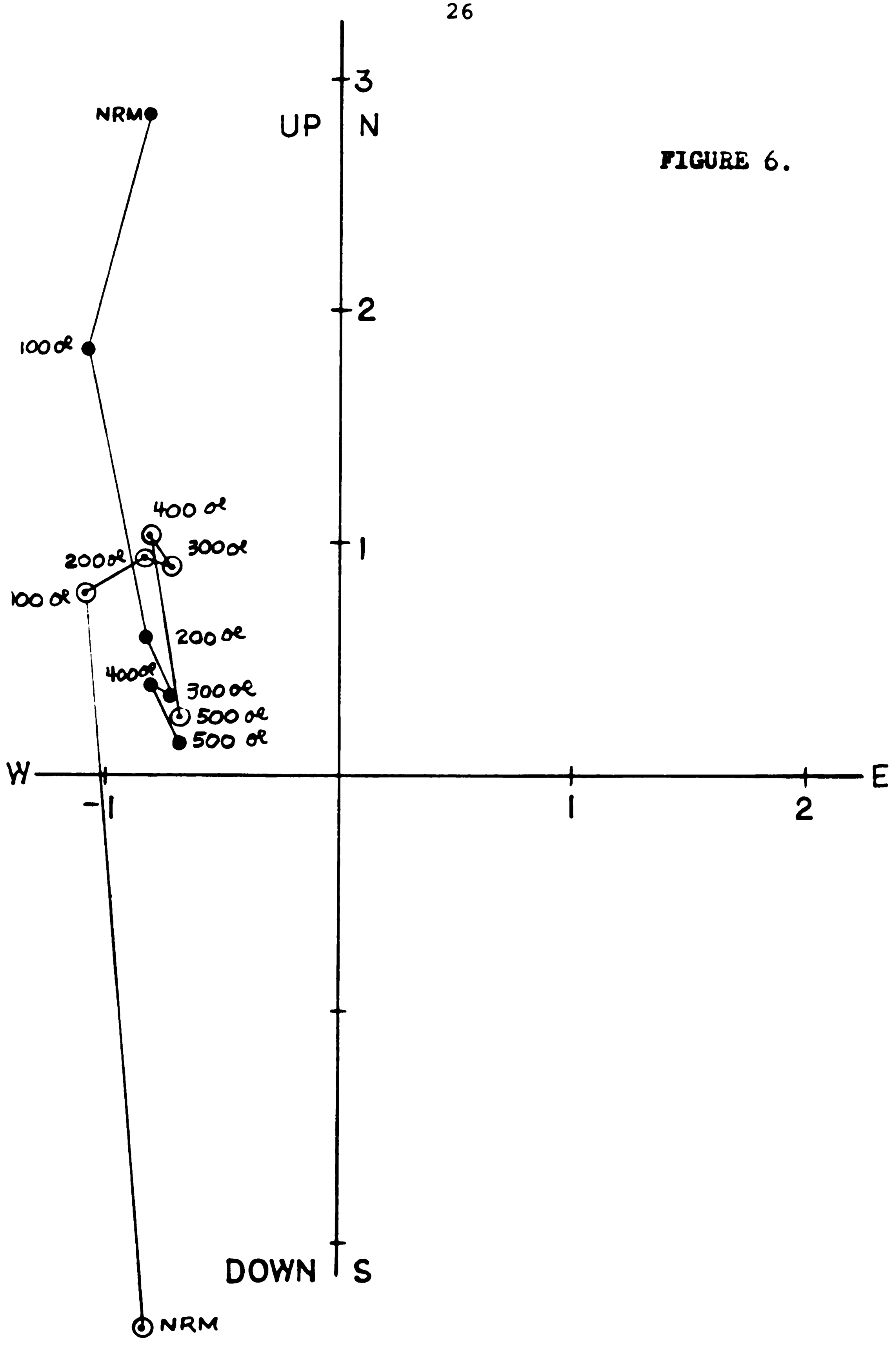

UP
N
DOWN
S
W
E
2
1
-1
-2
-3
-2
1
2
NRM
75 oe
150 oe
250 oe
350 oe
500 oe
650 oe

Figure 6. Typical Zijderveld Diagram for A.C. Demagnetized Gneiss (Sample A-5B).

Solid circles are in the horizontal plane; open circles are in the vertical plane; units are times 10^{-5} emu/sample.

FIGURE 6.



3
UP
N
NRM
2
100 oe
1
400 oe
300 oe
200 oe
100 oe
200 oe
400 oe
300 oe
500 oe
500 oe
W
E
-1
1
2
DOWN
S
NRM

Figure 6a. Resultant Vector Subtraction Diagram for A-5B.

Vectors to open circles are in the vertical plane; vectors to solid circles are in the horizontal plane; units are times 10^{-5} emu/sample.

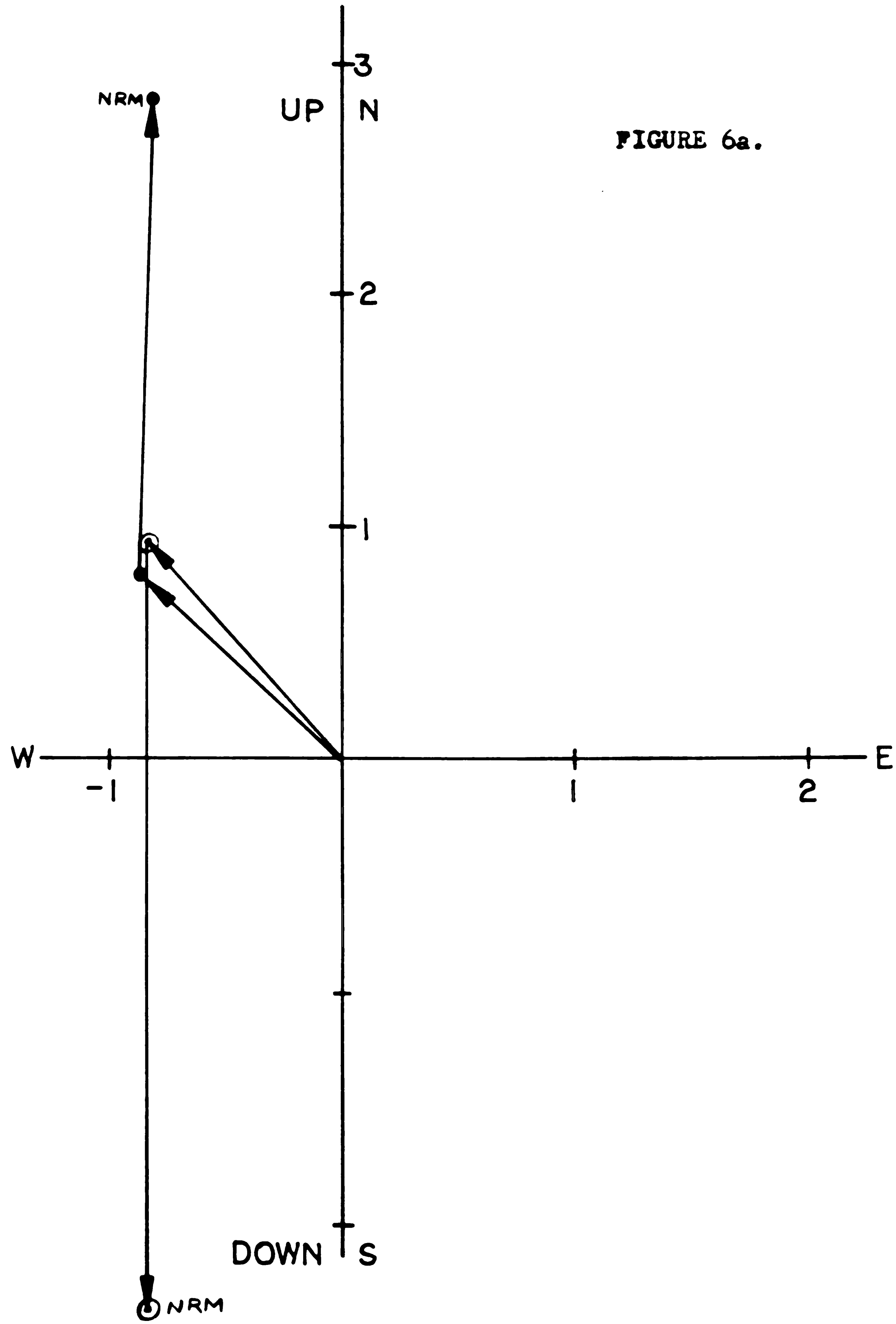


FIGURE 6a.

Figure 7. Typical Thermal Demagnetization Diagram for Gneiss (Sample A-5A).

Open circles are in the vertical plane; solid circles are in the horizontal plane; units are 10^{-5} emu/sample.

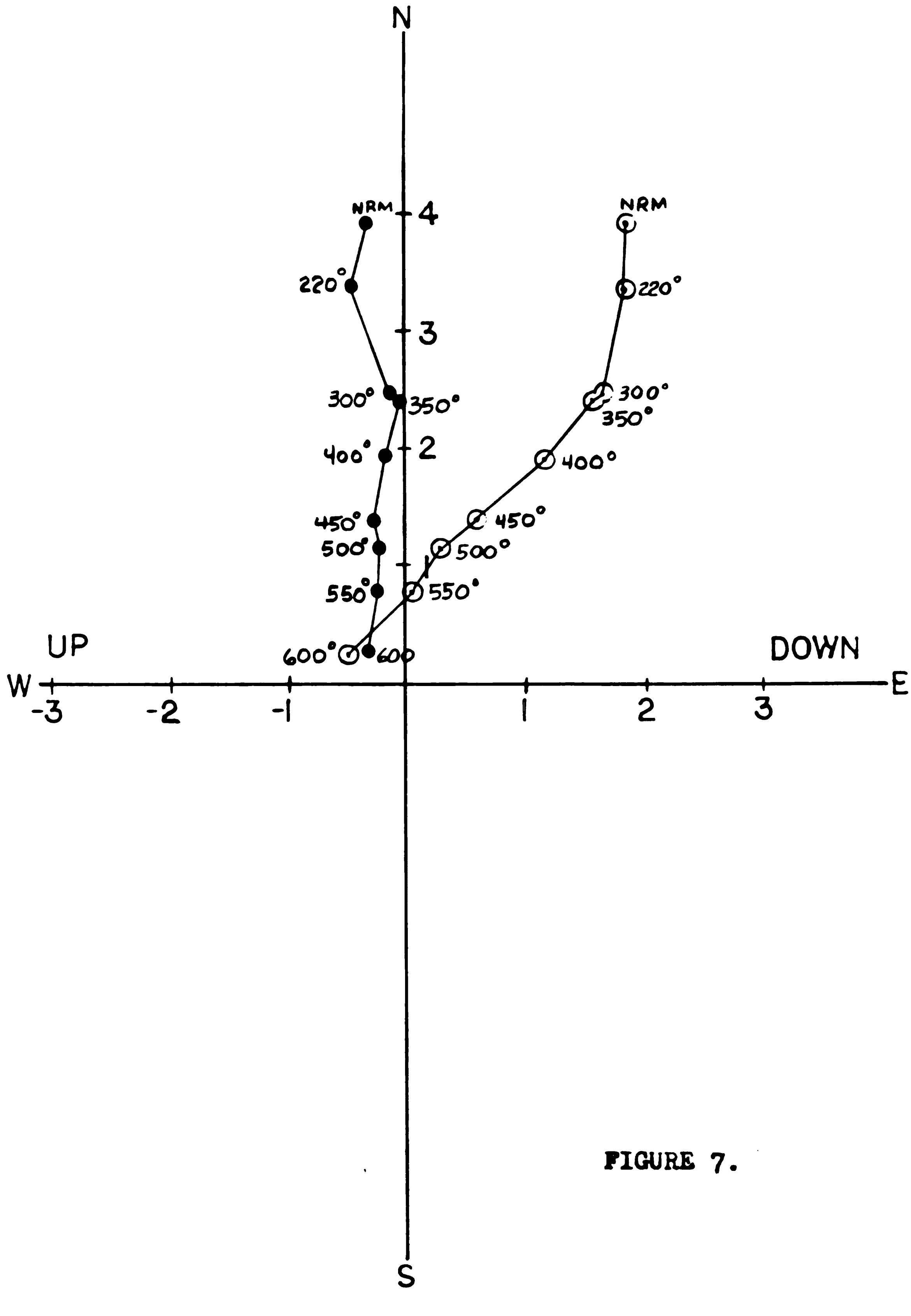

N
S
W
E
UP
DOWN
NRM
220°
300°
350°
400°
450°
500°
550°
600°
600
4
3
2
1
-3
-2
-1
1
2
3

FIGURE 7.

