Paleomagnetism of Some Lake Superior Keweenawan Rocks

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By KENNETH G. BOOKS

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Remanent magnetization directions for lower and middle Keweenawan rocks fall into three groups that have their polarities alternately normal, reversed, and normal

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By Kenneth G. Books

ABSTRACT

The averaged directions of remanent magnetization for the Keweenawan rock units investigated fall into three general groupings that have their polarities alternately normal, reversed, and normal. The older normal polarity and subsequent reversed polarity groups are found in lower Keweenawan rocks and have significantly different directions from the younger group with normal polarity which characterizes middle Keweenawan rocks. From all available paleomagnetic data for this area, it seems that magnetization directions among various rock units in the lower Keweenawan around Lake Superior are characteristically scattered, which may indicate long periods between volcanic events, a rapid rate of change in magnetic field directions, or changes due to metamorphism. Less scatter of magnetization directions among middle Keweenawan rock units may indicate a shorter time interval between volcanic events or a slower rate of change in magnetic field direction. Upper Keweenawan magnetization directions, though not included in this study, are again more scattered among rock units.

Beginning with known basal Keweenawan, the three magnetic polarity groups are represented in rocks on all sides of Lake Superior. The older normal polarization is found in the basal rocks near Ironwood, Mich., and in the lower part of the lower Keweenawan Sibley Series on Sibley Peninsula, Ontario. The reversely polarized group is a distinctive representation of a time interval that is present at many locations around the lake. Reverse polarization is found in some 6,700 feet of South Trap Range lava flows near Ironwood, Mich., lava flows near Grand Portage, Minn., gabbro in Cook County, Minn., sedimentary rocks of the Sibley Series in Ontario, and lava flows at Alona Bay on the eastern end of the lake.

The younger normal polarization is also widespread and is represented in the great bulk of the extrusive and intrusive rocks around Lake Superior that are classified as middle Keweenawan in age. This group includes the Portage Lake Lava Series on the Keweenaw Peninsula and most of the North Shore Volcanic Group of Goldich and others (1961) in Minnesota.

With the completion of this study, paleomagnetic field directions are now available for all major geologic units of the Keweenawan Series in the Lake Superior region.

INTRODUCTION

The area of investigation lies in parts of the States of Michigan, Wisconsin, and Minnesota adjacent to Lake Superior (fig. 1) and is underlain mainly by igneous rocks of late Precambrian age.

Because of its economic significance and structural complexities, the Precambrian of the Lake Superior region has been the object of geologic investigations for more than a century, and the section of lava flows of Keweenawan age near the lake is probably as well known as any such succession in North America. Nevertheless, the positioning of some nonfossiliferous rocks in the geologic column has been hard to assess, because of inherent difficulties in determining time relationships between extrusive rocks at some distance from each other, and even more difficulty in relating different intrusive rocks of the same age.

Before radiometric dating methods were developed, most Precambrian rocks were correlated by comparison of facies and petrographic similarities, unconformities, and degree of metamorphism. Goldich and others (1961) built a time scale of radiometric dates for the Precambrian of Minnesota, into which geologic units and events in the Lake Superior region can be fitted.

Paleomagnetism can also be used to correlate rock units within the Precambrian. In recent years much progress has been made in measurement and interpretation of natural remanent magnetization of rocks. Paleomagnetic studies are based on the knowledge that rocks can acquire a stable magnetization in the direction of the earth's magnetic field during formation, and this direction can be measured by sensitive instruments in the laboratory. Therefore, by collecting many oriented samples from a particular rock unit, the direction of the earth's magnetic field at the time the rock was formed can be determined, provided that the magnetization has been preserved. By collecting and averaging magnetization directions of samples from various rock units, it is possible to establish a sequence of paleomagnetic field directions to which data from rocks of all types may be compared. DuBois (1962) has attempted to show how paleomagnetism studies can aid and supplement geological interpretations in the Lake Superior region and has laid the groundwork for such studies in the area. The present investigation continues this type of study by detailed analysis of the paleomagnetic field directions in the Keweenawan lava flows and related rocks on both the southeast and northwest shores of Lake Superior.

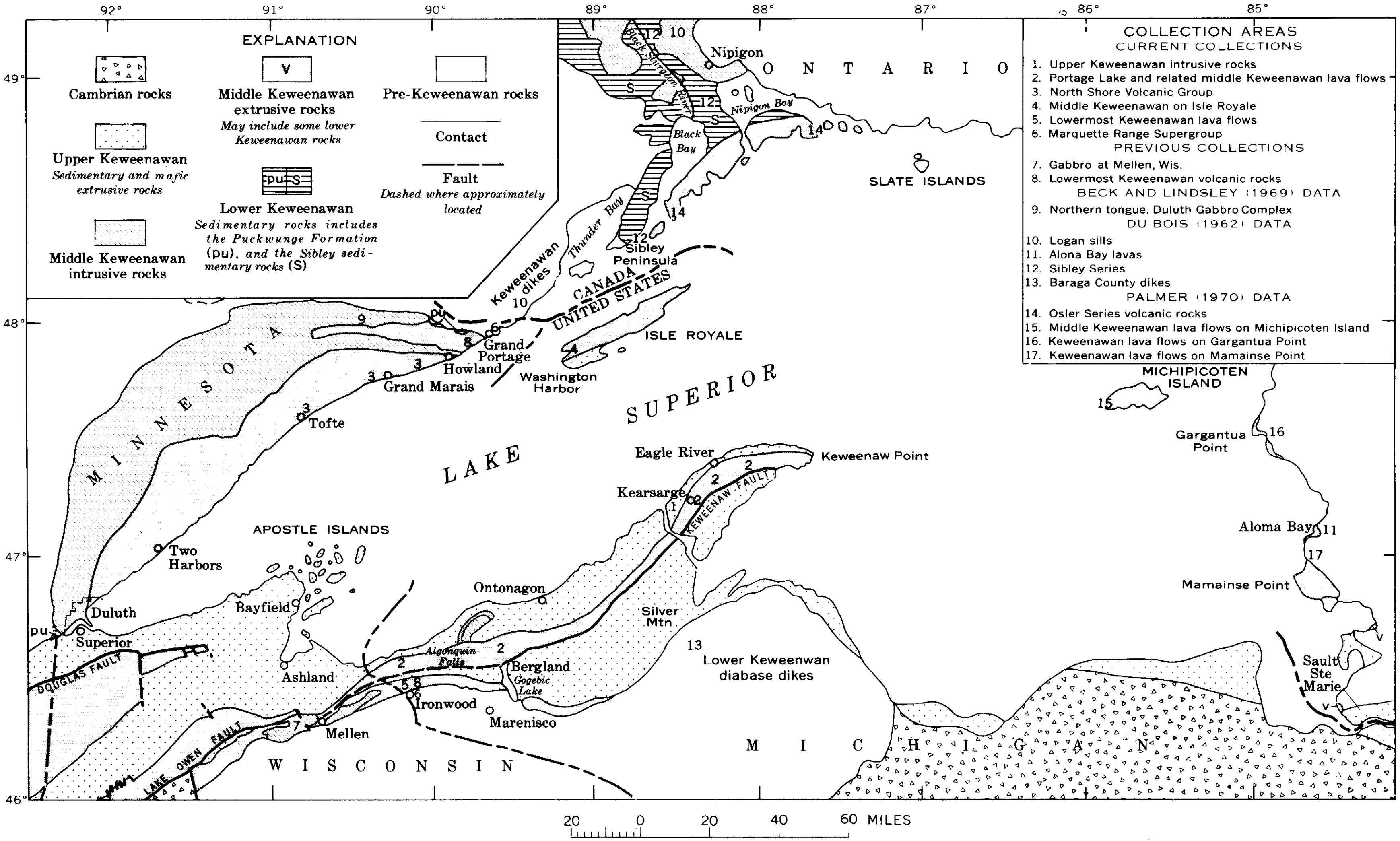

Figure 1.—Generalized geologic map of the Lake Superior region. Modified from Leith, Lund, and Leith (1935, pl. 1), White (1966a, fig. 1), and Halls (1966, figs. 4, 5).

ACKNOWLEDGMENTS

For geologic background material, this report draws on many published sources, which are listed under references. For paleomagnetic background material, the publication by DuBois (1962) has been invaluable.

I wish to acknowledge the guidance of Walter S. White, U.S. Geological Survey, on matters geologic in the Lake Superior region, for field and office help on stratigraphy and structure and geologic background material relating to the Keweenaw Peninsula collections, and for critical reviews and suggestions on this and previous manuscripts. I further wish to acknowledge help and direction from Myrl E. Beck, Jr., who was with the U.S. Geological Survey in the initial stages of the project; also, Harold A. Hubbard, U.S. Geological Survey, supplied me with geologic data and advice on the Ironwood-Mellen area. Finally, I wish to thank N. King Huber, U.S. Geological Survey, for stratigraphic locations on Isle Royale and William E. Huff, Jr., for field and laboratory help.

FIELD AND LABORATORY TECHNIQUES

COLLECTION AND MEASUREMENT

The Keweenawan rock samples were obtained with portable coring equipment (Doell and Cox, 1965, p. A22–A24) that yields short cores approximately 2.49 cm (centimeters) in diameter. These cores were oriented in place relative to the horizontal and to geographic north, and in the laboratory they were cut into two 2.54-cm lengths on dual nonmagnetic diamond circular saws.

Natural remanent magnetization down to 10^{-4} emu/cm^3 (electromagnetic units per cubic centimeter) was measured on the U.S. Geological Survey motor-driven spinner magnetometer. Both cores from each sample were measured for remanence, and one was subjected to magnetic cleaning in a-c (alternating-current) fields. The coring rig, orientation techniques, and description of the U.S. Geological Survey magnetometer are explained in a paper by Doell and Cox (1965, p. A1–A25).

Samples with natural remanent magnetizations less than 10^{-4} emu/cm^3 amounted to less than 5 percent of the total number collected and were from intrusive rhyolites, quartz porphyries, and some andesite lava flows. These samples were measured on a high-sensitivity, motor-driven, rock generator (spinner) magnetometer designed by Phillips and Kuckes (1967). This instrument uses a commercially made lock-in amplifier and low-noise, high-gain preamplifier. The main design features of the pickup coil transducing system, with a high signal-to-noise ratio, include the use of a compensated dual-coil array and aluminum eddy current shielding. The instrument has a claimed sensitivity of 6×10^{-8} emu/cm^3 for 10-cm^3 cores, and we have had good results down to 3×10^{-7} emu/cm^3 in the U.S. Geological Survey laboratory. Over a period of 2 years of use, comparative measurements within the limits of the U.S. Geological Survey magnetometer for the same samples indicated a difference in results between the two magnetometers that is well within the claimed measurement error of 5° for direction and 10 percent for intensity for the high-sensitivity instrument.

All data in this paper were reduced with computer programs and are presented in terms of declination (D), measured in degrees east of geographic north, and inclination (I), measured in degrees below the horizontal. All directions are corrected for present geologic dip of the rock unit unless otherwise noted. Radii for circles of confidence (α_{95}) have been determined by a Fisher (1953) statistical computer program at the 95 percent level; K is the precision parameter. Unless otherwise noted, N refers to number of individual samples. In the summary table, N is the number of sites for which Fisher (1953) analyses have been computed. In the various figures, remanence results are plotted on the lower hemisphere of an equal-area net to permit direct comparison of directions on a single plane, regardless of polarity. Solid circles represent polarization north-seeking down and open circles represent polarization south-seeking down.

Due to local declination anomalies that were commonly several degrees and occasionally near 10°, all magnetic compass readings at the collecting site had to be verified with a sun dial compass.

Routine procedure included calibration of the sun dial compass with watch time for the particular latitude and in the particular area of site locations. Calibration stations were established at Kearsarge and Ironwood, Mich., at Mellen, Wis., and at Grand Marais, Minn. These stations were reoccupied whenever the sample collection period exceeded several weeks. A comparison of the magnetic compass reading of true north with that determined by the sun dial compass was made for each core. With the sun dial compass as base, the differential was applied as a correction to all magnetic compass readings for each core. The sun dial compass marks are placed at 5-minute intervals so that the instrument can be set up to within 2½ minutes of time. This is equivalent to about 1° in azimuthal readings on the magnetic compass, and the precision of declination readings for each core sample is probably near 1°.

SOURCES OF ERROR

The total core collection and orientation errors in the field and in the laboratory are most probably less than 3°. The prime source of error in computing paleomagnetic field directions is probably due to uncertainty in the geologic dip component of the attitude for the lava flows, as their orientations are not easily measured in the field. Geologic dip measurements in the Kearsarge, Mich., area where drill-hole data are plentiful are probably accurate to 1° (W. S. White, written commun., 1970), but dip values may be as much as 5° inaccurate in other places on the Keweenaw Peninsula. Dip values outside the peninsula are less certain. The North Shore Volcanic Group in Minnesota and the Isle Royale lavas dip less than 20°; consequently, the possibility of large errors in dip measurements is lessened, and geologic dip values are probably accurate to 5°. In the Ironwood, Mich., and Mellen, Wis., areas, the rocks commonly dip as much as 80°, and dip measurement errors are proportionately greater; dip values may be 5° to 10° inaccurate on individual flows and could be greater.