Figure 7a. Resultant Vector Subtraction Diagram for A-5A.

Vectors to open circles are in the vertical plane; vectors to solid circles are in the horizontal plane; units are times 10^{-5} emu/sample.

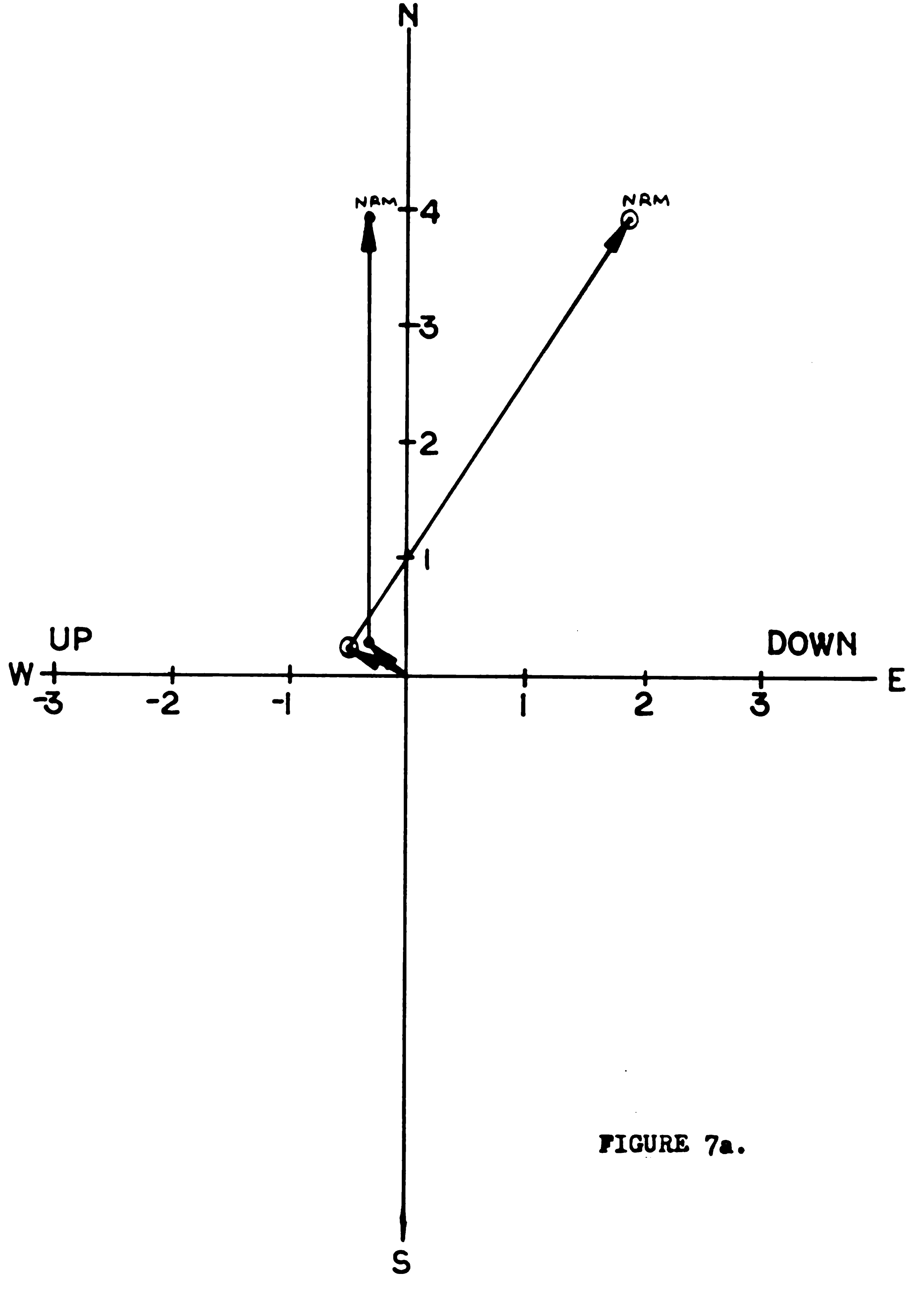


FIGURE 7a.

Figure 8. Typical Diagram for Thermally Demagnetized Metadiabase (Sample 2-1B).

Open circles are in the vertical plane; solid circles are in the horizontal plane; units are times 10^{-5} emu/sample.

FIGURE 8.

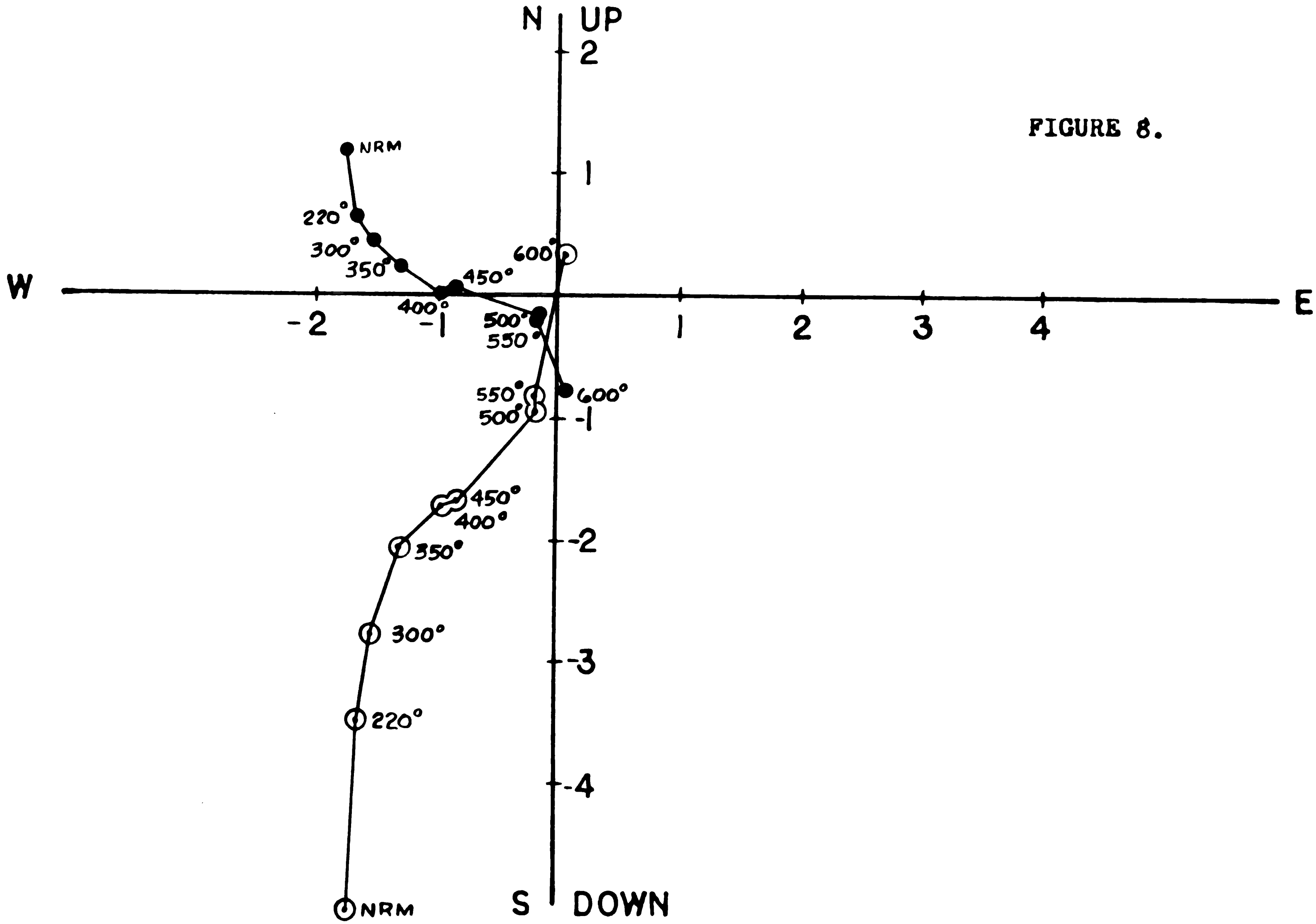

N
UP
S
DOWN
W
E
2
1
-1
-2
-3
-4
-2
-1
1
2
3
4
NRM
220°
300°
350°
400°
450°
500°
550°
600°
600°
550°
500°
450°
400°
350°
300°
220°
NRM

Figure 9. Typical Zijderveld Diagram for Baked Gneiss (Sample C-8B).

Open circles are in the vertical planes; solid circles are in the horizontal plane; units are times 10^{-5} emu/sample.