MAGNETIC CLEANING

Many groups of samples from igneous bodies collected for paleomagnetic research have scattered remanent magnetization directions, and the average direction may not represent the direction of the earth's magnetic field at the time the rocks cooled. Such a scatter can often be attributed to secondary components of magnetization superimposed upon the original magnetization after cooling. One of the most common secondary components encountered is viscous magnetization, which may be acquired over a long period of time. The intensity of this magnetization is proportional to the logarithm of time (Rimbert, 1959), and the direction is parallel to that of the magnetic field in which it is acquired.

Other secondary components which arise from lightning, chemical alteration, and stress effects may also be superimposed on the original magnetization. The components due to lightning effects tend to be scattered, as observed between samples from the same site. Both viscous magnetization and magnetization due to lightning may be removed by alternating (ac) field demagnetization. The components due to chemical alteration and stress effects may be stable and will be in the direction of the earth's magnetic field at the time of the remagnetization.

The partial demagnetization technique used in this investigation is that utilized by U.S. Geological Survey laboratories. In this method an alternating magnetic field ($\tilde{H}$) is slowly decreased as the sample orientation is changed by simultaneous rotation about three orthogonal axes.

All samples reported in this paper were subjected to a-c partial demagnetization in order to eliminate any unstable secondary components. The optimum peak demagnetizing field selected was based on an empirical procedure utilized by others (Cox 1961; Irving and others, 1961). This procedure involves selecting a few samples from one collecting site and studying the dispersion of magnetic directions after each demagnetization step. The a-c demagnetization that is found necessary to produce minimum dispersion is selected and applied to all samples from the site. Table 1 shows examples of partial demagnetization data in steps of 100, 200, and 300 Oe (Oersteds) for some of the sites in the Portage Lake Lava Series. Though small, the within-site scatter increases beyond the 100-Oe demagnetization level (as shown by α_{95} values), which indicates that 100 Oe is the optimum peak field for Portage Lake lavas, using this procedure. The 100-Oe demagnetization level for the Portage Lake lavas was also generally applicable for other igneous rock samples from the Lake Superior region, though some of the sites on the older and lithologically distinct flows required 150-Oe levels, and Beck and Lindsley (1969, table 1) found 75-Oe levels to be optimal for rocks of the Beaver Bay Complex of Grout and Schwartz (1939).

TABLE 1.—*Partial demagnetization data for four sites on the Portage Lake Lava Series, Keweenaw Peninsula, Mich.*

[*N* is number of within-site samples. $\tilde{H}$ is peak alternating magnetic field (in Oersteds) used in magnetic cleaning. Other data for these samples are found in tables 2 and 3]

Site No.	*N*	Mean direction of magnetization at collecting site: Declination, *D* (degrees)	Inclination, *I* (degrees)	Precision parameter, *K*	Radius of confidence circle, α_{95}
		Natural remanent magnetization			
PL4	6	266.9	42.7	85.5	7.3
8	5	304.9	50.6	30.0	14.2
335	5	296.9	33.7	616.7	3.7
345	5	275.0	41.3	22.7	19.7
		$\tilde{H}$=100 Oe			
PL4	6	261.0	43.2	204.6	4.7
8	5	297.7	44.2	423.2	3.7
335	5	296.1	33.7	762.4	3.3
345	5	281.2	38.3	104.7	7.5
		$\tilde{H}$=200 Oe			
PL4	6	263.8	43.8	197.2	4.8
8	5	297.9	44.1	374.1	4.0
335	5	294.9	34.8	303.5	4.4
345	5	286.4	35.6	34.2	13.3
		$\tilde{H}$=300 Oe			
PL4	6	264.4	41.8	109.9	6.4
8	5	297.1	44.6	410.6	3.8
335	5	294.7	35.0	382.1	3.9
345	5	289.4	31.1	9.4	26.4

GENERAL GEOLOGY

The Keweenawan Series of the Lake Superior region is characterized by great thicknesses of mafic volcanic rocks exposed around the margin of the lake (fig. 1). Structurally the series forms a large syncline with dips ranging from near zero to vertical. On the western end of the lake, the syncline trends northeast and has low-angle dips on the north limb and steep dips on the south limb. Gravity and magnetic highs and well data (Lyons, 1959; Thiel, 1956; Craddock and others, 1963) indicate that the Keweenawan igneous sequence extends southwest across the midcontinent toward Kansas. The Keweenawan rocks have been separated into three subdivisions:

1. The term lower Keweenawan has long been applied to sedimentary rocks that overlie the Animikie Series (now called Marquette Range Supergroup)[1] and are comformable with overlying Keweenawan lava flows. The maximum exposures of these rocks are on the Sibley Peninsula of northwest Ontario and consist principally of red, fine-grained sandstones and siltstones. In Minnesota, lower Keweenawan rocks are represented by the Puckwunge Formation (Grout and others, 1951, p. 1051–1053) that consists of conglomerate and sandstone; near Grand Portage the Puckwunge overlies the Rove Slate of the Animikie Group with no visible discordance, and near Duluth it rests on the Thomson Formation as used by Schwartz (1942) with marked angular unconformity. Lower Keweenawan rocks also have been reported (Aldrich, 1929, p. 109–110) in northern Wisconsin overlying Animikie rocks. The Sioux Formation in Minnesota and Barron Quartzite of Winchell (1895) in Wisconsin are also possibly lower Keweenawan (Goldich and others, 1961, p. 149).

It now seems desirable locally, if not regionally, to place the boundary between lower and middle Keweenawan rocks several thousand feet above the lava flows that immediately overlie these lower Keweenawan sedimentary rocks, thereby including a thick sequence of mafic lava flows within the lower Keweenawan (Hubbard, 1967; Books, 1968). Hubbard suggested that at least one unconformity separates the rocks of the so-called South Trap Range in the Ironwood-Mellen area (described in a later section) from the overlying Portage Lake Lava Series, which, in its type area, makes up the whole of the middle Keweenawan.

2. The middle Keweenawan is composed mainly of a thick sequence of basaltic andesite lava flows with subordinate beds of sedimentary rock and rhyolite conglomerate. Rhyolite flows account for perhaps 10 percent of the total thickness of flows on the north shore in Minnesota (Grout and others, 1951, p. 1054) but are less well represented on the south shore.

These lavas are exposed around the periphery of Lake Superior in Michigan, Wisconsin, Minnesota, and in Ontario on the north and east shores. Michipicoten Island and most of Isle Royale are also underlain by middle Keweenawan lava flows. Grout, Sharp, and Schwartz (1959) gave a thickness of 25,000 feet for the lava flows exposed along the southern half of the Minnesota coast, and a greater thickness (White, 1966b) is suggested by the breadth of outcrop in the Keweenawan lavas in northwestern Wisconsin. White (1966b, p. 30) summarized by suggesting that parts of the section may be repeated in Minnesota and Wisconsin, and that thicknesses of 20,000 to 30,000 feet or more exist in parts of the Lake Superior basin.

Middle Keweenawan intrusive rocks are abundant in the Lake Superior region, especially in Minnesota and along the northwest shore. Sills, dikes, and more irregular bodies of basaltic rocks intrude the gently dipping Keweenawan and older rocks. With the exception of the Duluth Gabbro Complex and the Beaver Bay Complex of Grout and Schwartz (1939), these bodies are known generally as the Logan intrusions. Paleomagnetic pole directions (DuBois, 1962, p. 59) indicate that some of these intrusive rocks in the Nipigon, Ontario, and Baraga County, Mich., areas are probably lower Keweenawan.

The Duluth Gabbro Complex is a large sill-like mass intruded below the middle Keweenawan lava flows and is, by far, the largest Keweenawan intrusion in the region. It extends northeast into Cook County, Minn., where it divides and extends approximately another 40 miles eastward as two separate sills (Grout and others, 1959, p. 40–41). Elsewhere around Lake Superior, Keweenawan dikes occur locally in large numbers, and one other large sill-like mass akin to the Duluth Gabbro Complex intrudes Keweenawan lava flows near Mellen, Wis.

3. The upper Keweenawan sequence consists largely of fine-grained sandstones and shales. On the Keweenawan Peninsula and west into Wisconsin, these sedimentary rocks overlie a thick conglomerate (the Copper Harbor Conglomerate) interbedded with a few lava flows. Upper Keweenawan rocks are exposed mainly in northern Michigan and Wisconsin but are also found in Minnesota southwest of Duluth, and on Isle Royale.

KEWEENAW PENINSULA

GEOLOGIC SETTING

On the Upper Peninsula of Michigan the Keweenawan rocks form part of the southern limb of the Lake

[1] The Animikie Group of Ontario and Minnesota is only partly equivalent to the Animikie Series as previously used in Michigan and Wisconsin (James, 1958). In that area, the Animikie Series included the Chocolay, Menominee, Baraga, and Paint River Groups, and, according to the stratigraphic code, should have supergroup rank. To avoid the confusion inherent in an Animikie Group and an Animikie Supergroup, Cannon and Gair (1970) abandoned the term Animikie Series and replaced it with the term Marquette Range Supergroup. In this paper, the term Animikie Series is used only when used by the author cited; otherwise the term Marquette Range Supergroup is used. The term Animikie Group remains in good usage in Minnesota and Ontario.

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Superior syncline so that at most localities they are inclined northwest toward the lake. Dips range from near horizontal to near vertical, and generally the lower beds dip more steeply than the upper beds. Strike of the rocks is generally northeast, but it turns from N. 33° E. near Kearsarge to S. 79° E. on Keweenaw Point.

The Portage Lake Lava Series is more than 15,000 feet thick in the Delaware 7½-minute quadrangle, Michigan (Cornwall, 1954). This sequence is terminated at the base by the Keweenaw fault which has thrust the flows over the adjacent Jacobsville Sandstone to the south, cutting out an unknown thickness of lava flows. The Portage Lake lavas are composed of basalt and andesite flows with a few thin interbedded rhyolite conglomerates. Some of the flows are fine grained, but most flows increase in grain size from both top and bottom toward the center. Capping each flow is a layer of amygdaloidal lava generally 5 to 10 feet thick. Conglomerate and sandstone beds within the lava series are mostly rhyolitic material. The bulk of the clastic particles are less than 6 inches in diameter, and boulders more than 1 foot in diameter are uncommon (White and others, 1953). The Copper Harbor Conglomerate (Lane, 1911, p. 37–40) comformably overlies the Portage Lake Lava Series and consists mainly of pebble to boulder conglomerate and lesser amounts of sandstone. Lava flows interstratified with the conglomerate are typically fine-grained andesite.

Intrusive rhyolites are exposed at a number of locations on the Keweenaw Peninsula and are typically pale reddish brown on fresh surfaces and lighter on weathered surfaces. Most of the rhyolites intrude middle Keweenawan lava flows, but one intrudes rocks at least 10,000 feet above the Portage Lake Lava Series. These intrusions are believed to be of middle and upper Keweenawan age (White and others, 1953).

DESCRIPTION OF RESULTS

PORTAGE LAKE LAVA SERIES

A total of 380 samples from 76 sites were collected from flows of the Portage Lake Lava Series for remanent magnetization measurements. Of these, 35 samples from seven sites were not utilized because of the large scatter of directions after partial demagnetization in a-c fields as great as 300 Oe.

Of the remaining 69 sites, 17 are scattered along the peninsula northeast of Kearsarge, Mich., and 52 represent a rather detailed sample collection across the lava flow sequence in the vicinity of Kearsarge in the Ahmeek 7½-minute quadrangle, Michigan (White and others, 1953). The bulk of the collections around Kearsarge represent the central parts of flows, which are probably least affected by later metamorphic events. Figure 2 is a stratigraphic column (simplified from White and others, 1953) indicating the horizons at which the samples were collected.

Remanence data from the Kearsarge section are subdivided into three parts as follows: (1) all samples below conglomerate No. 14, (2) all samples between conglomerate Nos. 14 and 15, and (3) all samples above conglomerate No. 15. The separation into three parts is based on a significant difference in the direction of magnetization for the samples between conglomerate Nos. 14 and 15 and the directions for samples both below conglomerate No. 14 and above conglomerate No. 15. Results are shown in figures 3–5 and table 2.

The paleomagnetic results for the 17 sites in the Portage Lake Lava Series northeast of Kearsarge are shown in figure 6 and table 3. These flows have an average remanence direction that is not significantly different from directions of magnetization in the intervals below conglomerate No. 14 and above conglomerate No. 15 near Kearsarge, Mich.

In order to investigate the possibility of rotation of the lava flows around vertical axes during the anticlinal bending in the northern part of the Keweenaw Peninsula, samples from the Ashbed Flow were collected at points where the strike ranged from N. 38° E. to N. 78° E. This component of structural movement (rotation about vertical axes) is not diminished by geologic-dip corrections, and, if present, it would remain in the data and would be reflected as differences in the declination of the paleomagnetic field directions. In table 4, a comparison of the variations in strike with the variations in paleomagnetic declination indicates no systematic relationships, and hence there is no evidence for rotation about vertical axes in this region.

RHYOLITE FLOWS NORTH OF LAKE GOGEBIC, MICHIGAN

Thirteen samples from three separate sites represent rhyolite lava flows from the top of the lava series along the Bergland fire tower road north of Bergland, Mich. Paleomagnetic results are given in figure 7 and table 5.

W. S. White (written commun., 1970) suggested that these flows belong to a group that locally overlies the Portage Lake Lava Series in this area. Whether this group underlies the Copper Harbor Conglomerate or grades laterally into it is not yet known. The proximity of the mean direction of magnetization for the rhyolite flows to those for the Portage Lake Lava Series and the Copper Harbor Conglomerate makes paleomagnetic measurements of little use in distinguishing this local group of flows from the formations above and below it.

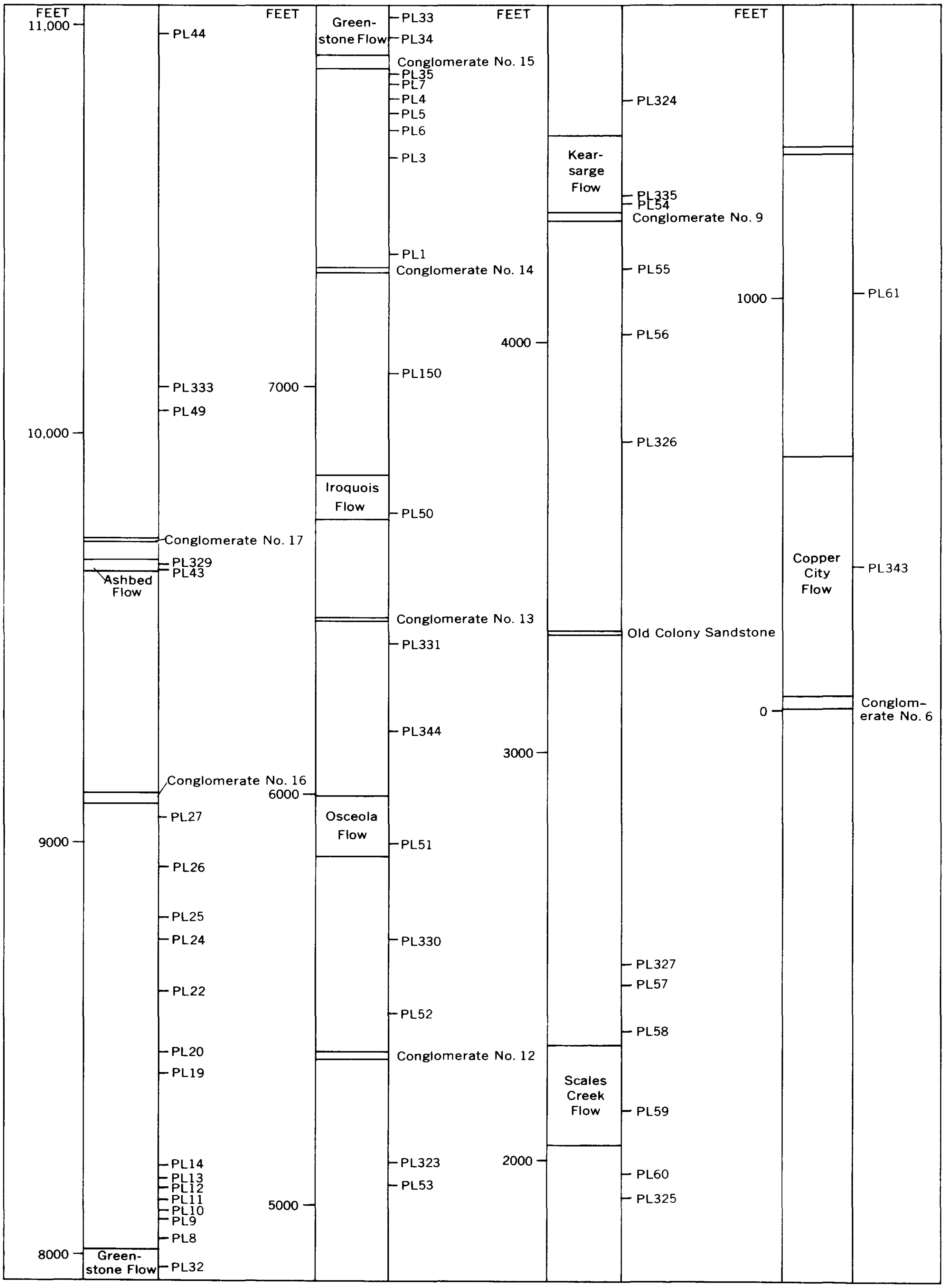
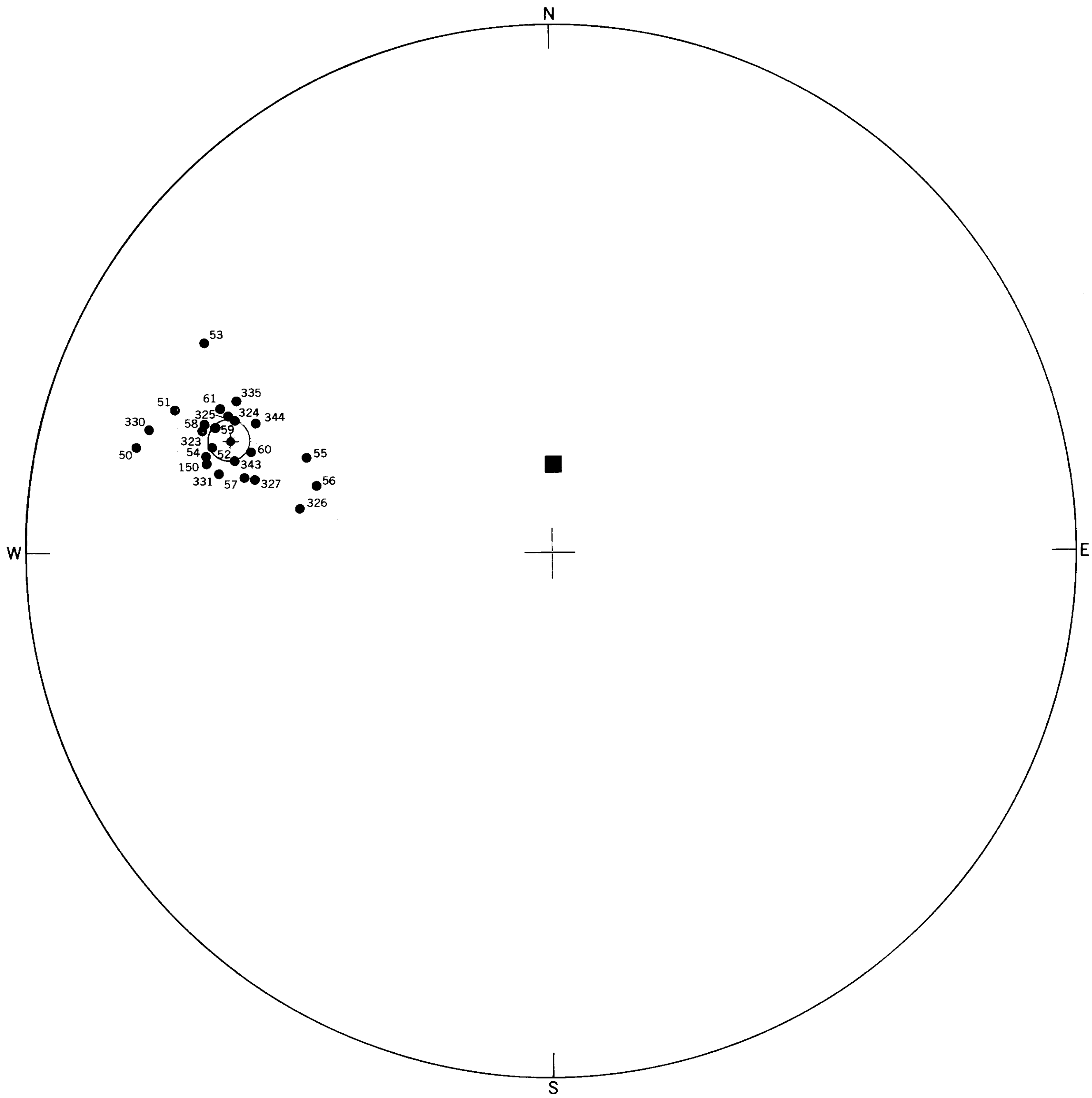


FIGURE 2.—Simplified columnar section for the Portage Lake Lava Series near Kearsarge, Mich., showing stratigraphic position of samples studied. Section from White, Cornwall, and Swanson (1953). Labels next to points in this figure and succeeding figures refer to sampling sites.



EXPLANATION

FIGURE 3.—Directions of remanent magnetization for flows of the Portage Lake Lava Series below conglomerate No. 14 (Houghton Conglomerate) near Kearsage, Mich. Data corrected for geologic dip. Equal-area projection, lower hemisphere. See table 2 and figure 2 for sample locations.

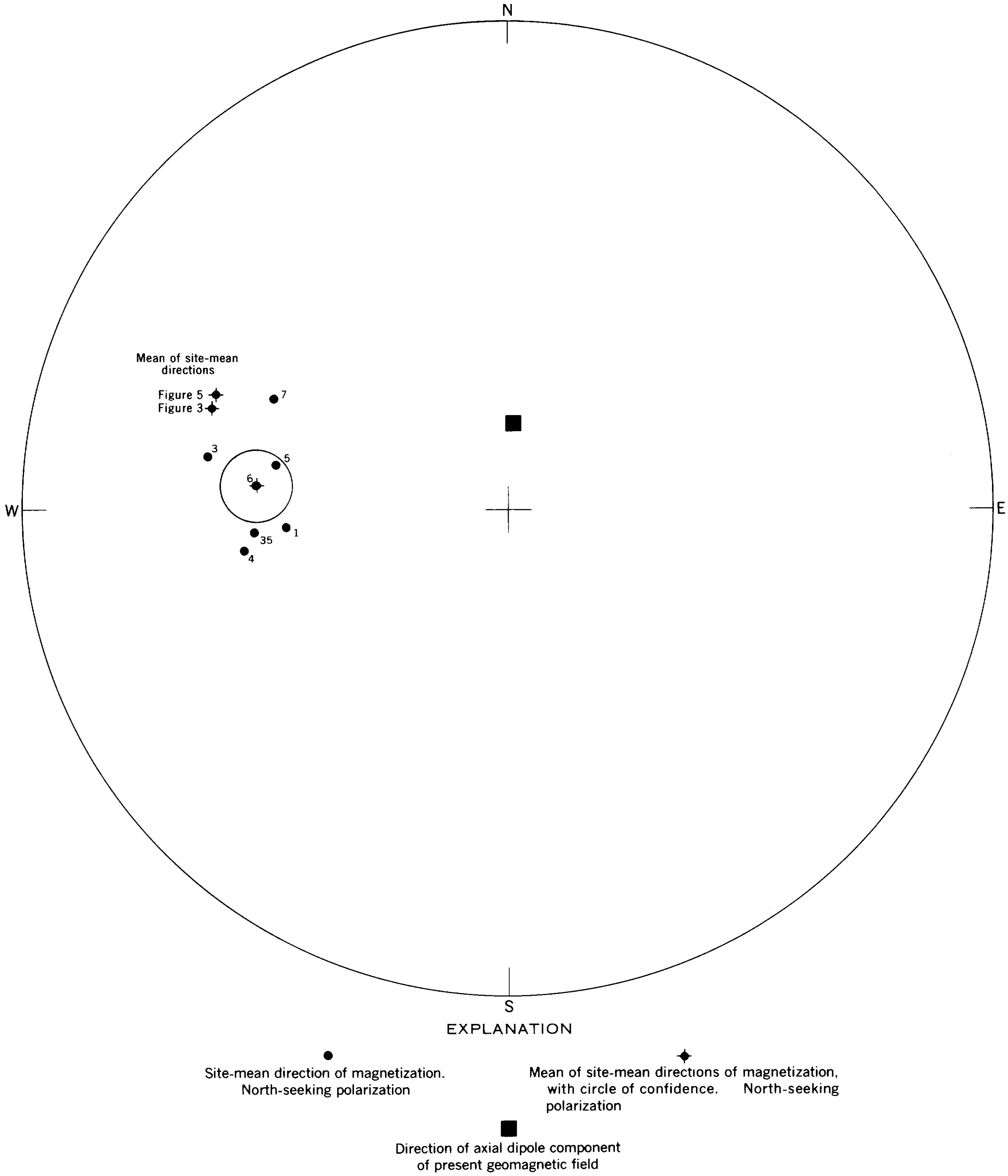
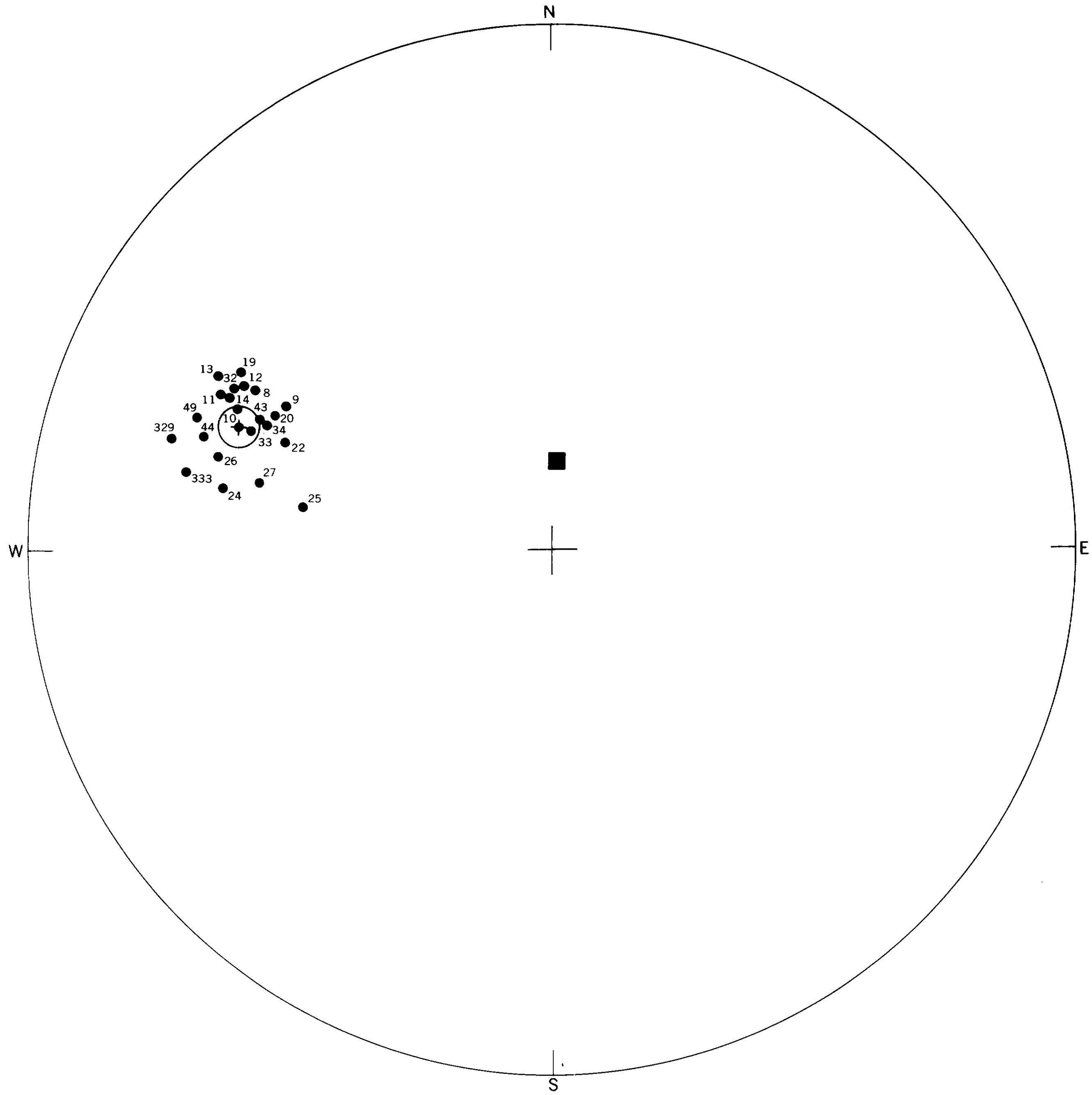