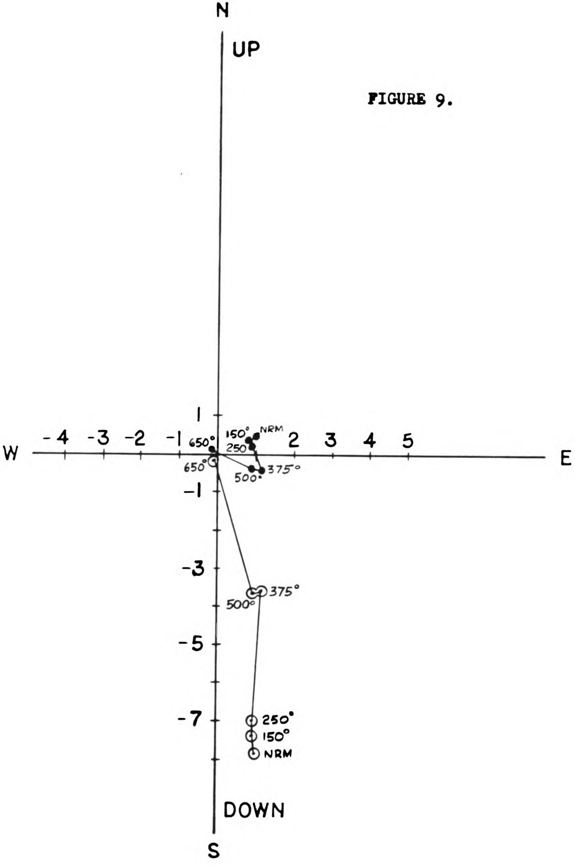
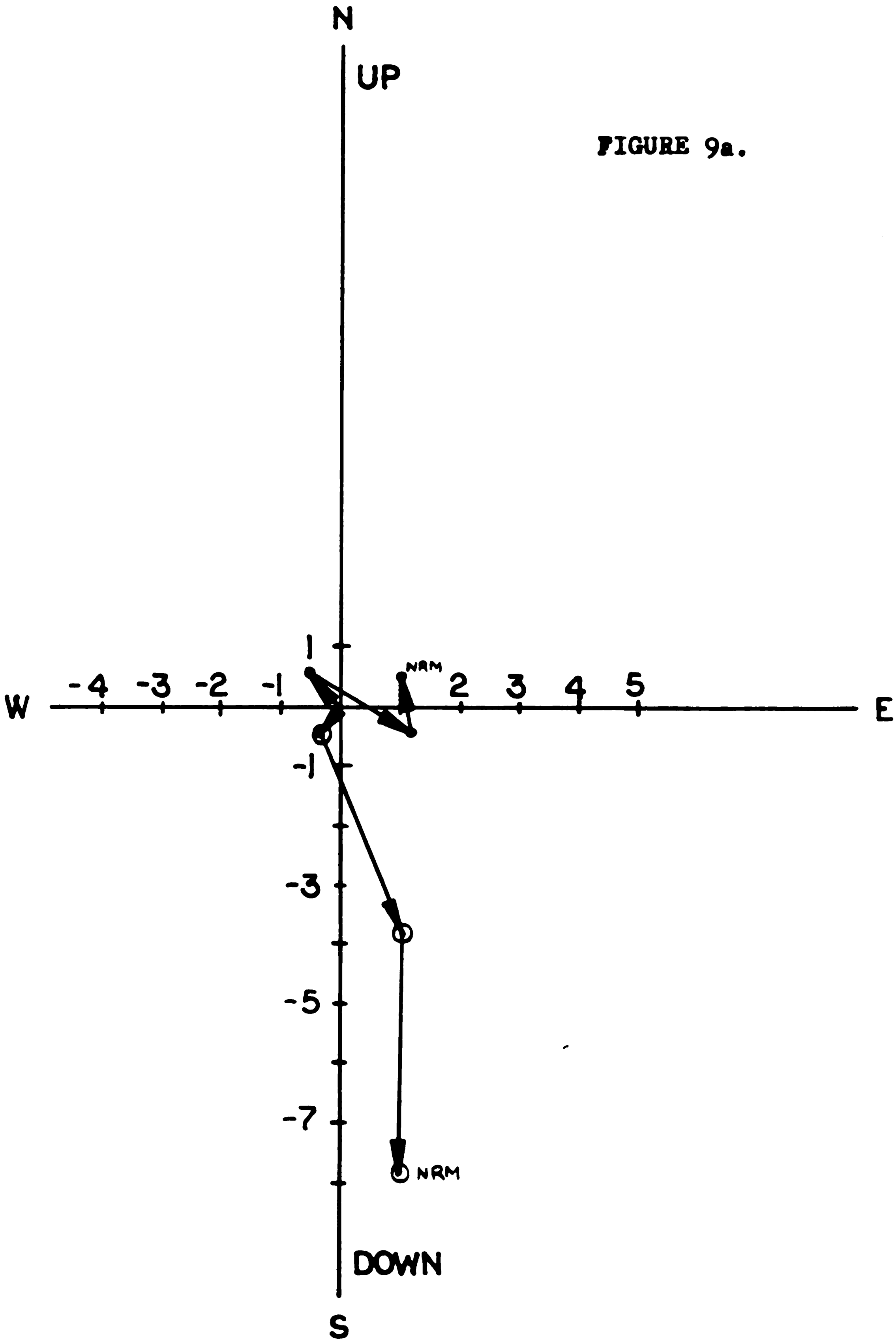

N
UP
-4
-3
-2
-1
1
2
3
4
5
W
E
150°
NRM
250
650°
650°
500°
375°
-1
-3
375°
500°
-5
-7
250°
150°
NRM
DOWN
S

FIGURE 9.

Figure 9a. Resultant Vector Subtraction Diagram for C-8B.

Vectors to open circles are in the vertical plane; vectors to solid circles are in the horizontal plane; units are times 10^{-5} emu/sample.

FIGURE 9a.



unbiased in their treatment of data (inevitably some bias must occur when the programmer creates the program). Graphical methods, on the other hand, are typically slower, more approximate, and more likely to be biased; while bias is normally something to be avoided, in this case it can be valuable since it allows the experimenter the ability to vary parameters and incorporate information in ways not readily programable. Ideally use of computers and Zijderveld diagrams should compliment each other in yielding similar results, that occurs in this study with more use being made of Ziderveld diagrams due to their simplicity of use and clearity of results. During thermal demagnetization, at any given temperature the vector measured is the sum of the T.R.M. and any secondary components formed at temperatures higher than the one used. If all goes well, as the step temperature is increased, more and more domains will be randomized till all secondary components are destroyed and only the original T.R.M. is left. Finally the Curie temperature is reached and all remanent magnetization is destroyed. This method in particular lends itself to analysis on Zijderveld diagrams where, working from the origin out, one encounters and can identify the poles due to intrusion, metamorphis, and the viscous effects of the Earth's field (Figures 10 and 11).

Figure 10. Intensity Spectra for A.C. Demagnetized Gneiss.

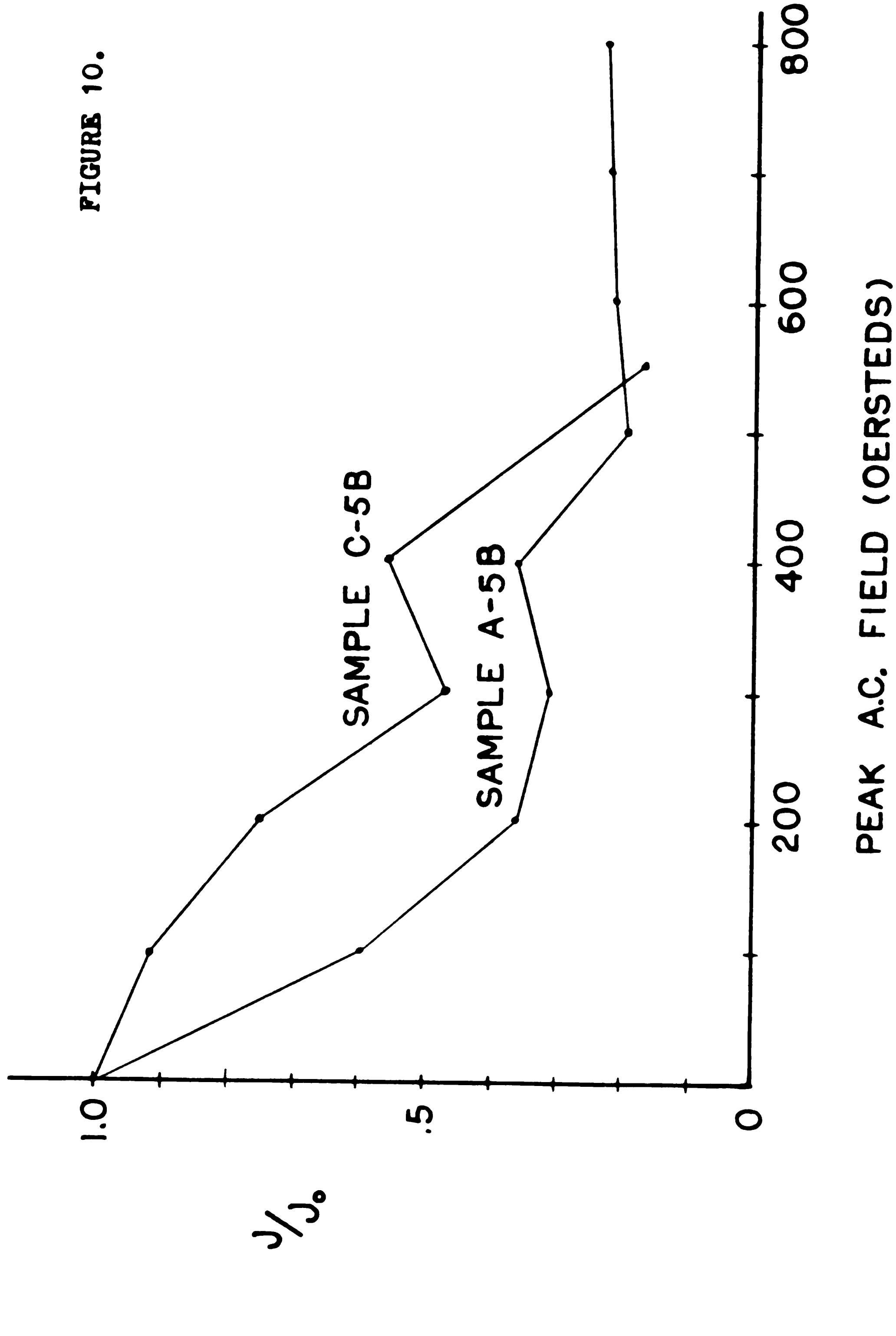
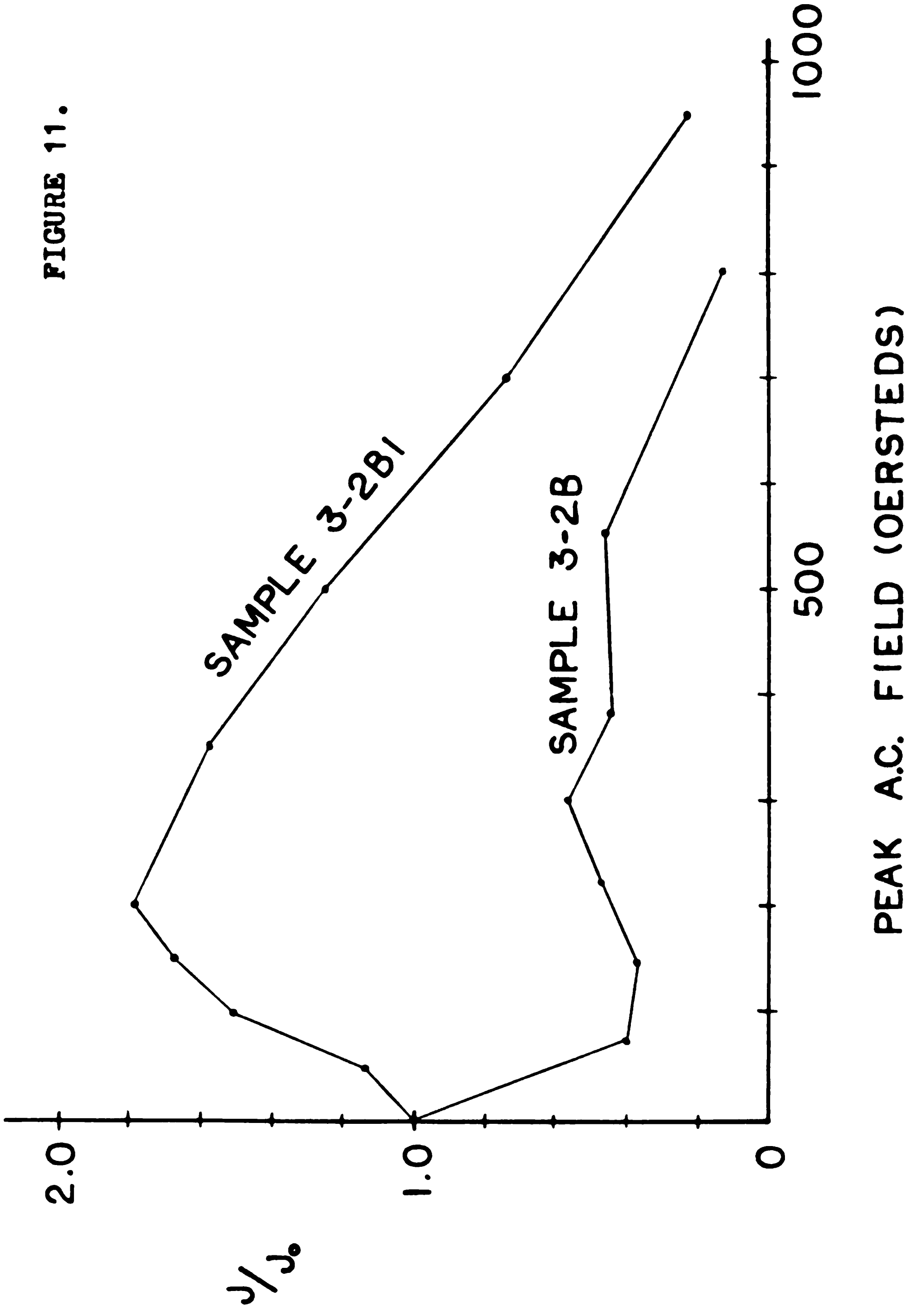

J/J₀
1.0
.5
0
200
400
600
800
PEAK A.C. FIELD (OERSTEDS)
SAMPLE C-5B
SAMPLE A-5B

FIGURE 10.