FIGURE 4.—Directions of remanent magnetization for flows of the Portage Lake Lava Series between conglomerate No. 14 (Houghton) and conglomerate No. 15 (Allouez) near Kearsarge, Mich. Data corrected for geologic dip. Equal-area projection, lower hemisphere. See table 2 and figure 2 for sample locations.



EXPLANATION

● Site-mean direction of magnetization. North-seeking polarization

✦ Mean of site-mean directions of magnetization, with circle of confidence. North-seeking polarization

■ Direction of axial dipole component of present geomagnetic field

FIGURE 5.—Directions of remanent magnetization for flows of the Portage Lake Lava Series above conglomerate No. 15 (Allouez Conglomerate) near Kearsarge, Mich. Data corrected for geologic dip. Equal-area projection, lower hemisphere. See table 2 and figure 2 for sample locations.

TABLE 2.—*Paleomagnetic results for Portage Lake Lava Series near Kearsarge, Mich.*

[Paleomagnetic data are corrected for geologic dip. Stratigraphic locations of samples are shown in fig. 2]

Site No.	Number of samples (*N*)	Mean direction of magnetization at collecting site		Remanent intensity (emu/cm³×10⁻⁶)	Location and attitude of lava flow
		Declination, *D* (degrees)	Inclination, *I* (degrees)		
Samples from below conglomerate No. 14					
PL150	4	284.4	33.0	4,110	700 ft north, 1,100 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 37° E., dip 38.5° NW.
50	5	284.2	19.9	900	Iroquois Flow. 2,050 ft south, 2,700 ft west of SE. cor. sec. 6, T. 56 N., R. 32 W. Strike N. 35° E., dip 40° NW.
331	5	283.3	35.3	1,450	1,950 ft south, 2,350 ft west of NE. cor. sec. 6, T. 56 N., R. 32 W. Strike N. 38° E., dip 40° NW.
344	3	294.7	38.2	450	350 ft south, 950 ft east of NW. cor. sec. 7, T. 57 N., R. 32 W. Strike N. 38° E., dip 40° NW.
51	3	290.9	24.8	480	Osceola Flow. 850 ft south, 100 ft west of NE. cor. sec. 6, T. 56 N., R. 32 W. Strike N. 40° E. dip 41° NW.
330	5	286.8	21.0	431	725 ft north, 2,500 ft west of SE. cor. sec. 6, T. 56 N., R. 32 W. Strike N. 33° E., dip 40° NW.
52	5	287.4	32.9	1,580	1,300 ft south, 1,700 ft east of NW. cor. sec. 7, T. 56 N., R. 32 W. Strike N. 32° E., dip 40° NW.
323	4	289.6	30.6	235	2,150 ft south, 1,850 ft east of NW. cor. sec. 7. T. 56 N., R. 32 W. Strike N. 34° E., dip 40° NW.
53	5	300.8	24.6	694	1,500 ft south, 2,100 ft east of NW. cor. sec. 7, T. 56 N., R. 32 W. Strike N. 32° E., dip 40° NW.
324	5	293.0	35.0	2,600	1,900 ft south, 2,150 ft west of NE. cor. sec. 7, T. 56 N., R. 32 W. Strike N. 31° E., dip 40° NW.
335	4	296.1	33.7	249	Kearsarge Flow. 2,250 ft north, 1,900 ft east of SW. cor. sec. 27, T. 57 N., R. 32 W. Strike N. 43° E., dip 38° NW.
54	5	285.6	32.0	320	Kearsarge Flow. 1,350 ft south, 1,500 ft west of NE. cor. sec. 7, T. 56 N., R. 32 W. Strike N. 31° E., dip 41° NW.
55	5	291.1	48.8	148	1,850 ft south, 1,300 ft west of NE. cor. sec. 7, T. 56 N., R. 32 W. Strike N. 31° E., dip 41.5° NW.
56	5	285.6	51.5	125	1,800 ft south, 1,350 ft west of NE. cor. sec. 7, T. 56 N., R. 32 W. Strike N. 31° E., dip 41.5° NW.
326	5	279.8	50.0	197	2,500 ft north, 200 ft east of SW. cor. sec. 8, T. 56 N., R. 32 W. Strike N. 27.5° E., dip 40° NW.
327	4	283.8	41.5	132	2,350 ft north, 600 ft east of SW. cor. sec. 8, T. 56 N., R. 35 W. Strike N. 27.5° E., dip 40° NW.
57	4	283.6	39.6	720	2,750 ft south, 800 ft east of NW. cor. sec. 8, T. 56 N., R. 32 W. Strike N. 26° E., dip 45° NW.
58	4	290.9	30.2	3,200	2,760 ft south, 800 ft east of NW. cor. sec. 8, T. 56 N., R. 32 W. Strike N. 26° E., dip 45° NW.
59	4	290.3	32.5	1,280	Scales Creek Flow. 2,600 ft south, 1,200 ft east of NW. cor. sec. 8, T. 56 N., R. 32 W. Strike N. 27° E., dip 46° NW.
60	4	288.5	40.0	353	2,750 ft south, 1,300 ft east of NW. cor. sec. 8, T. 56 N., R. 32 W. Strike N. 27° E., dip 46° NW.
325	5	293.2	33.6	307	1,300 ft south, 100 ft west of NE. cor. sec. 7, T. 56 N., R. 32 W. Strike N. 25° E., dip 44° NW.
61	4	294.2	31.7	114	3,450 ft south, 2,350 ft east of NW. cor. sec. 8, T. 56 N., R. 32 W. Strike N. 22° E., dip 49° NW.
343	5	285.7	37.1	2,030	Copper City Flow. 250 ft south, 2,350 ft east of NW. cor. sec. 17, T. 56 N., R. 32 W. Strike N. 17.5° E., dip 52° NW.
Samples from between conglomerate Nos. 14 and 15					
PL35	5	264.9	45.6	554	2,150 ft north, 1,175 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 38° E., dip 38° NW.
7	4	294.6	45.2	747	1,350 ft north, 1,850 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 37.5° E., dip 38° NW.
6	4	274.7	45.2	117	2,000 ft north, 1,150 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 38° E., dip 37.5° NW.
5	5	280.8	49.7	330	2,100 ft north, 1,200 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 38° E., dip 37.5° NW.
4	6	261.0	43.2	107	750 ft north, 2,350 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 37° E., dip 38° NW.
3	5	279.5	36.6	1,020	700 ft north, 2,200 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 37° E., dip 38° NW.
1	5	265.6	51.6	2,200	0 ft north, 2,200 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 37° E., dip 38.5° NW.
Samples from above conglomerate No. 15					
PL44	3	287.9	29.6	1,800	Section line, 1,250 ft south of NW. cor. sec. 1, T. 56 N., R. 33 W. Strike N. 37° E., dip 34.5° NW.
333	5	281.8	28.8	2,380	2,450 ft north, 900 ft west of SE. cor. sec. 36, T. 57 N., R. 33 W. Strike N. 34° E., dip 33.5° NW.

TABLE 2.—*Paleomagnetic results for Portage Lake Lava Series near Kearsarge, Mich.*—Continued

Site No.	Number of samples (*N*)	Mean direction of magnetization at collecting site		Remanent intensity (emu/cm³×10⁻⁶)	Location and attitude of lava flow
		Declination, *D* (degrees)	Inclination, *I* (degrees)		
Samples from above conglomerate No. 15—Continued					
PL49	5	290.1	27.5	1,720	3,350 ft north, 2,200 ft west of SE. cor. sec. 36, T. 56 N., R. 33 W. Strike N. 35° E., dip 35° NW.
329	3	286.1	24.4	188	Ashbed Flow. 1,400 ft north, 2,250 ft west of SE. cor. sec. 20, T. 57 N., R. 32 W. Strike N. 39° E., dip 27.5° NW.
43	4	293.7	38.1	1,410	Ashbed Flow. 2,050 ft north, 450 ft west of SE. cor. sec. 36, T. 57 N., R. 33 W. Strike N. 38° E., dip 36° NW.
27	4	282.8	41.5	2,640	2,750 ft north, 2,950 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 37° E., dip 35.5° NW.
26	5	285.9	33.6	1,450	2,900 ft north, 3,350 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 37° E. dip 36° NW.
25	5	279.3	49.7	298	2,650 ft north, 3,300 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 37° E., dip 36.5° NW.
24	4	280.2	35.7	2,260	2,550 ft north, 3,250 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 37° E., dip 36.5° NW.
22	6	291.4	43.6	802	2,200 ft north, 3,200 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 37.5° E., dip 37° NW.
20	5	295.3	40.2	880	2,150 ft north, 3,000 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 37.5° E., dip 37° NW.
19	3	299.0	31.7	1,150	1,950 ft north, 2,975 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 37.5° E., dip 37° NW.
14	5	294.7	32.0	713	1,275 ft north, 2,950 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 37° E., dip 37.5° NW.
13	5	296.9	28.2	634	1,250 ft north, 2,900 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 38° E., dip 37.5° NW.
12	5	297.8	33.6	1,300	1,125 ft north, 2,875 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 37.5° E., dip 37.5° NW.
11	5	293.6	30.3	826	1,110 ft north, 2,850 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 38° E., dip 38° NW.
10	5	293.6	33.7	423	1,100 ft north, 2,825 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 38° E., dip 38° NW.
9	4	297.6	40.8	837	1,200 ft north, 2,800 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 37.5° E., dip 38° NW.
8	5	297.1	45.5	526	1,050 ft north, 2,800 ft west of SE. cor. sec. 31, T. 57 N., R. 32 W. Strike N. 38° E., dip 38° NW.
32	5	296.4	32.0	431	Greenstone Flow. 600 ft north, 3,700 ft west of SE. cor. sec. 29, T. 57 N., R. 32 W. Strike N. 46° E., dip 35.5° NW.
33	5	291.0	37.2	3,330	500 ft north, 3,650 ft west of SE. cor. sec. 29, T. 57 N., R. 32 W. Strike N. 46° E., dip 35.5° NW.
34	4	293.7	39.1	767	350 ft north, 3,600 ft west of SE. cor. sec. 29, T. 57 N., R. 32 W. Strike N. 46° E., dip 35.5° NW.

QUARTZ PORPHYRY NORTH OF LAKE GOGEBIC, MICHIGAN

Thirteen samples from three sites represent the quartz porphyry outcrops along the Bergland-White Pine road about 4 miles north of Lake Gogebic, Mich. This geologic unit lies between typical middle Keweenawan lava flows and is intruded by a basalt dike in this area. Dip of the lower contact is approximately 35° NW. (Brooks and Garbutt, 1969), and data in figure 8 and table 6 have been corrected for this dip.

RHYOLITE INTRUSION IN SEC. 4, T. 56 N., R. 32 W.

Paleomagnetic data for eight samples are shown in figure 9 and table 7. The samples are from a poorly exposed rhyolite body that intrudes the Portage Lake Lava Series east of Kearsarge, Mich.

RHYOLITE INTRUSION IN SECS. 24 AND 25, T. 56 N., R. 34 W.

Paleomagnetic data for six samples from one site are shown in figure 10 and table 8. These samples are from a rhyolite body that intrudes the Freda Sandstone in secs. 24 and 25, T. 56 N., R. 34 W. southwest of Kearsarge, Mich. No other intrusions are known to cut rocks so high in the stratigraphic column. Dip of the Freda in this area is 22° NW., and figure 10 and table 8 show the direction of magnetization corrected for this dip.

IRONWOOD-MELLEN AREA

GEOLOGIC SETTING

Formations of the Keweenaw Peninsula in Michigan can be traced southwest toward the Wisconsin border.

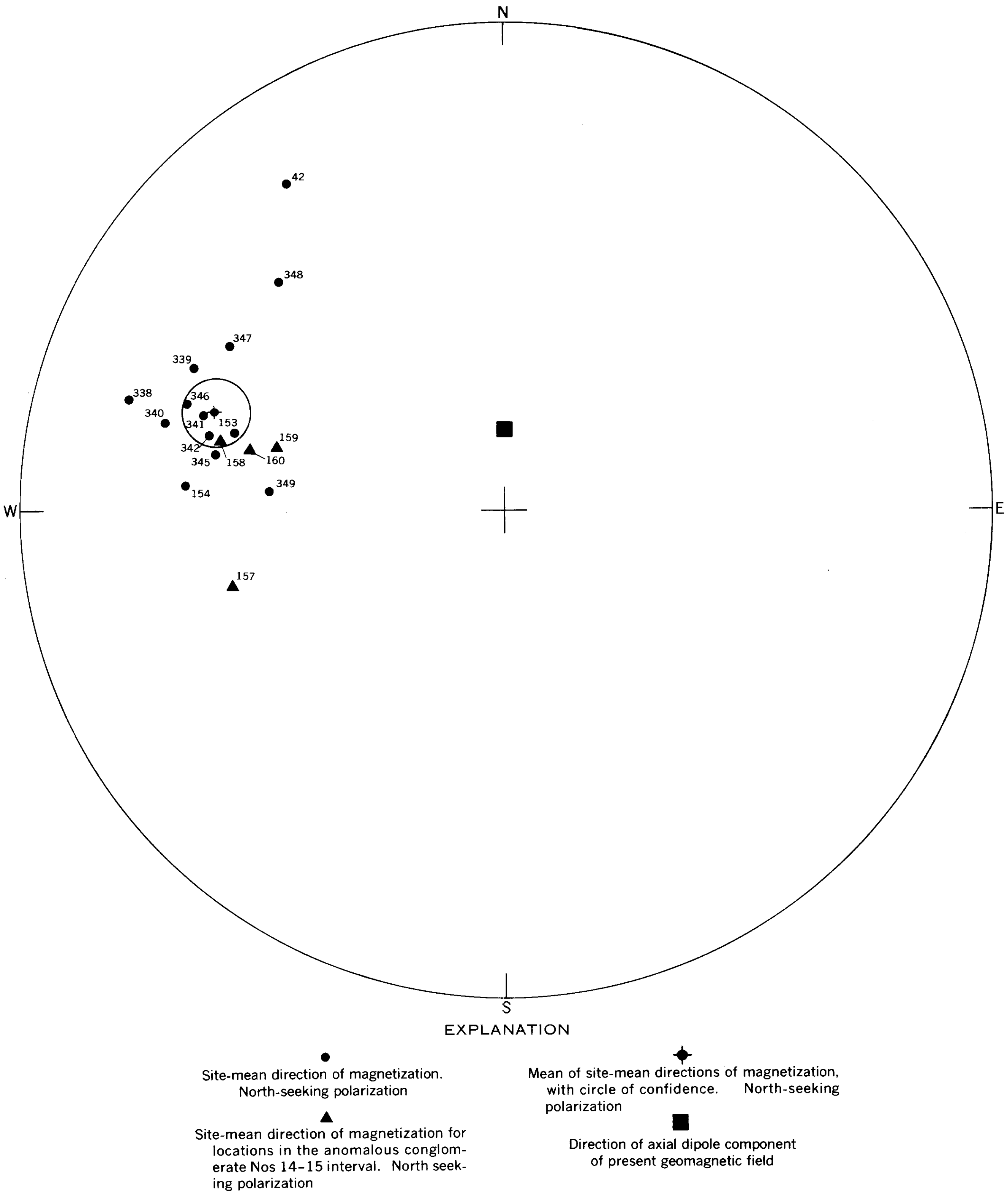


FIGURE 6.—Directions of remanent magnetization for miscellaneous flows of the Portage Lake Lava Series northeast of the Kearsarge, Mich., area. Data corrected for geologic dip. Equal-area projection, lower hemisphere. See table 3 for sample locations.

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TABLE 3.—*Paleomagnetic results for miscellaneous flows of the Portage Lake Lava Series northeast of Kearsarge, Mich.*

[Paleomagnetic data are corrected for geologic dip]

Site No.	Number of samples (*N*)	Mean direction of magnetization at collecting site: Declination, *D* (degrees)	Mean direction of magnetization at collecting site: Inclination, *I* (degrees)	Remanent intensity (emu/cm³×10⁻⁶)	Location and attitude of lava flow
PL340	5	284.8	27.9	197	Ashbed Flow. 650 ft north, 2,700 ft west of SE. cor. sec. 8, T. 58 N., R. 30 W. Strike N. 76° E., dip 26° NW.
338	4	286.9	19.7	2,240	Ashbed Flow. 100 ft south, 2,750 ft west of NE. cor. sec. 30, T. 58 N., R. 31 W. Strike N. 61° E., dip 28° NW.
339	4	294.6	29.8	1,810	Ashbed Flow. 1,700 ft south, 950 ft east of NW. cor. sec. 21, T. 58 N., R. 31 W. Strike N. 70° E., dip 27.5° NW.
342	5	284.5	36.8	2,370	Ashbed Flow. 600 ft south, 250 ft east of NW. cor. sec. 12, T. 58 N., R. 29 W. Strike N. 77.5° E., dip 22° NW.
349	4	274.6	49.1	154	Greenstone Flow. 1,500 ft south, 100 ft west of NE. cor. sec. 30, T. 58 N., R. 31 W. Strike N. 77° E., dip 24° NW.
348	4	315.6	33.6	2,980	Greenstone Flow. 600 ft south, 4,150 ft west of NE. cor. sec. 16, T. 58 N., R. 30 W. Strike N. 77° E., dip 24° NW.
347	4	301.0	33.4	752	Greenstone Flow. 600 ft south, 2,500 ft west of NE. cor sec. 16, T. 58 N., R. 30 W. Strike N. 77° E., dip 24° NW.
346	4	288.7	30.9	338	Greenstone Flow. 1,000 ft south, 2,000 ft west of NE. cor. sec. 16, T. 58 N., R. 30 W. Strike N. 77° E., dip 24° NW.
345	5	281.2	38.3	308	Greenstone Flow. 2,100 ft south, 160 ft west of NE. cor. sec. 16, T. 58 N., R. 30 W. Strike N. 77° E., dip 24° NW.
158 [1]	5	283.0	38.9	639	2,250 ft north, 550 ft west of SE. cor. sec. 16, T. 58 N., R. 30 W. Strike N. 79° E., dip 24° NW.
160 [1]	4	283.0	44.3	293	2,150 ft north, 650 ft west of SE. cor. sec. 16, T. 58 N., R. 30 W. Strike N. 79° E., dip 25° NW.
159 [1]	4	284.3	48.8	498	2,000 ft north, 500 ft west of SE. cor. sec. 16, T. 58 N., R. 30 W. Strike N. 79° E., dip 25° NW.
157 [1]	5	254.7	40.4	2,660	1,350 ft north, 300 ft east of SW. cor. sec. 15, T. 58 N., R. 30 W. Strike N. 79° E., dip 25° NW.
341	5	287.9	34.9	138	Scales Creek Flow. 1,100 ft south, 400 ft west of NE. cor. sec. 25, T. 58 N., R. 30 W. Strike N. 74.5° E., dip 42° NW.
154	5	274.2	33.1	256	2,400 ft north, 2,400 ft east of SW. cor. sec. 30, T. 58 N., R. 29 W. Strike N. 70° E., dip 56° NW.
153	6	286.2	41.0	115	800 ft north, 1,950 ft east of SW. cor. sec. 30, T. 58 N., R. 29 W. Strike N. 71.5° E., dip 59° NW.
42	4	326.7	19.5	376	1,000 ft south, 2,050 ft east of NW. cor. sec. 32, T. 58 N., R. 29 W. Strike N. 79° E., dip 63° N.

[1] Site is in the anomalous interval between conglomerate Nos. 14 and 15.

TABLE 4.—*Comparison of declination and strike along the Ashbed Flow in the Portage Lake Lava Series at sites in the northern part of the Keweenaw Peninsula*

[Site locations are given in tables 2 and 3]

Site No.	Strike	Declination, *D* (degrees)
PL43	N. 38° E.	293.7
329	N. 39° E.	286.1
338	N. 61° E.	286.9
339	N. 70° E.	294.6
340	N. 76° E.	284.8
342	N. 78° E.	284.5

In the Ironwood, Mich., area they are joined by lavas of the so-called South Trap Range; these are Keweenawan volcanic rocks distinct from those of the main outcrop belt of the Portage Lake Lava Series that can be traced eastward past the south end of Lake Gogebic, Mich. Two isolated exposures, one at Silver Mountain in Michigan (fig. 1) and one 3 miles southeast at Sturgeon Falls, are 25 miles northeast of the most easterly exposure of the main belt of South Trap Range rocks. Lavas of the South Trap Range are mostly basalts, but they are lithologically distinct (Hubbard, 1968, p. 35) from the middle Keweenawan basalts farther north. In the Marenisco, Mich., area the South Trap Range basalts lie unconformably upon the Animikie (Van Hise and Leith, 1911, p. 234; Fritts, 1965) and near Ironwood they dip 60° to 85° northward. Near Lake Gogebic the flat-lying Jacobsville Sandstone overlaps the South Trap Range lavas onto the Animikie (Van Hise and Leith, 1911; Fritts, 1965) and again farther east the South Trap Range lavas are overlapped and buried by the Jacobsville Sandstone.

Westward from the Ironwood area the South Trap Range lavas dip steeply northward and appear to be conformable on (Marquette Range Supergroup) rocks of the Gogebic Iron Range. According to Aldrich (1929, p. 108–109) proof of the unconformity in this area rests entirely upon broad field relations; however, suggestions of an unconformable relationship have been observed (Van Hise and Leith, 1911, p. 234; Aldrich, 1929, p. 108–109) west of Mellen, Wis.

At Mellen and westward a gabbro-granophyre complex has been intruded along zones of weakness in