Figure 11. Intensity Spectra for A.C. Demagnetized Metabiabase.

FIGURE 11.


SAMPLE 3-2BI
SAMPLE 3-2B
J/J₀
2.0
1.0
0
500
1000
PEAK A.C. FIELD (OERSTEDS)

Sampling Techniques and Sample Preparation

Irving describes a set of minimum criteria that must be met for the acceptance of paleomagnetic data (Irving, 1964), foremost among these criteria is "that there be consistent observations from five or more separately oriented samples" (per lithologic units). However, since the true age of the dikes was unknown and also the temporal and lithologic continuity of one dike to another uncertain, every attempt was made to collect five separate blocks of each lithologic type (gneiss and/or metadiabase) at each of the seven sites in order that dates from each site could be established separately and then compared to each other. As it turned out, one of the original seven sites could not be used in the study, however, this did not effect the statistical validity of the dates obtained for the other sites. Although McElhinny has proposed that the minimum number of separately oriented sample blocks be eight instead of five, he allows the acceptance of data with fewer than this number if they were drawn from several sites and their poles agree with each other. So, in either case this study meets the minimum requirements and more.

The most important aspect of the field sampling scheme, next to obtaining enough sample blocks, is a test to independently establish the stability of the pole over geologic time, apart from any statistical tests. As mentioned earlier, the method of choice is the "baked contact test" (McElhinny, 1973, and Irving, 1964). "When an igneous rock intrudes a rock formation at a time subsequent to the formation of the latter, the intrusion heats the surrounding rock which upon cooling will acquire a remanence in the same field as that in which the intrusive rock becomes magnetized. Since the country rock and the igneous intrusion are generally very different materials, agreement between the direction of the intrusion and of the country rock provides evidence for the stability of the magnetization of the intrusion" (McElhinny, 1973). For that reason gneiss and metadiabase were collected together at all possible sites. So, at each of the earlier described sites various insitu blocks were selected, oriented by Brunton compass, labeled, recorded, and removed. Preparation of the blocks for paleomagnetic analysis required that they be reoriented in the laboratory, cut, and cored. Depending on the size of the original oriented block, anywhere between two and six specimens were cut and analyzed. Error amassed during these steps was probably less than 5° per sample-block, far less than the variability between specimens from the same block. Therefore, for reasons of practicality, the errors encountered up to this point were carried forward into the analysis of specimens and incorporated into the plotting of poles.

Analysis

Once prepared, the cores were transported to the University of Michigan's Paleomagnetic Laboratory where, with the help of Dr. Rob VanDerVoo and Doyle Watts, the analysis of the magnetic vectors took place. Enough samples were prepared to do at least one A.C. and one thermal demagnetization per oriented block, though usually there were enough to do two of each. Typical step demagnetization measurements were taken for A.C. samples at: N.R.M., 100 oe, 200 oe, 300 oe, 400 oe, 500 oe, 600 oe, and 700 oe. Due to the age of the A.C. specimen demagnetizer, peak fields above 500 oe sometimes caused the solenoid to induce an antihysteretic component in the samples. For that reason measurements above this value are usually excluded (Figure 7).

Superparamagnetism, an interesting phenomena, was noted in some of the more highly sheared metadiabases at A.C. fields above 300 oe and at temperatures above 450°C (Figures 12 and 13). This effect develops when extremely small domains (below .03 microns for magnetite) are randomized by A.C. or thermal means. The relaxation energy of these randomized domains is such that when they are perturbed by even a very weak magnetic field they align themselves parallel to it. Although part of this magnetism can be observed to decay during the time of a measurement, the bulk will not decay for many hours or days, effectively masking the weaker remanent vector for that length of time (McElhinny, 1973).

Due to their extremely low intensity, the magnetism of the majority of the metadiabase samples and all the gneiss samples were determined on the U of M's cryogenic magnetometer. Sample intensities ranged between 6×10^{-3}

Figure 12. A.C. Intensity Spectra for Superparamagnetic Samples.

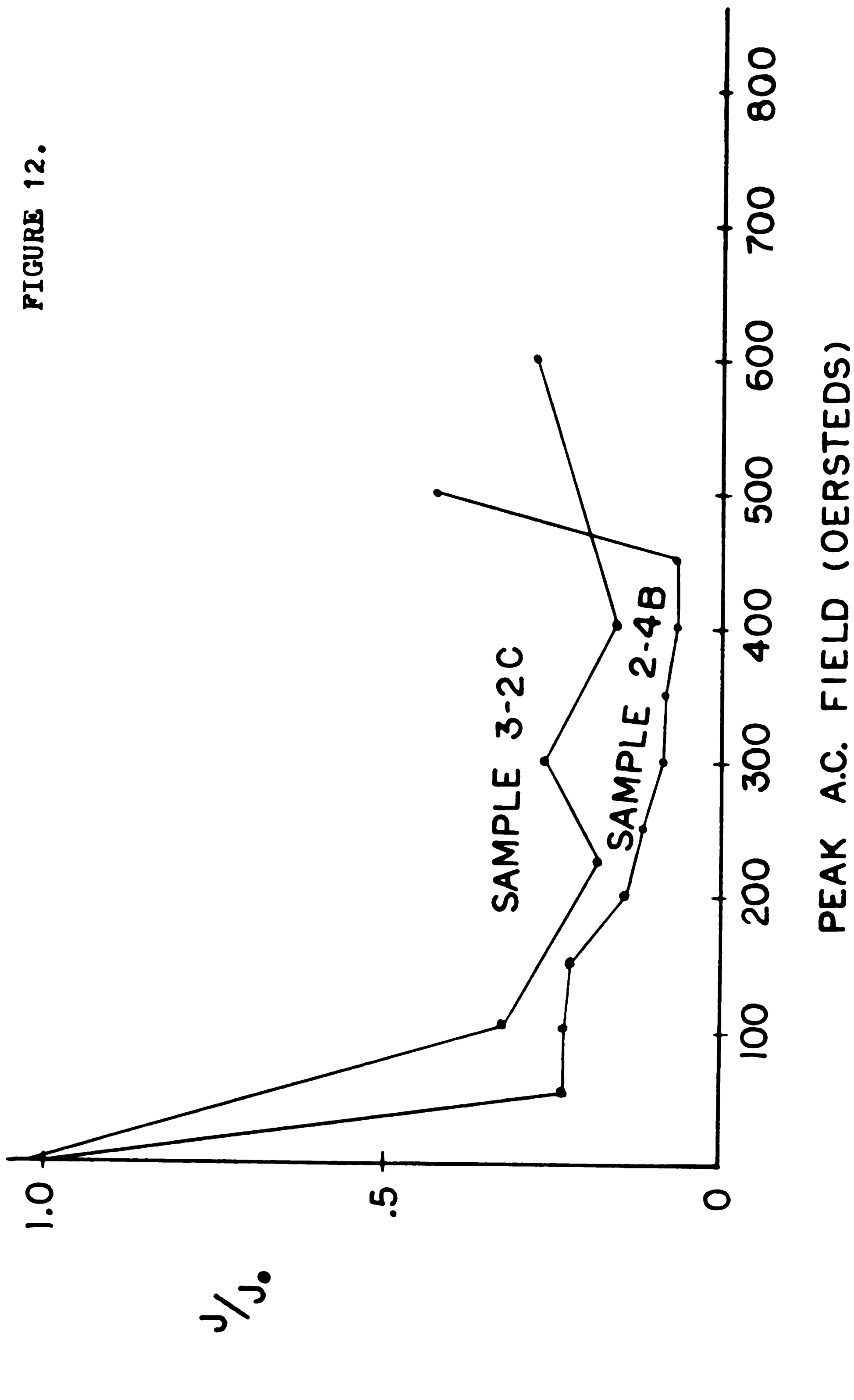

J/J₀
1.0
.5
0
100
200
300
400
500
600
700
800
PEAK A.C. FIELD (OERSTEDS)
SAMPLE 3-2C
SAMPLE 2-4B

FIGURE 12.

Figure 13. Thermal Intensity Spectra for Superparamagnetic Samples.

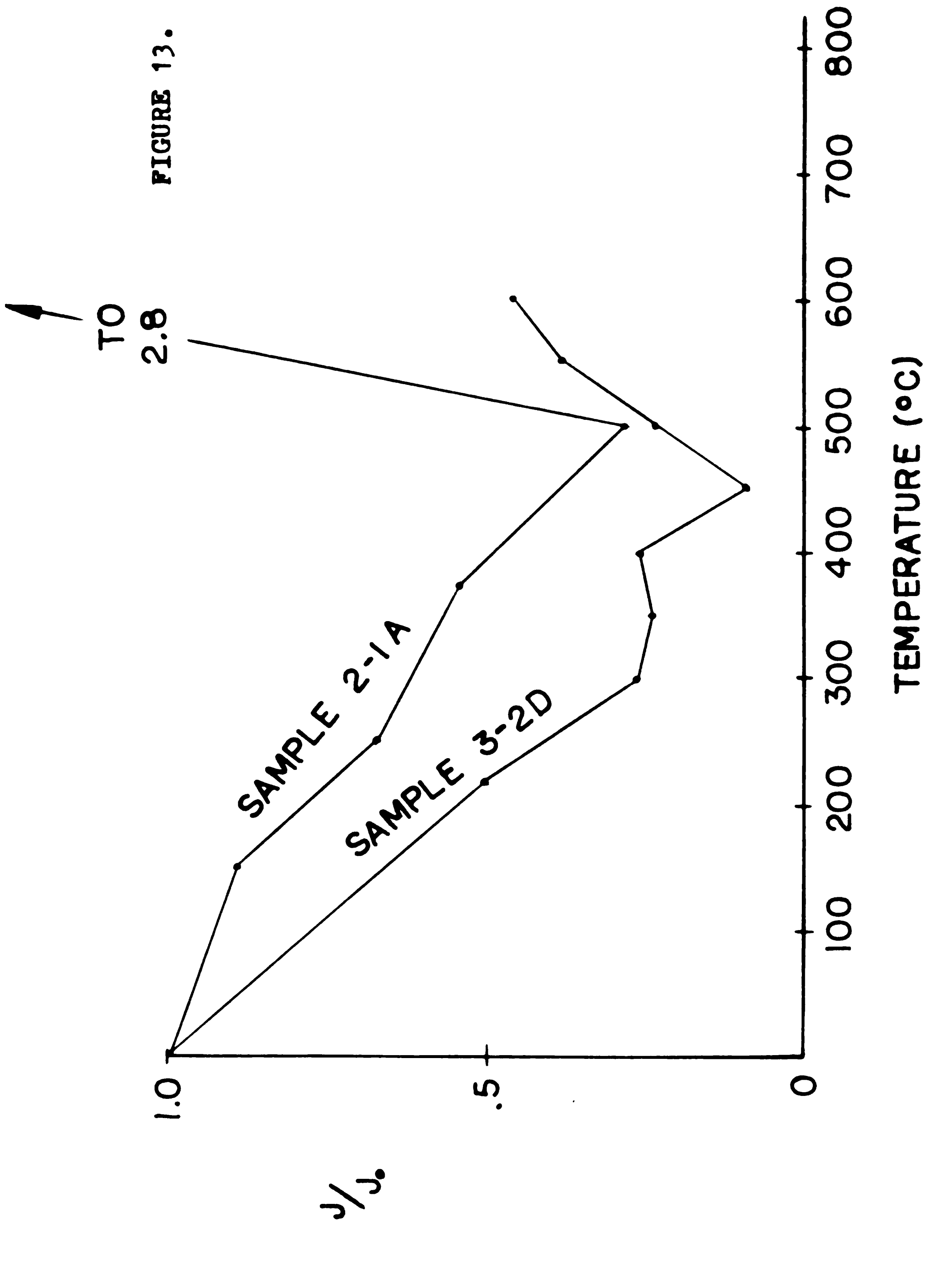

TO
2.8
SAMPLE 2-1A
SAMPLE 3-2D
1.0
.5
0
J/J₀
100
200
300
400
500
600
700
800
TEMPERATURE (°C)

FIGURE 13.

and 5 x 10^{-8} emu/cc and averaged about 1 x 10^{-5} emu/cc. The balance of the more strongly magnetized samples being measured on the spinner magnetometer.