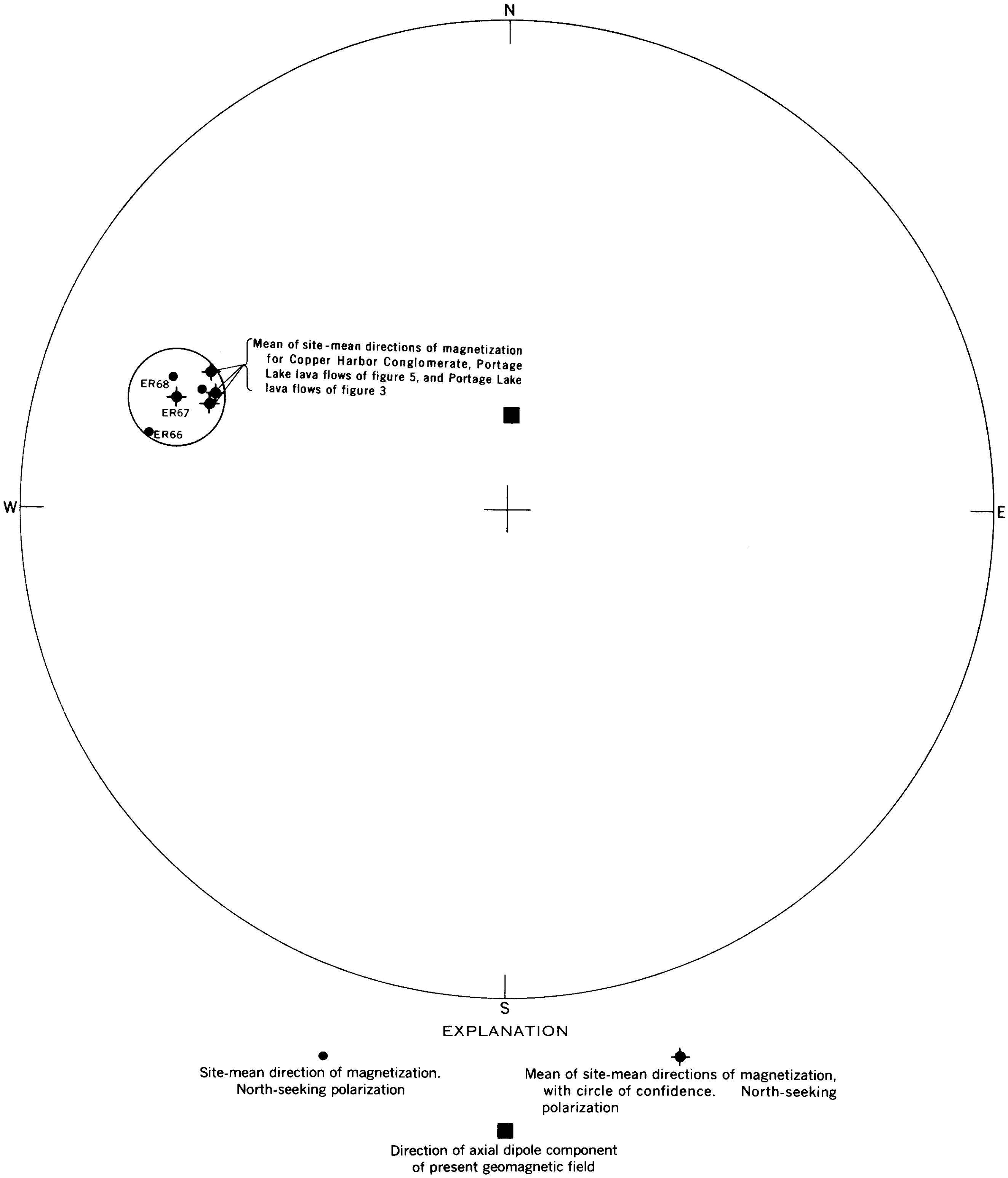


FIGURE 7.—Directions of remanent magnetization for middle Keweenawan rhyolite flows north of Lake Gogebic, Mich. Data corrected for geologic dip. Equal-area projection, lower hemisphere. See table 5 for site locations. Data for Copper Harbor Conglomerate from DuBois (1962).

TABLE 5.—*Paleomagnetic results for middle Keweenawan rhyolite flows north of Lake Gogebic, Mich.*

[Sites are in T. 49 N., R. 42 W. Data are corrected for geologic dip]

Site No.	Number of samples (*N*)	Mean direction of magnetization at collecting site		Remanent intensity (emu/cm³×10⁻⁶)	Location and attitude of lava flow
		Declination, *D* (degrees)	Inclination, *I* (degrees)		
ER66	5	281.1	24.8	44.6	1,000 ft south, 1,050 ft west of NE. cor. sec. 5. Strike N. 64° E., dip 23° NW.
67	4	290.3	32.7	15.8	1,100 ft south, 1,100 ft west of NE. cor. sec. 5. Strike N. 64° E., dip 23° NW.
68	4	290.4	26.4	24.5	2,000 ft north-northeast of Bergland fire tower. 800 ft north, 0 ft west of SE. cor. sec. 32. Strike N. 65° E., dip 23° NW.

middle Keweenawan lava flows. Leighton (1954, p. 406) has shown that layering in the gabbro dips about 20° less than that in the enclosing lavas. His interpretation of the relation suggests the flows were inclined before intrusion of the gabbro and that further tilting occurred after intrusion. Paleomagnetic evidence (Books and others, 1966, p. D123) supports this interpretation.

DESCRIPTION OF RESULTS

LOWERMOST KEWEENAWAN LAVA FLOWS

In the Ironwood area, the South Trap Range rocks crop out in two parallel east-west ridges that have a total width of about 1.6 miles; these ridges are separated from the main belt of the Portage Lake Lava Series to the north by an area of low relief 2 miles wide in which the nature of the bedrock is not known. Northeast of Ironwood the lowest South Trap Range flows are underlain by quartzite in sec. 12, T. 47 N., R. 47 W.

Samples were collected at various sites across the South Trap Range outcrop belt and represent about 8,000 feet of lava flows. Results representing the upper 6,700 feet of flows have already been reported (Books, 1968). Those data show south-seeking polarization similar to that found in the upper part of the lower Keweenawan Sibley Series of the Nipigon basin by DuBois (1962, p. 42–45). Results representing the lowermost 400 feet of lava flows in the Ironwood area as well as the basal quartzite northeast of Ironwood are presented in figure 11 and table 9. These data show a magnetization that is northseeking down.

PORTAGE LAKE LAVA SERIES

Portage Lake lavas north of Ironwood trend approximately N. 80° E., across the Black River. Collections were made from four sites in the quarry at Chippewa Hill, Mich., in sec. 32, T. 49 N., R. 46 W., and from five sites 1 mile north near Algonquin Falls on the Black River. Figures 12 and 13 and tables 10 and 11 show the results.

NORTH SHORE OF LAKE SUPERIOR

GEOLOGIC SETTING

The Puckwunge Formation of sandstone, quartz conglomerate, and quartzite forms the base of the Keweenawan Series in Minnesota, whereas to the northeast, in the Thunder Bay district, Ontario, the lower Keweenawan sedimentary rocks are represented by the Sibley Series. In both areas the sedimentary rocks are overlain by thick sequences of volcanic rocks, known in Minnesota as the North Shore Volcanic Group (Goldich and others, 1961) and in the Thunder Bay district, as the Osler Series. On Isle Royale, Mich., the middle Keweenawan lavas are overlain by upper Keweenawan clastic sedimentary rocks.

These Keweenawan rocks form the northwest flank of the Lake Superior syncline and dip toward the lake at shallow angles that rarely exceed 20°. In general, the traces of individual stratigraphic units form a broad arc that is almost parallel to the shoreline, but near Duluth and Grand Portage, Minn., the units curve lakeward and intersect the shoreline at sharp angles.

Grout, Sharp, and Schwartz (1959, p. 37–38) have made a detailed study of the volcanic succession between Grand Portage and Tofte, Minn. A total of 94 flows were found in this interval—the lowest is at Grand Portage and the highest, at Tofte. Total estimated thickness along the shoreline (less interflow sedimentary rocks, numerous diabase intrusions, and the Duluth Gabbro at Hovland, Minn.) is 17,500 feet. Thickness of the complete section could be as much as 29,000 feet.

DESCRIPTION OF RESULTS

NORTH SHORE VOLCANIC GROUP

Sample collections were made from 52 of the total of 94 flows (Grout and others, 1959, p. 37–38) found between Grand Portage and Tofte, Minn. The collection sites are on or close to the shoreline and extend from flow No. 2 to flow No. 94 of Grout, Sharp, and Schwartz (1959). Paleomagnetic results for 11 site locations on

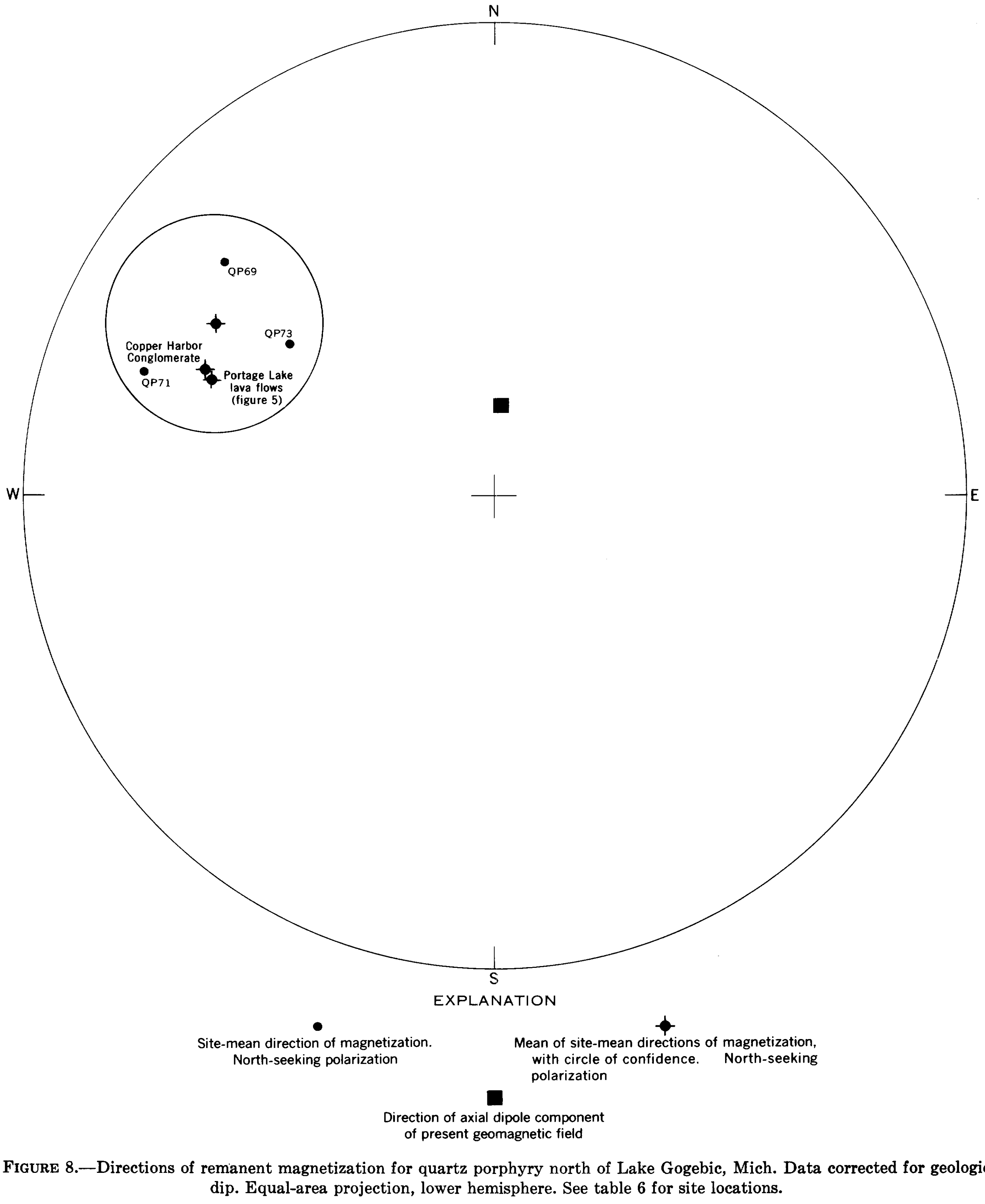


FIGURE 8.—Directions of remanent magnetization for quartz porphyry north of Lake Gogebic, Mich. Data corrected for geologic dip. Equal-area projection, lower hemisphere. See table 6 for site locations.

TABLE 6.—*Paleomagnetic results for quartz porphyry north of Lake Gogebic, Mich.*

[Sites are in sec. 17, T. 49 N., R. 42 W. Quartz porphyry strikes N. 68° E. and dips 35° NW. Data are corrected for geologic dip]

Site No.	Number of samples (*N*)	Mean direction of magnetization at collecting site: Declination, *D* (degrees)	Inclination, *I* (degrees)	Remanent intensity (emu/cm³ $\times 10^{-6}$)	Location
QP69	4	310.5	25.0	11.7	3,200 ft south, 600 ft east of NW. cor.
71	4	289.1	20.9	7.2	3,700 ft south, 750 ft east of NW. cor.
73	5	305.8	44.8	13.7	Section line, 1,500 ft east of SW. cor.

the lowermost 20 flows (representing 4,550 feet of strata) include a reversal of the paleomagnetic field direction and have been described by Books (1968). Paleomagnetic data for the remaining overlying flows, less five site locations where the data were too scattered to utilize, are shown in figure 14 and table 12.

ISLE ROYALE LAVA FLOWS

Nine site locations, represented by 44 samples, are in the vicinity of Lane's (1911, pl. 1) Greenstone Flow in the Washington Harbor area of Isle Royale. Resulting directions of magnetization fall into two distinct groups as shown in figure 15. Site locations are given in table 13.

DISCUSSION OF RESULTS

LOWER KEWEENAWAN

The Sibley Series of Tanton (1927) is lower Keweenawan according to the generally accepted classification of Keweenawan rocks (Leith and others, 1935). DuBois (1962, p. 42–45) collected at several different locations on the Sibley Peninsula and on the Black Sturgeon River (fig. 1). He cited (DuBois, 1962, p. 44–45) two reliable groupings that have opposing magnetic field directions. The group with the north pole on the lower hemisphere (fig. 16, point JI) was collected not far above the Animikie rocks on the Sibley Peninsula. The group with the south pole on the lower hemisphere (fig. 16, point JII) was collected from the upper part of the Sibley Series (DuBois, 1962, p. 44). He also indicated that the Logan sills of Lawson (1893) (fig. 16, point F), the Alona Bay lavas (fig. 16, point G), and the Baraga County dikes (Graham, 1953) (fig. 16, point H) have the south pole on the lower hemisphere, and he included them in the lower Keweenawan along with the Sibley Series.

Palmer (1970) collected at various sites on the north shore of Lake Superior. He reported that the Logan sills in Ontario, the section of volcanic rocks at Alona Bay, Ontario, and the Osler Series near Thunder Bay, Ontario, have a reversed polarity; the Michipicoten Island volcanics have a positive polarity; and the North Shore Volcanic Group of Minnesota, the lavas at Gargantua Point, Ontario, and the section at Mamainse Point, Ontario, have both normal and reversed polarity sequences.