Results and Discussion

Once the specimens were step demagnetized, the data were transfered onto Zijderveld diagrams and analysed to yield pole positions and blocking temperatures-fields. Among the gneiss samples blocking temperatures were typically bimodal (three magnetic components). In all cases a low temperature (low coercivity) V.R.M. (viscous remanent magnetism) component existed, separated between 150° and 300°C and below 150 oe associated with the Earth's present field direction, and in baked gneiss an intermediate and high temperature component separated between 550° and 650°C and corresponding to the separation of the Penokean P.T.R.M. (partial thermal remanent magnetism) metamorphic pole from the T.R.M. due to the intrusion of the metadiabase (Figures 9 and 9a). In those gneisses not baked by metadiabase, a low temperature viscous pole (280°C) could be separated from the original T.R.M. of the gneiss (Figures 7 and 7a).

Blocking temperatures for the metadiabase are also bimodal but tend to occur at lower temperatures than the gneiss. However, a great difficulty was encountered due to the tendency of samples to become superparamagnetic below temperatures where useful blocking phenomena could be expected. Still there were enough specimens that did not become superparamagnetic to establish the existence of a low temperature V.R.M. pole (present day Earth's field), a P.T.R.M. metamorphic pole and the original T.R.M. pole separated between 300° and 500°C (Figure 8).

Analysis of the paleopoles derived from the unmetamorphosed diabase and associated baked gneiss samples showed that the poles for both are basically unimodal about one mean pole with the slight amount of scatter attributably to minor isothermal viscous effects (Site B, Figure 17).

As was mentioned earlier, many metadiabase dikes often display sheared margins and a foliation, both believed to have been impressed during the Penokean Orogeny. While it can be argued that the pre-metamorphic paleopoles should have been rotated during the metamorphism into accordance with the shears, this appears not to have happened. Alternatively, it can be argued that since the poles for metadiabase dikes oriented at different angles to the direction of Penokean compression agree closely with poles for baked gneiss samples (Figures 14, 15, 16, and 17) this shows that insitu recrystalization of minerals within dikes, in response to stress, is more important than physical shearing in producing a foliation.

Specimen poles determined for a particular lithology (gneiss or metadiabase) and site were then grouped together according to the order in which they were thermally blocked out. These groups were then put into a computer program (Appendix A) designed to analyze statistically their scatter,

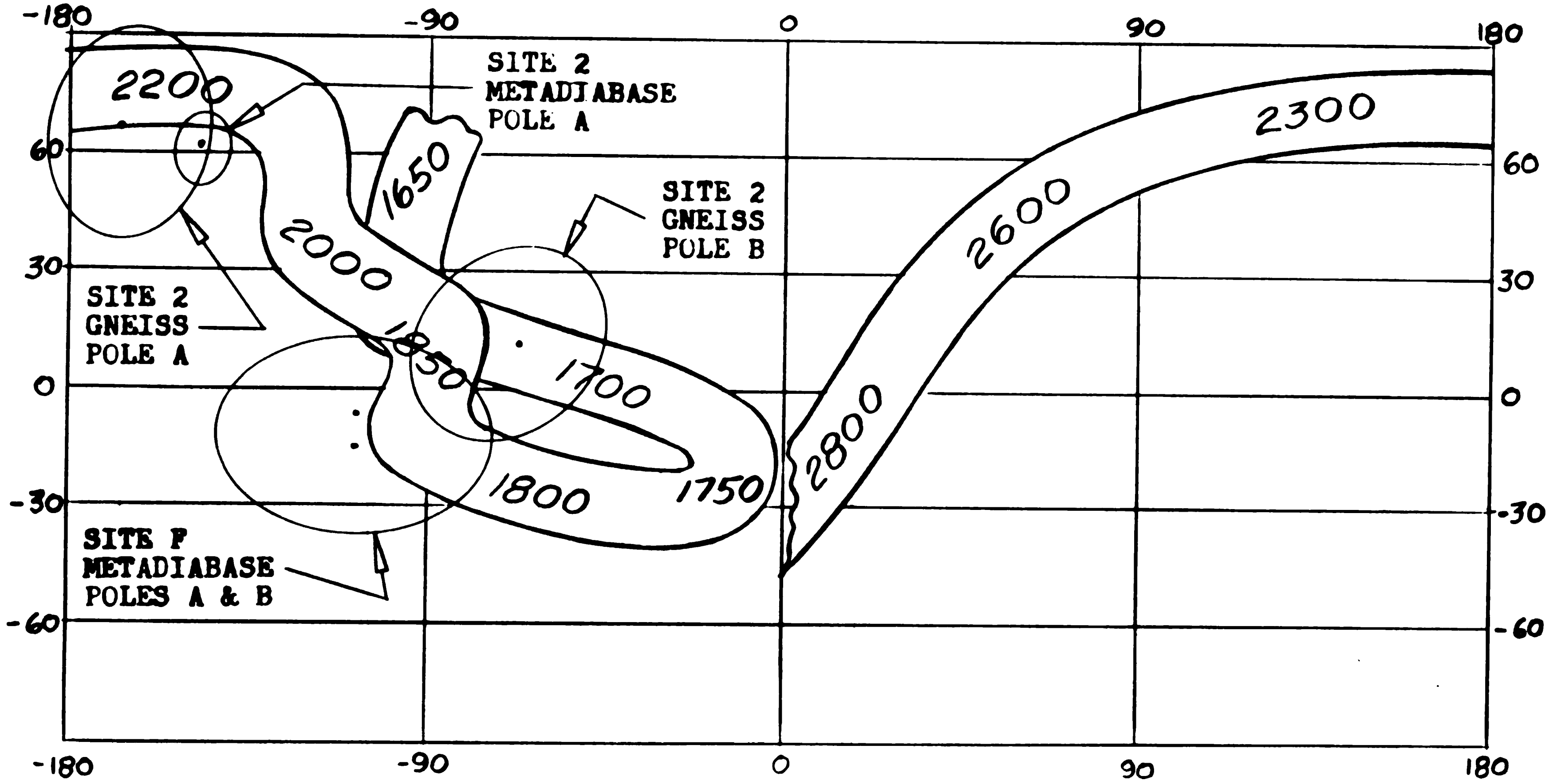


FIGURE 14 - APPARENT POLAR WANDER PATH AND POLES FOR SITES 2 AND F

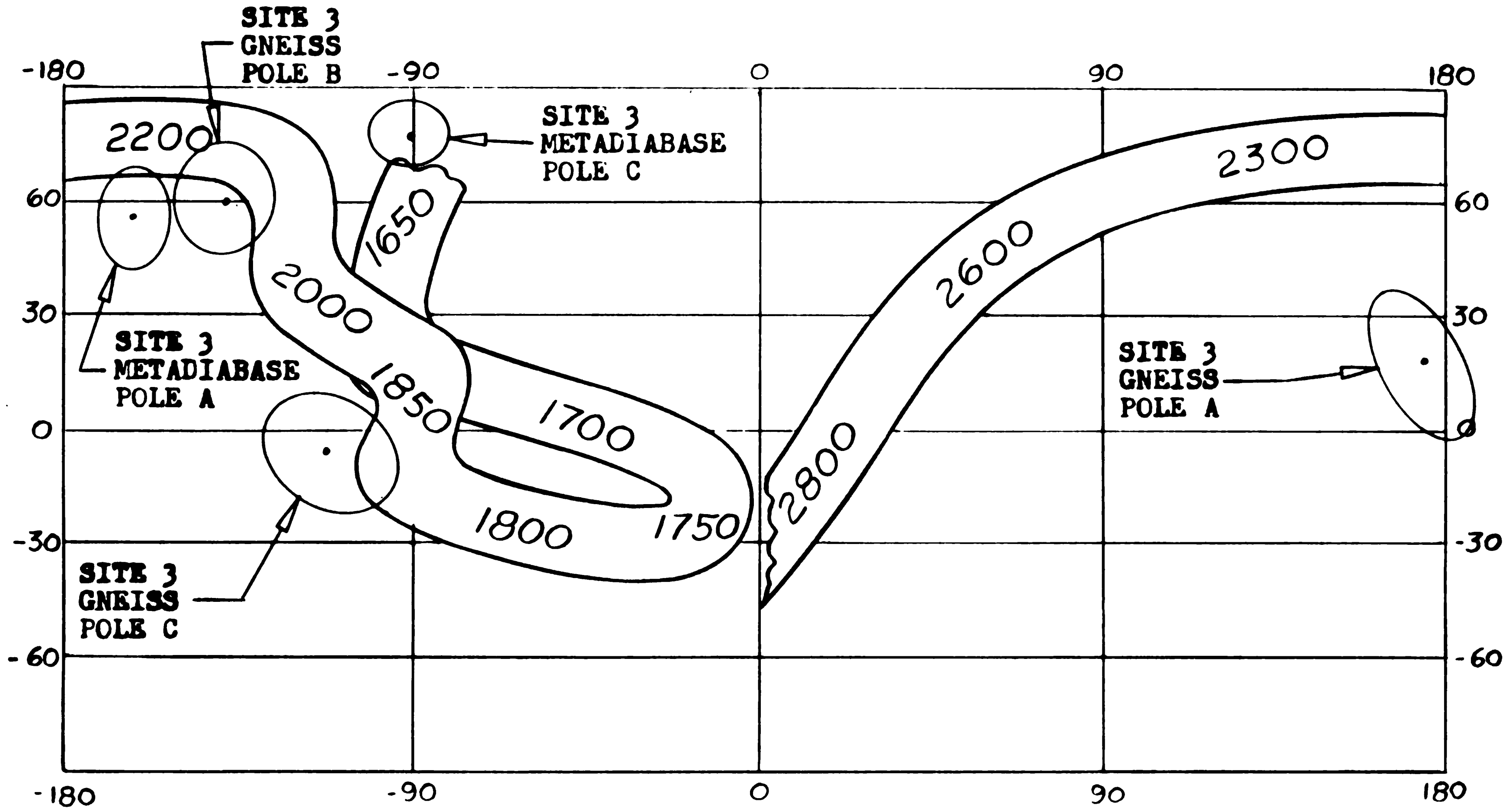


FIGURE 15 - APPARENT POLAR WANDER PATH AND POLES FOR SITE 3

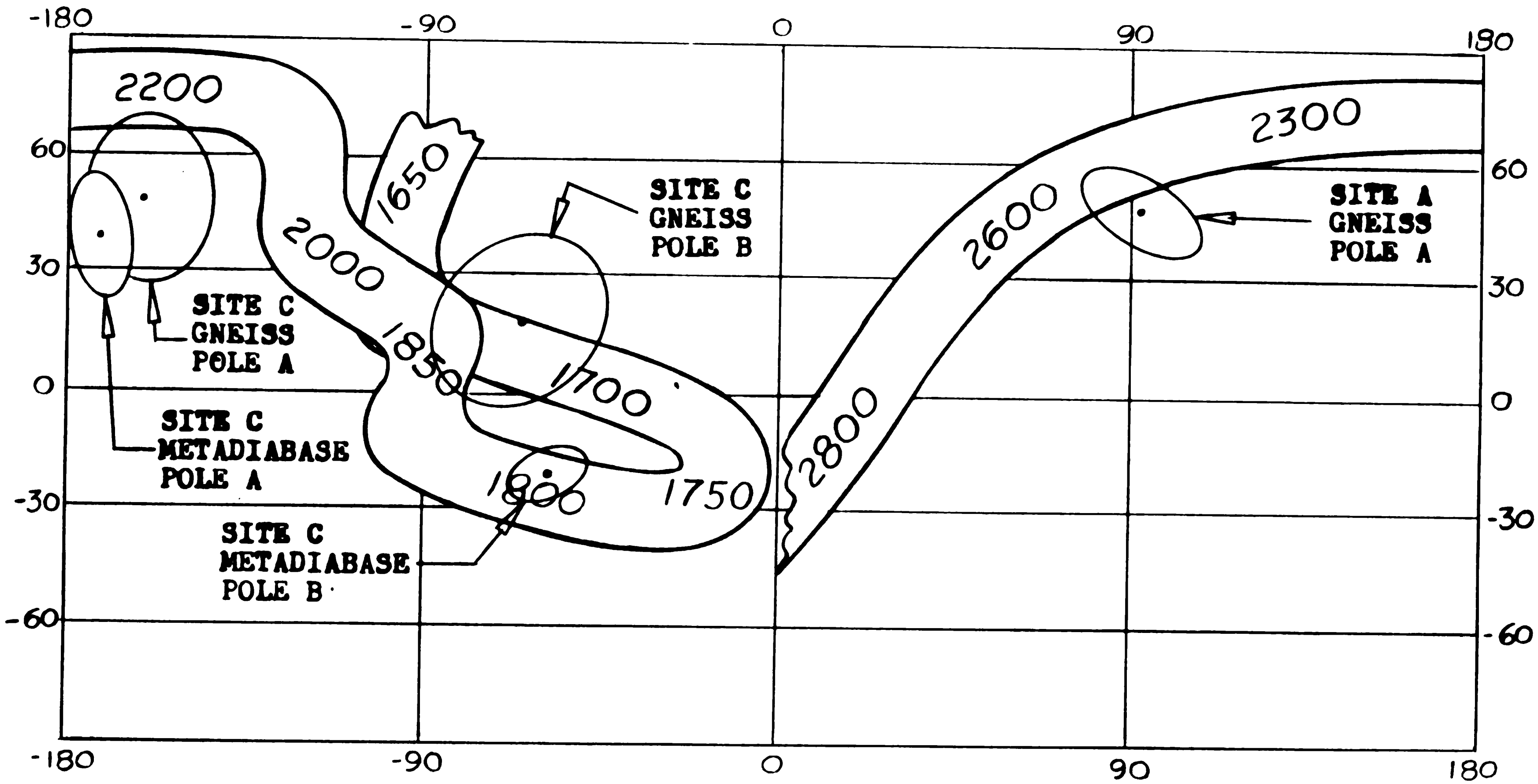


FIGURE 16 - APPARENT POLAR WANDER PATH AND POLES FOR SITES A AND C

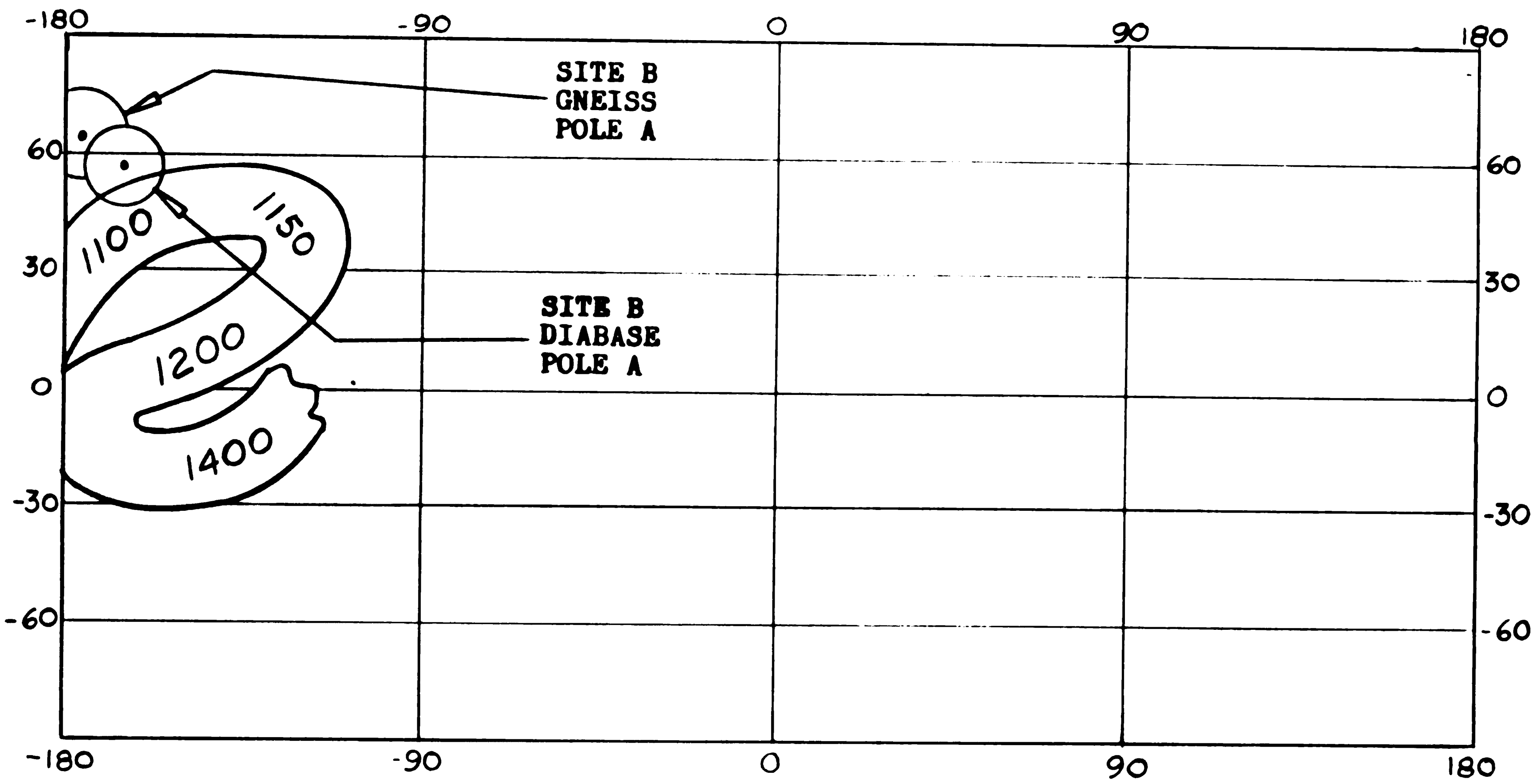


FIGURE 17 - APPARENT POLAR WANDER PATH AND POLES FOR SITE B.

determine a mean pole inclination and declination, and a V.G.P. (virtual geomagnetic pole) latitude and longitude, in accordance with Fisher's criteria as outlined by Irving (1964). While a list of pole positions and results from tests can be found following the text in Appendix A, a summary of V.G.P. results for each site and the 95% confidence ellipse are printed superimposed on the revised A.P.W. path (Irving, 1979) in the preceding figures (Figures 14, 15, 16, and 17). Each 95% confidence ellipse represents the effective summation of errors amassed in previous procedures. Dates found on the A.P.W. paths are in millions of years. Roughly speaking, A.P.W. paths are constructed for a recognized continential unit by comparing and connecting the paleomagnetic pole positions from isotopically dated (or after the Precambrian, stratigraphically dated) samples. The A.P.W. path thus forms a concise way to picture the magnetic stratigraphy of a continent which of course bears on the nature of the orogenic and tectonic activity that formed the continent. For that reason there are different A.P.W. paths designed for different continents and for different time periods (though for one continent they will ideally be continuous through time).

A.P.W. paths for the Precambrian tend to be more speculative than for the Phanerozoic due to their dependence on isotopic dates (often difficult to obtain) to fix the poles at the proper times, due to effects of later metamorphisms, fragmentary records, and due to the possibilities of several coexisting continental fragments instead of one unified mass. For this reason the A.P.W. tract for Precambrian times is a fairly wide path with a total error width of 20° (± 10° from the center of the tract). Still in all, a relatively simple, reasonably well documented A.P.W. path has been constructed by Irving (1979) for the Precambrian back to about 2.35 G.a. beyond which, he admits, the path rapidly becomes more speculative as information about those times decreases. Still, for those times it is better than no path at all.

As can be seen in the previous figures (Figures 14 and 16), the high temperature T.R.M. poles for the baked gneisses and metadiabases range between the 2.13 and 2.19 G.a. section of the A.P.W. tract with reasonably small error ellipses. This then is the suggested date of intrusion of the metadiabase dikes into the gneiss. The high values of the precision (Fisher, 1953), the high correspondence between the metadiabase poles and the baked gneiss poles for the "baked contact test," and the close grouping of poles between the three sites indicate that this date is of high reliability. Furthermore, the thermal stability of the baked gneiss can be demonstrated by its acquisition and maintainance of reversed Keweenawan magnetization imparted to it during the intrusion of the Site B dike, almost a billion years after the last event in the area. The unbaked gneiss yields a T.R.M. pole directly on the A.P.W. path dating it at about 2.5 G.a. Although of lower absolute reliability than the previously discussed poles, the author considers this pole to be as accurate and reliable as the first, due to the coincidence of the dated pole position and the times given for the intrusion and metamorphism of the gneiss during the Algoman Orogeny (King, 1969). The P.T.R.M. metamorphic poles are of lowest reliability in this study. Although the values range from 1.91 to 1.85 G.a., spanning the period often quoted for the Penokean Orogeny in this area, the scatter of some of the individual poles has become quite great, as seen by the larger error circles. Although a greater amount of scatter among these poles is expected from magnetic theory (the lower the blocking temperature the more susceptible the pole is to perturbations of position during the course of time), the P.T.R.M. metamorphic poles for metadiabase of Site 2 and 3 must be excluded from interpretation because they violate Irving's third criteria of reliability, requiring better than a 25° radius of confidence. Although usually of little significance in Precambrian studies, it is interesting to note that the Penokean poles are made up of two groups, one normal and one reversed in magnetization. While both determine the same V.G.P. pole it is possible that a magnetic reversal may have occurred during the cooling following the metamorphism and was recorded by the paleopoles. Finally the lowest temperature V.R.M. pole, calculated for selected sites, was found to coincide with the present day Earth's field (Figure 15, Site 3, metadiabase pole C). All told, the poles determined in this study more than satisfy all of Irving's minimum reliability requirements and in the opinion of the author represent valid Precambrian paleopoles.