Books (1968) reported on 14 sites in the South Trap Range (fig. 16, point C) near Ironwood, Mich., and on 11 sites in the lowermost flows (fig. 16, point E) near Grand Portage, Minn. Beck and Lindsley (1969, p. 2011) reported on seven sites in the northern tongue of the Duluth Gabbro (fig. 16, point 11) extension into Cook County, Minn. All these sites have paleomagnetic field directions that are south-seeking below the horizontal.

In addition, the author has collected samples from the lower 400 feet of lava flows near Ironwood, Mich., and from sedimentary units below the basal Keweenawan flows; these samples represent new data for which results are shown separately in figure 11. From a summary of the new paleomagnetic data and previously published data (fig. 16), it is apparent that the directions of magnetization fall into two groups with opposing directions of magnetization. The two north-seeking magnetization directions (fig. 16, group A) are representative of rocks that lie above and are apparently structurally conformable with units believed to be of Marquette Range Supergroup age. At Ironwood, this direction (fig. 16, point 10) includes the basal quartzite and overlying lower 400 feet of basal Keweenawan lava flows. On the Sibley Peninsula, Ontario, this direction includes DuBois' (1962, fig. 20) Group I, replotted on an equal-area projection (fig. 16, point JI). The south-seeking magnetization directions (fig. 16, group B) are representative of rock units at many locations around Lake Superior. At Ironwood, this direction of magnetization (fig. 16, point C) appears in volcanic rocks that are stratigraphically above and are conformable with volcanic rocks (fig. 16, point 10) lower down in the same section that have the nearly opposite direction of magnetization. On the Sibley Peninsula and in the Nipigon basin, the south-seeking directions of magnetization include DuBois' (1962, fig. 20) Group II, replotted on an equal-area projection (fig. 16, point JII). This direction probably represents rocks in a higher stratigraphic position than the Sibley Series rocks represented at point JI because most samples for this data were collected from the red dolomite unit on the Black Sturgeon River (DuBois, 1962, table XII). Wilson (1910, p. 67–69) believed that these rocks represent the upper part of the Sibley in the Nipigon basin.

Evidently, then, similarities exist between magnetic field directions and between magnetic field direction changes in the Ironwood, Mich., and Sibley Peninsula,

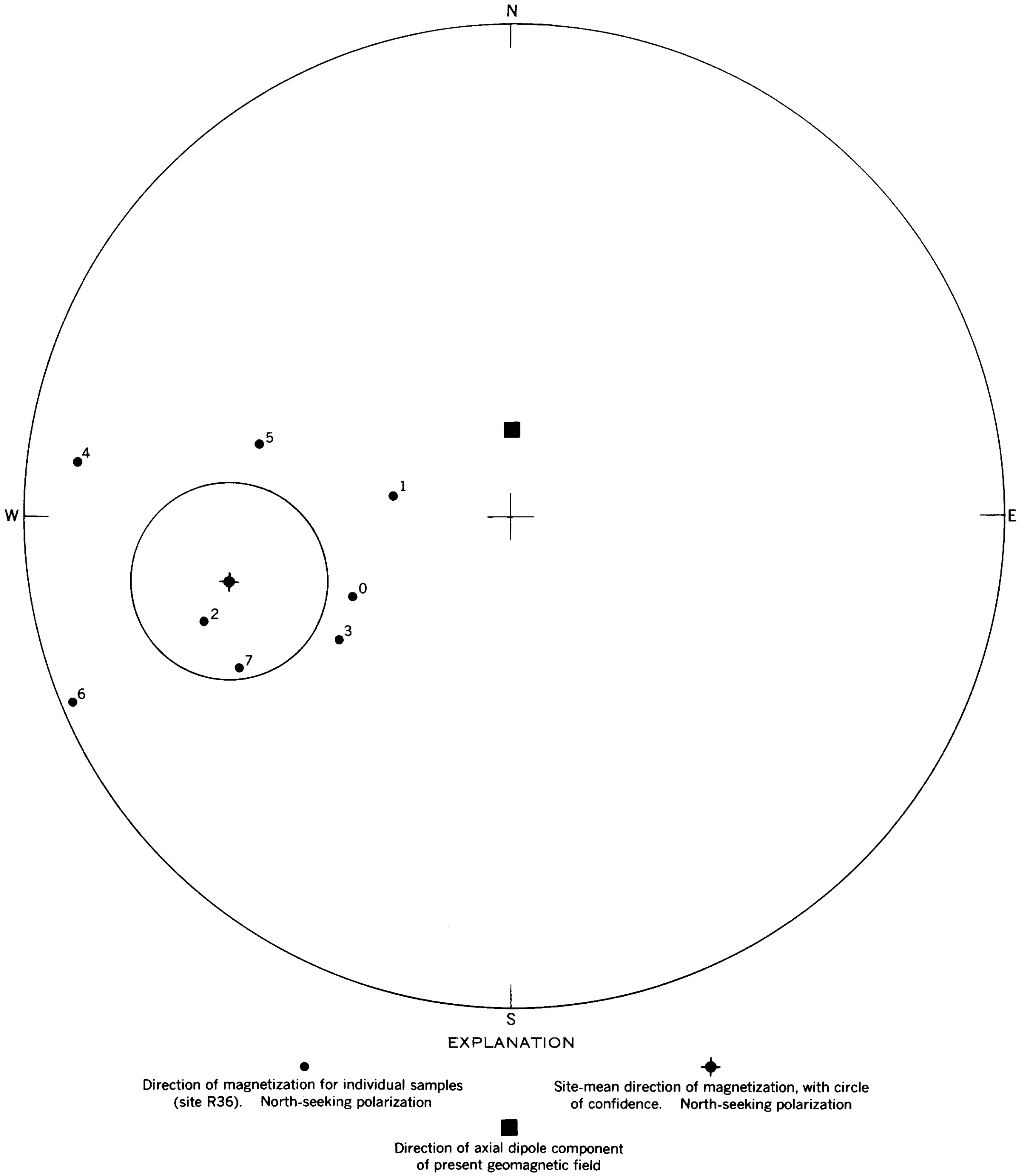


FIGURE 9.—Directions of remanent magnetization for samples from the rhyolite intrusion in sec. 4, T. 56 N., R. 32 W., east of Kearsarge, Mich. Data uncorrected for geologic dip. Equal-area projection, lower hemisphere. See table 7 for sample locations.

TABLE 7.—*Paleomagnetic results for rhyolite intrusion in sec. 4, T. 56 N., R. 32 W., east of Kearsarge, Mich.*

[Data are uncorrected for geologic dip]

Sample No.	Direction of magnetization at collecting site		Remanent intensity (emu/cm³ ×10⁻⁶)	Location from southeast corner of section
	Declination, *D* (degrees)	Inclination, *I* (degrees)		
R36-0	241.8	60.0	3.51	870 ft north, 2,540 ft west.
1	278.3	70.3	4.20	870 ft north, 2,530 ft west.
2	251.5	32.2	3.74	800 ft north, 2,450 ft west.
3	233.1	54.0	3.29	880 ft north, 2,500 ft west.
4	276.5	11.2	4.21	850 ft north, 2,500 ft west.
5	285.5	45.5	3.64	890 ft north, 2,570 ft west.
6	246.2	2.2	4.33	860 ft north, 2,510 ft west.
7	239.9	36.0	3.62	860 ft north, 2,520 ft west.

Ontario, areas. The paleomagnetic sequence of events during lower(?) Keweenawan time for these two areas as well as for other lower(?) Keweenawan locations throughout the Lake Superior region appears to be as follows:

1. First, the earth's magnetic field had a north-seeking polarization during the time interval in which the sedimentary and igneous rock units represented in figure 16, group A, were formed. In the Ironwood, Mich., area the upper limit of this interval can be located rather closely because the polarity change occurs somewhere between 400 feet and 1,200 feet above the base of the Keweenawan flows. The lower limit of this interval falls somewhere below the lowest Keweenawan rocks of the region. Figure 17 and table 14 show paleomagnetic results for one site from a pre-Keweenawan (Animikie) Marquette Range Supergroup sedimentary rock unit east of Ironwood, Mich., that not only appears to conformably underlie nearby basal Keweenawan rocks, but also has a similar direction of magnetization. Thus, the time interval represented by the direction of magnetization in the basal Keweenawan quartzite and lower 400 feet of flows in the Ironwood area may have its lower limit in rocks classified by Irving and Van Hise (1892), Van Hise and Leith (1911), Allen and Barrett (1915), and Atwater (1938) as of Animikie age. Such a possibility is supported by similar directions of magnetization for one site from the Rove Slate of the Animikie Group in the Grand Portage area, Minnesota (fig. 17, table 14).

An alternative explanation for the similar directions in the lowermost Keweenawan rocks and the Marquette Range Supergroup sedimentary rocks would require that the original magnetization directions were subsequently changed to those presently found. This interpretation does not seem impossible for the Ironwood area, because the basal Keweenawan there has been sufficiently metamorphosed to produce actinolite. However, this interpretation does not explain the near reversal in magnetic directions that begins some 1,200 feet above the basal Keweenawan flows in the Ironwood area (fig. 16, point C); the later, middle Keweenawan magnetic field directions, which are significantly different (fig. 17, Portage Lake Lava Series and North Shore Volcanic Group); and the similar direction found in the Rove Formation (fig. 17) near Grand Portage, Minn. As the reversed field directions for units above the basal flows—both near Ironwood and near Grand Portage—are believed to be original magnetization (Books, 1968, p. 251–253), any change in original magnetic directions for the basal flows must have occurred before the overlying reversely magnetized units were formed. In addition, if any phenomenon had effected such a magnetic direction change in the basal Keweenawan flows and Marquette Range Supergroup rocks it must have been sufficiently widespread to include the Ironwood and Grand Portage areas.

2. Second, following a magnetic reversal, the earth's magnetic field in the Lake Superior region had a south-seeking polarization during the time interval in which the sedimentary and igneous rock units represented in figure 16, group B, were formed. This time interval was of sufficient length for some 6,700 feet of lava flows to be extruded in the Ironwood, Mich., area as well as for the formation of various other sedimentary and igneous rock units around the periphery of Lake Superior.

The northern tongue of the Duluth Gabbro extension (fig. 16, point 11) in northern Cook County, Minn., is included in this time interval, indicating that this gabbro complex must have begun to form very early in the history of volcanism in the Lake Superior region.

In addition, Palmer's work (1970) on the north and east shores of Lake Superior indicates that the Osler Series near Thunder Bay, some of the lavas at Gargantua Point, and some of the lavas at Mamainse Point, Ontario, may also belong in this same general time interval, as these units, in part, have a south-seeking polarization.

MIDDLE KEWEENAWAN

The middle Keweenawan is represented by the Portage Lake Lava Series of the Upper Peninsula of Michigan, their equivalents to the southwest in Wisconsin, the major exposures of lava flows in Minnesota along the northwest shore of Lake Superior from Grand Portage to Tofte, and the lava flows on Isle Royale; also included are the major intrusions in the region, most of the Duluth Gabbro Complex, the Beaver Bay Complex, the Logan intrusions, and various rhyolitic and granitic rocks. Although the Copper Harbor Conglomerate has been arbitrarily classed as the lowermost formation of the upper Keweenawan (White and others, 1953), it is included with the middle Keweenawan formations because, as DuBois has pointed out (1962, p. 61–62), there is little change in the direction of magnetization between the Copper Harbor and the