Four thermal events have then been defined by the paleomagnetics, which, when combined with the regional geology, will allow a possible thermal history to be constructed for this area. The original T.R.M. pole in the Compeau Creek Gneiss (Site A), dated at about 2.5 G.a., corresponds to either the original gneiss intrusion or its intense deformation during the Algoman Orogeny. Following a period of little tectonic activity, the gneiss was intruded by metadiabase at about 2.16 G.a. This reset the gneiss poles in the dike wall region (Sites 2, 3, and C) and is suspected to be coincident with the faulting and subsidence which led to the development of the Marquette Trough. The Trough itself appears as a marginal or intracratonic basin with similarities to the fault bounded Triassic basins on the Atlantic coast. In this case the metadiabase would be associated with the incipient rifting and active motion in the grabens between the two Archean terrains. Although no decisive paleomagnetic evidence can be offered to decide whether there was a narrow or wide ocean basin associated with this rifting, the amount of time between the hypothesized period of trough opening and its closure, folding, and metamorphism during the Penokean Orogeny is enough to permit the development of quite a major ocean (Cambray, 1976). Finally another period of relative quiet ended at about 1.11 G.a. when the area was subjected to another series of diabase intrusions and incipient rifting (Chase and Gilmer, 1973). The intrusion of the diabase reset the gneiss poles in the vicinity of the dike (Site B), yielding the date mentioned. Apart from some possible Eocambrian sedimentation and minor uplifts, the tectonic history of the area was ended.

In summary, probably the only serious problem that can arise in accepting the previously stated pole positions and dates is attributable to the metamorphic effect on the blocking temperature magnetization (Chamalaun, 1964 and Briden, 1965). McElhinny (1973) suggests that during metamorphism, if the temperatures are either high enough (contact metamorphism) or lasted a long enough time at lower temperatures (regional metamorphism), the blocking temperatures could be so affected that any original T.R.M. magnetism would be completely destroyed, as is the case in the baked gneisses. Comparisons using these data show that temperatures and times may have been enough in this region to obliterate any magnetism older than the Penokean metamorphism. However, other authors in more recent publications (Buchan and Dunlop, 1976 and Pullaiah, Irving, Buchan, and Duplop, 1975) have questioned the extent to which regional metamorphism can effect an original T.R.M. pole. Results from the experiments they carried out led them to suggest that in rocks with a stable remanent magnetization, the original T.R.M. vector can survive intact and detectable after metamorphism into the Upper Greenschist facies (Pullaiah et al., 1975). Although it must be stressed that there are problems in the paleomagnetic analysis of rocks of this age, the results of these studies offer additional reassurance beyond the aforementioned success of the "baked contact test," agreement of poles between sites, and the corroboration from statistical tests, that the poles determined in this study are valid.

CONCLUSIONS

A summary of the findings of this study are as follows:

1. Standard paleomagnetic techniques will succeed when applied to the meta-igneous rocks of the Marquette area.
2. The Compeau Creek Gneiss is paleomagnetically dated at 2.5 G.a. ± .06 G.a., which is in good agreement with dates for the Algoman Orogeny.
3. The date of metadiabase intrusion into the study area is determined to be 2.18 G.a. ± .04 G.a.
4. The P.T.R.M. metamorphic overprint found in both the gneiss and metadiabase is dated at 1.88 G.a. ± .04 G.a. which is consistent with dates given for the Penokean Orogeny in this area.
5. Intrusion of the Keweenawan Series dikes into the gneiss is dated at 1.11 G.a. ± .02 G.a.

BIBLIOGRAPHY

BIBLIOGRAPHY

Berger, A. R. "Dynamic Analysis Using Dikes with Oblique Internal Foliations." Geol. Soc. Am. Bull., v. 82, 1971, pp. 781-786.

Briden, J. C. "Ancient Secondary Magnetizations in Rock." Jour. Geophysical Research, v. 70 (1965), 5205-5221.

Buchan, K. L., and D. J. Dunlop. "Paleomagnetism of the Haliburton Intrusions: Superimposed Magnetizations, Metamorphism, and Tectonics in the Late Precambrian." Jour. of Geophysical Research, v. 81 (1976), 2951-2967.

Burke, K. and J. F. Dewey. An Outline of Precambrian Plate Development in Continental Drift, Sea Floor Spreading and Plate Tectonics. New York: Academic Press, 1973.

Cambray, F. W. Field Guide to the Marquett District, Michigan, May 14, 15, 1977, Michigan Basin Geological Society, 1977.

Cannon, W. F. "The Penokean Orogeny in Northern Michigan." Geol. Assoc. of Canada, Spec. Paper, No. 12, 1973.

Cannon, W. F. and J. E. Glair. "A Revision of Stratigraphic Nomenclatures for Middle Precambrian Rocks in Northern Michigan." Geol. Soc. of Am. Bull., v. 81, 1970, pp. 2843-2846.

Cannon, W. F. and G. Simmons. "Geology of Part of the Southern Complex, Marquette District, Michigan." Jour. Research U.S. Geol. Survey, v. 1, 1973, 165-172.

Chamalaun, F. H. "Origin of the Secondary Magnetization of the Old Red Sandstones of the Anglo-Welsh Cuvetete." Jour. Geophysical Research, v. 69 (1964), 4327-4337.

Chase, C. G. and T. H. Gilmer. "Precambrian Plate Tectonics: The Midcontinent Gravity High." Earth and Planetary Science Letters, v. 21, 1973, pp. 70-78.

Clark, L. D., W. F. Cannon, and J. S. Klasner. Bedrock Geologic Map of the Negaunee SW Quadrangle, Marquette County, Michigan, U.S.G.S., 1975.

Dewey, J. F. and J. M. Bird. "Mountain Belts and the New Global Tectonics." Jour. of Geophysical Research, v. 75 (1970).

Fisher, R. A. "Dispersion on a Sphere." Proc. Roy. Soc. London, v. A217, 1953.

Glair, J. E. and R. E. Thaden. "Geology of the Marquette and Sands Quadrangles, Marquette County, Michigan." U. S. Geological Survey Professional Paper 397, 1968.

Goldich, S. S., A. O. Nier, H. Baadsgaard, J. H. Hoffman, and H. W. Krueger. "The Precambrian Geology and Geochronology of Minnesota." Minnesota Geological Survey Bulletin, v. 41, 1961.

Hutchinson, R. W. and G. G. Engels. "Tectonic Evolution in the Southern Red Sea and its Possible Significance to Older Rifted Continental Margins." Geol. Soc. Amer. Bull., v. 83, 1972, pp. 2989-3002.

Irving, E. Paleomagnetism and Its Application to Geological and Geophysical Problems. New York: John Wiley and Sons, 1964.

Irving, E. "Paleopoles and Paleolatitudes of North America and Speculations about Displaced Terrains." Canadian Journal of Earth Sciences, v. 16 (1979), 669-694.

Irving, E. and J. C. McGlynn. "Proterozoic Magnetostratigraphy and the Tectonic Evolution of Laurentia." Phil. Trans. Roy. Soc. London, v. A280, 1976, pp. 433-468.

King, P. B. "The Tectonics of North America: A Discussion to Accompany the Tectonic Map of North America, Scale 1 : 5,000,000." U.S. Geological Survey Professional Paper 628, 1969.

McElhinny, M. W. Paleomagnetism and Plate Tectonics. Cambridge: Cambridge University Press, 1973.

Moorhouse, W. W. The Study of Rocks in Thin Section. New York: Harper and Row, 1959.

Morey, G. B. and P. K. Sims. "Boundry Between Two Precambrian W Terranes in Minnesota and Its Geological Significance." Geol. Soc. Am. Bull., v. 87, 1976. pp. 141-152.

Nagata, T. Rock Magnetism. Tokyo: Maruzen Co. LTD, 1961.

Pullaiah, G., E. Irving, Buchan, K. L., and D. J. Dunlop. "Magnetization Changes Caused by Burial and Uplift." Earth and Planetary Science Letters, v. 28, 1975, pp. 133-143.

Puffett, W. P. "Geology of the Negawnee Quadrangle, Marquette County, Michigan." U. S. Geological Survey Professional Paper 788, 1974.

Ramdohr, P. The Ore Minerals and Their Intergrowths. Oxford: Pergamon Press, 1969.

Shanabrook, D. C. "A Geophysical and Geological Study of the Basement Complex Along the Pesheke River, Marquette County, Northern Michigan." M.S. thesis, Michigan State University, 1978.

Sims, P. K. "Presidential Address--Precambrian Tectonics and Mineral Deposits, Lake Superior Region." Economic Geology, v. 71, No. 6, 1976.

Stacey, F. D. "The Koenigsberger Ratio and the Nature of Thermoremanence in Igneous Rocks." Earth and Planetary Science Letters, v. 2, 1967, pp. 67-68.

Stupavsky, M. and D. T. A. Symons. "Separation of Magnetic Components from A. F. Step Demagnetization Data by Least Squares Computer Methods." Jour. of Geophysical Research, v. 83 (1978), 4925-4931.

VanSchmus, W. R. "Early and Middle Proterozoic History of the Great Lakes Area, North America." Phil. Trans. Roy. Soc. London, v. A280, 1976, pp. 605-628.

Windley, B. F. The Evolving Continents. London: John Wiley and Sons, 1977.

Zijderveld, J. D. A. "A. C. Demagnetism of Rocks: Analysis of Results." Methods in Paleomagnetism. Ed. D. W. Collinson, K. M. Creer, and S. K. Runcorn. New York: Elsevier, 1967, pp. 254-286.

APPENDIX A

APPENDIX A

Once a set of paleopoles were calculated for each specimen and grouped with respect to lithology, the results were analyzed statistically to determine the degree of scatter among poles, the V.G.P. pole position on the Earth's surface (latitude and longitude) and the amount of confidence that can be placed on that value. To perform these tasks a computer program was written by the author utilizing the equations listed by Irving (1964). This program, printed at the end of this section, was written in extended FORTRAN 4 for use on Michigan State University's Control Data 6500 computer system. Explainatory text for the program follows here.

Given a sample of points dispersed on a sphere about a common center, the best estimate of the position of this center (the mean direction) is the vector sum of the individual specimen unit vectors. In paleomagnetic studies the direction of magnetization in the rock samples is given by the declination (D), measured clockwise from true north, and by the inclination (I), measured positively downwards from the horizontal. This direction may be alternatively specified by three direction cosines as follows:

north component	$l = \cos D \cos I$
east component	$m = \sin D \cos I$
vertical component	$n = \sin I$

The direction cosines of the resultant of N sample directions are proportional to the sum of the separate direction cosines as follows:

$$X = 1/R \sum_{i=1}^{N} l_i \qquad Y = 1/R \sum_{i=1}^{N} m_i \qquad Z = 1/R \sum_{i=1}^{N} n_i .$$

The vector sum of these component sums will give a resultant vector (mean direction) of length R, where

$$R^2 = (\Sigma\, l_i)^2 + (\Sigma\, m_i)^2 + (\Sigma\, n_i)^2 \qquad \text{and } R \leq N.$$

The declination and inclination of this mean direction then follow from these equations:

$$D_m = \arctan\,(\Sigma m_i / \Sigma l_i) \qquad I_m = \arcsin\,(\Sigma m_i / R).$$

The parameter κ is called the precision parameter (Fisher, 1953) and determines the dispersion of the points. When $\kappa = 0$ they are uniformly distributed on the sphere (and therefore random) and when κ is large the points cluster about the true mean direction. When κ is not too small the distribution is confined to a small portion of the sphere near the maximum, and tends to conform to a two-dimensional Gaussian distribution. In such cases the precision parameter κ is in effect the reciprocal of the variance in all directions. The best estimate k of the precision parameter κ is given for $k > 3$ as

$$k = (N-1/N-R).$$

The probability of any one direction being observed to make a angle θ with the true mean can be given for the various probabilities as follows:

1) $P = .5$ $\theta_{50} = 67.5/ k$ degrees

2) $P = .37$ $\theta_{50} = 81/\sqrt{k}$ degrees

3) $P = .05$ $\theta_{95} = 140/\sqrt{k}$ degrees

These are analogous to 1) the quartile distance, 2) the standard deviation, and 3) the 95% deviation, for normal distributions. The last represents the angle from the mean beyond which only 5% of the directions lie. Fisher (1953) has shown that the true mean direction of the population of N directions lies within a circular cone about the resultant vector R with a semiangle of α. When α is small the approximate relations

standard error of the mean $A_{63} = 81/\sqrt{kN}$

circle of 95% confidence $A_{95} = 140/\sqrt{kN}$

may be used. In order to determine whether a paleomagnetically determined direction differs significantly from some known direction, such as the A.P.W. path or the present Earth's field at the sampling site, A_{95} may be used directly. The two directions are significantly different at the 95%

confidence level if the angle between them is greater than A_{95}.

The question then arises as to whether or not these directions could arise from the sampling of a random population, in that case the mean direction would have no signifiance. For a truly random population κ is zero, in practice however, k, the best estimate of κ, is never zero, this therefore requires the following test. For a sample of size N, the length of the resultant vector R will be large if a preferred direction exists or small if it does not. Assuming no preferred direction exists, a value R_o may be calculated which will be exceeded by R with any stated probability. Irving (1964) has tabulated R_o for sample sizes up to N = 100 for P = .05. To carry out the test one merely enters the table at the row corresponding to the sample size N in order to find the value of R_o which will be exceeded with the given probability.

The V.P.G. paleomagnetic pole (λ', ϕ') can then be calculated from the site mean direction of magnetization (D_m, I_m) according to:

λ = station latitude $\qquad \phi$ = station longitude

$$p = \arctan (2/\tan I_m)$$

$$\lambda' = \arcsin (\sin \lambda \cos p + \cos \lambda \sin p \cos D_m)$$

$$B = \arcsin (\sin p \sin D_m/\cos \lambda')$$

$$\text{if } \cos p \geq \sin \lambda \sin \lambda' \qquad \phi' = \phi + B$$

$$\text{if } \cos p < \sin \lambda \sin \lambda' \qquad \phi' = \phi + 180 - B$$

Since the mean direction has its associated circle of confidence, A_{95}, corresponding to errors in inclination and declination, the error in the inclination will correspond to an error dp in the ancient colatitude, p, given by:

$$dp = \frac{1}{2}A_{95}(1+3\cos^2 p).$$

The error dp lies along the great circle passing through the sampling site S and the V.P.G. pole P and is the error in determining the distance from S to P. The error in declination corresponds to a displacement dm from P in the direction perpendicular to the great circle SP where:

$$dm = A_{95}(\sin p/\cos I_m).$$

The polar error (dp, dm) is termed the 95% confidence ellipse about the pole.

The following represents a summary of the statistical tests just outlined when applied to the paleopole data of this study.

Site	Lithology	Pole Number	N	R	K	I_m	D_m	A_{95}	λ'	φ'	dp	dm
2	Metadiabase	A	8	7.607	40.7	69.8	315.2	5.3	60.9	-146.8	7.8	9.1
2	Metadiabase	B	6	4.213	2.8	65.5	205.4	34.1	6.7	-104.3	45.0	55.5
2	Gneiss	A	7	6.361	9.4	64.0	327.7	17.3	67.8	-167.7	21.9	27.5
2	Gneiss	B	3	2.924	26.2	68.4	146.7	15.8	12.3	-67.0	22.5	26.6
2	Gneiss	C	3	2.859	14.2	63.2	14.6	21.4	79.6	7.8	26.6	33.8
3	Metadiabase	A	5	4.921	50.8	-62.5	130.6	8.9	55.7	-163.6	10.7	13.7
3	Metadiabase	B	4	2.843	2.6	66.7	173.4	43.5	6.0	-83.1	59.2	71.7
3	Metadiabase	C	6	5.964	139.0	73.0	358.9	4.8	78.0	-90.2	7.7	8.7
3	Gneiss	A	6	5.271	6.9	18.1	289.1	21.8	19.8	175.0	11.8	22.7
3	Gneiss	B	16	15.063	16.0	72.6	312.6	8.7	59.6	-138.1	13.8	15.5
3	Gneiss	C	7	6.564	13.8	-53.4	31.8	14.3	-4.6	-113.5	13.8	20.0
A	Gneiss	A	11	9.545	6.9	-8.4	179.9	16.1	47.6	92.7	8.2	16.2
B	Diabase	A	8	7.941	118.4	-62.0	131.7	4.5	56.2	-165.1	5.5	7.1
B	Gneiss	A	7	6.900	60.0	-61.3	143.5	6.8	64.2	-175.1	8.1	10.5
C	Metadiabase	A	3	2.972	70.4	-49.3	114.3	9.6	37.6	-171.1	8.5	12.8
C	Metadiabase	B	3	2.975	81.6	32.3	151.6	8.9	-21.0	-58.4	5.7	10.1
C	Gneiss	A	8	7.492	13.8	61.7	300.4	13.3	48.5	-160.1	15.9	20.6
C	Gneiss	B	6	5.663	14.8	-71.2	321.0	14.8	17.4	-65.6	22.6	25.9
F	Metadiabase	A	10	7.989	4.5	53.0	203.1	20.9	-7.2	-106.7	20.1	29.0
F	Metadiabase	B	10	6.779	2.8	-44.6	21.0	26.5	-14.7	-106.9	21.0	33.4

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PROGRAM STATPOL    73/73    OPT=1                    FTN 4.6+433        04/09/79 .15.23.48        PAGE     1

         PROGRAM STATPOL (INPUT,OUTPUT)
         REAL K,IM,N,INC,LAM,LAMPRI,MPI2,LAT,LONG,IN
      10 READ100,L,JN,JO,JP,JQ
         N=FLOAT(L)
         IF(L)1000,1000,20
      20 EL=0.0
         EM=0.0
         EN=0.0
         PI=ABS(ASIN(-1.)/90.)
         DO 30 M=1,L
            READ110,DEC,INC
            ELI=COS(INC*PI)*COS(DEC*PI)
            EMI=COS(INC*PI)*SIN(DEC*PI)
            ENI=SIN(INC*PI)
C                                                    DIRECTION COSINES
            EL=EL+ELI
            EM=EM+EMI
            EN=EN+ENI
C                                                    SUM OF THE COSINES
      30 CONTINUE
         RSQUARE=(EL**2.)+(EM**2.)+(EN**2.)
C                                                    SUM OF THE SQUARES
         R=SQRT(RSQUARE)
C                                                    RESULTANT VECTOR
         DM=ATAN(EM/EL)
         IM=ASIN(EN/R)
         DM=DM/PI
         IM=IM/PI
         IF(EL.LT.0.) DM=DM+180.
         IF(EL.GT.0..AND.EM.LT.0.) DM=DM+360.
C                                                    MEAN DIRECTION RADIANS
         K=(N-1.)/(N-R)
C                                                    PRECISION CONSTANT
         THETA63=81./SQRT(K)
C                                                    CIRCULAR STANDARD
C                                                    DEVIATION IN DEGREES
         THETA95=140./SQRT(K)
C                                                    1.96 X STANDARD
C                                                    DEVIATION IN DEGREES
         A50=67.5/SQRT(K*N)
C                                                    PROBABLE ERROE OF THE
C                                                    MEAN IN DEGREES
         A95=140./SQRT(K*N)
C                                                    RADIUS OF CIRCLE OF
C                                                    95 CONFIDENCE DEGREES
         SIGMA=ACOS(R/N)
C                                                    ANGULAR STANDARD DEV.
C                                                    IN RADIANS  63 PER
         ETA=SIGMA/SQRT(N)
C                                                    ANGULAR STANDARD DEV.
C                                                    OF MEAN IN RADIANS
         LAM=.8132264
         PHI=-1.5261934
C                                                    STATION COORDINATES
C                                                    IN RADIANS
         DN=DM*PI
         IN=IM*PI
         PIE=2.*ABS(ASIN(-1.))
         COLAT=ATAN(2./TAN(IN))
         LAMPRI=ASIN((SIN(LAM)*COS(COLAT))+(COS(LAM)*SIN(COLAT)*COS(DN)))
         BETA=ASIN((SIN(COLAT)*SIN(DN))/COS(LAMPRI))
         C=COS(COLAT)
         S=SIN(LAM)*SIN(LAMPRI)
         IF(C.GE.S) PHIPRI=PHI+BETA
         IF(C.LT.S) PHIPRI=PHI+PIE-BETA
C                                                    POLE CALCULATED
         DELCLAT=.5*A95*(1.+3.*(COS(COLAT))**2.)
C                                                    ERROR IN COLATITUDE ON
C                                                    GREAT CIRCLE CONNECTING
C                                                    STATION AND POLE RADS
         DELM=A95*SIN(COLAT)/COS(IN)
C                                                    ERROE PERPENDICULAR TO
C                                                    CIRCLE AT POLE  RADS
         SIGMA=SIGMA/PI
         ETA=ETA/PI
         LAMPRI=LAMPRI/PI
         PHIPRI=PHIPRI/PI


PROGRAM STATPOL    73/73    OPT=1                    FTN 4.6+433        04/09/79 .15.23.48        PAGE     2

         LAT=LAM/PI
         LONG=PHI/PI
C                                                    ALL COORDINATES IN
C                                                    RADIANS NOW DEGREES
         PRINT120
         PRINT130,JN,JO,JP,JQ,LAT,LONG
         PRINT140,DM,IM,A50
         PRINT150,THETA63,SIGMA,A95
         PRINT160,ETA,R,K
         PRINT170,LAMPRI,PHIPRI
         PRINT180,DELCLAT,DELM
     100 FORMAT(I10,4A9)
     110 FORMAT(F6.2,F10.2)
     120 FORMAT(*0*,111H-----------------------------------------------------
        1----------------------------------------------------------)
     130 FORMAT(*0*,4A9,14H STATION LAT =,F8.3,14X,14HSTATION LONG =,F8.3)
     140 FORMAT(*0*,10HMEAN DEC =,F8.3,19X,10HMEAN INC =,F8.3,19X,28HPROBAB
        2LE ERROR OF THE MEAN =,F8.3)
     150 FORMAT(*0*,18HCIRCULAR STD DEV =,F8.3,11X,17HANGULAR STD DEV =,F8.
        33,12X,29HRADIUS CIRCLE OF CONFIDENCE =,F8.3)
     160 FORMAT(*0*,25HANGULAR STD DEV OF MEAN =,F8.3,4X,11HRESULTANT =,F8.
        43,18X,20HPRECISION ESTIMATE =,F8.3)
     170 FORMAT(*0*,15HPOLE LATITUDE =,F8.3,14X,16HPOLE LONGITUDE =,F8.3)
     180 FORMAT(*0*,16HERROR OF COLAT =,F8.3,13X,17HERROR OF COLONG =,F8.3)
         GO TO 10
    1000 STOP
         END
```