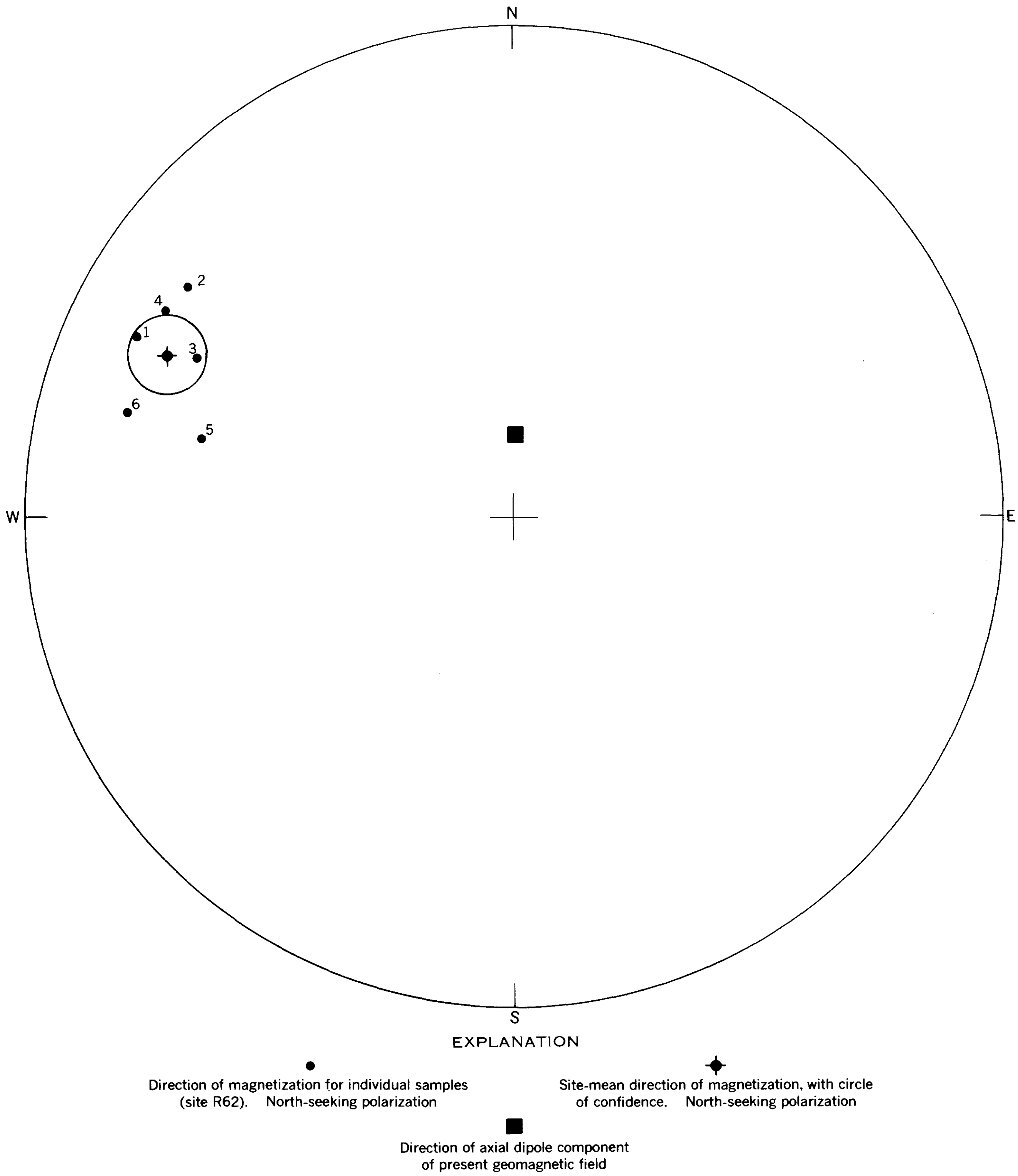


FIGURE 10.—Directions of remanent magnetization for samples from the rhyolite intrusion in secs. 24 and 25, T. 56 N., R. 34 W., southwest of Kearsarge, Mich. Data are corrected for dip of the Freda Sandstone, which the rhyolite intrudes here. Equal-area projection, lower hemisphere. See table 8 for sample locations.

TABLE 8.—*Paleomagnetic results for rhyolite intrusion in secs. 24 and 25, T. 56 N., R. 34 W., southwest of Kearsarge, Mich.*

[Data corrected for dip of Freda Sandstone, which the rhyolite intrudes in this area. Freda Sandstone strikes N. 25° E. and dips 22° NW]

Sample No.	Direction of magnetization at collecting site		Remanent intensity (emu/cm³ ×10⁻⁶)	Location from SW. cor. sec. 24
	Declination, *D* (degrees)	Inclination, *I* (degrees)		
R62-1	296.1	15.1	696	2,550 ft north, 3,350 ft east.
2	305.3	18.5	700	2,600 ft north, 3,330 ft east.
3	297.8	27.9	608	2,600 ft north, 3,300 ft east.
4	301.6	18.0	455	2,650 ft north, 3,260 ft east.
5	283.9	33.5	538	2,700 ft north, 3,200 ft east.
6	285.5	18.2	705	2,800 ft north, 3,100 ft east.

underlying Portage Lake Lava Series, but there is a large change at the conglomerate's boundary with the overlying Nonesuch Shale.

The data presented herein complete determination of directions of magnetization for most of the larger middle Keweenawan geologic units in this region. Previous paleomagnetic data are from DuBois (1962, table XVIII) for the Portage Lake Lava Series, the Duluth Gabbro, and the Copper Harbor Conglomerate; from Beck and Lindsley (1969, table 1) for the Beaver Bay Complex; from Beck (1970, table 2) for the Duluth Gabbro Complex; from Palmer (1970, tables 3–6) for the North Shore Volcanic Group and lava flows on Gargantua Point, Michipicoten Island, and Mamainse Point; and from Books, White, and Beck (1966, p. D120) for the gabbro near Mellen, Wis. The new data include directions of magnetization for the Portage Lake Lava Series and equivalents north of Ironwood, Mich., the North Shore Volcanic Group, the lava flows on Isle Royale, and the quartz porphyry north of Lake Gogebic, Mich. The results are shown in figure 18.

PORTAGE LAKE AND NORTH SHORE SEQUENCES

As noted in a previous section, the data for the Portage Lake Lava Series were divided into three parts, mainly because the middle division, between conglomerate Nos. 14 and 15, had a direction of magnetization significantly different from directions in the flows below and above. No further subdivisions in magnetic field direction data for Portage Lake lavas are shown because none are obvious. Similarly, no subdivisions in paleomagnetic data are shown for the North Shore Volcanic Group as no significant shift in the direction of the earth's magnetic field is discernible in these rocks. Figures 19 and 20 represent an attempt to correlate changes in the paleomagnetic field between the Portage Lake Lava Series and the North Shore Volcanic Group by comparing chronological movements in inclination and declination of the magnetic field for the two areas. Although the scatter in directions between sites may be attributed to secular variations, no obvious paleomagnetic patterns or correlations between the two sequences are found. If the flows in the two areas are of equivalent ages, either (1) the sampling was not sufficiently detailed to document equivalent variations in the earth's paleomagnetic field on both sides of the lake, or (2) an insufficient number of lava flows of equivalent extrusion times are present to provide similar paleomagnetic patterns in both areas.

If the two groups of lavas do not both represent the same time interval but overlap in part, the best fit for the paleomagnetic data would make the Scales Creek Flow (figs. 2, 19, and 20) of the Portage Lake Lava Series similar in age to a flow near flow No. 65 (figs. 19 and 20) of the North Shore Volcanic Group.

Where equivalent groups of lava flows are present at some distance from each other there is some indication that magnetic field direction similarities can be found. Figure 4 shows that the flows between conglomerate Nos. 14 and 15 of the Portage Lake Lava Series near Kearsarge, Mich., had a direction of magnetization significantly different from that which prevailed before (fig. 3) and after (fig. 5) their extrusion. The same departure in magnetization direction can be found in rocks representing the same stratigraphic interval in the Washington Harbor area of Isle Royale; this supports the generally accepted correlation first noted by Lane (1898). In figure 21, point 4B represents lava flows on Isle Royale that would be stratigraphically just below the probable position of the Greenstone Flow as recent mapping has shown that flow to be slightly south of where it is shown on Lane's map (N. K. Huber, written commun., 1969). Point 4A (fig. 21) represents the next lower group of lava flows. The site-mean directions of the comparable flows near Kearsarge, Mich., presented in figures 4 and 3, respectively, are plotted as points 6 and 7 in figure 21 for comparison. The flows above the aberrant interval near Kearsarge, Mich., represented by figure 5 and by point 5 in figure 21, are covered by water in the sampling area on Isle Royale.

QUARTZ PORPHYRY NORTH OF LAKE GOGEBIC, MICHIGAN

A large body of quartz porphyry within the lava series north of Lake Gogebic, Mich. (fig. 1), has long been regarded as an intrusion, but Brooks and Garbutt (1969) have recently presented evidence that the body is extrusive and separated from overlying mafic lava flows by an unconformity. Figure 22 shows the mean direction for this quartz porphyry before (A) and after (A″) a 35° correction for dip of the underlying lava flows. The proximity of A″ to the average direction for the Portage Lake Lava Series and Copper

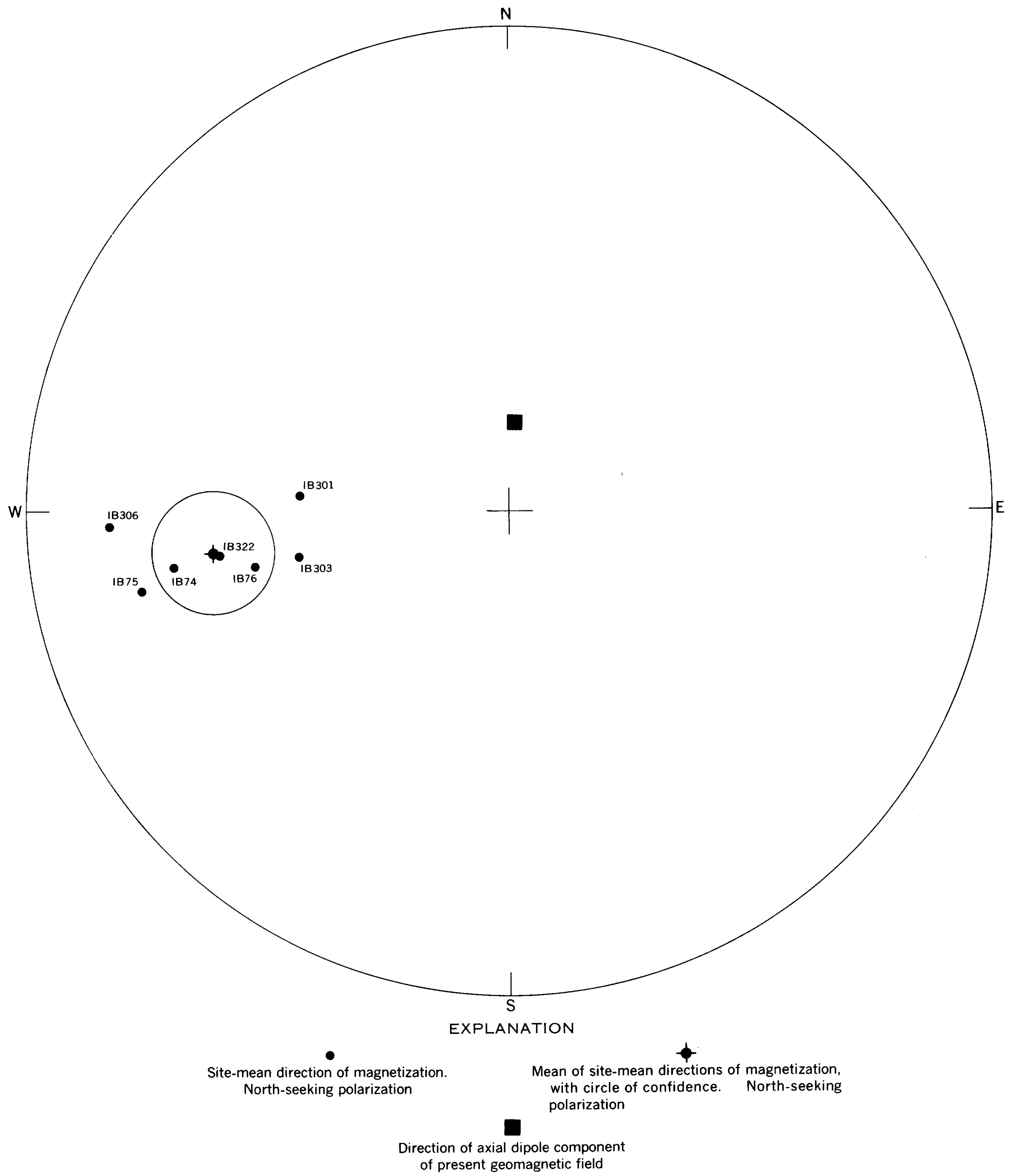


FIGURE 11.—Directions of remanent magnetization for the basal quartzite (site IB322) and lowermost 400 feet of South Trap Range lava flows near Ironwood, Mich. Data corrected for geologic dip. Equal-area projection, lower hemisphere. See table 9 for site locations.

TABLE 9.—*Paleomagnetic results for the basal quartzite and lowermost 400 feet of the South Trap Range flows near Ironwood, Mich.*
[All sites are in T. 47 N., R. 47 W. Data corrected for geologic dip]

Site No.	Number of samples (*N*)	Mean direction of magnetization at collecting site		Remanent intensity (emu/cm³×10⁻⁶)	Location and attitude
		Declination, *D* (degrees)	Inclination, *I* (degrees)		
IB74	6	260.8	29.3	1,150	600 ft north, 2,150 ft west of SE. cor. sec. 12. Strike N. 78° E., dip 69° NW.
75	4	257.6	21.7	10,400	650 ft north, 2,150 ft west of SE. cor. sec. 12. Strike N. 78° E., dip 69° NW.
76	6	258.1	44.4	5,640	750 ft north, 2,150 ft west of SE. cor. sec. 12. Strike N. 78° E., dip 69° NW.
301	5	274.7	53.8	1,420	1,800 ft south, 2,000 ft west of NE. cor. sec. 10. Strike N. 82° E., dip 65° NW.
303	6	258.2	52.6	6,460	1,850 ft south, 2,050 ft west of NE. cor. sec. 10. Strike N. 82° E., dip 65° NW.
306	4	268.1	17.9	550	700 ft north, 2,200 ft west of SE. cor. sec. 12. Strike N. 78° E., dip 69° NW.
322 [1]	5	261.3	38.1	904	590 ft north, 2,150 ft west of SE. cor. sec. 12. Strike N. 78° E., dip 69° NW.

[1] Site IB322 represents the basal quartzite.

Harbor Conglomerate is consistent with the interpretation of Brooks and Garbutt (1969), but not inconsistent with intrusion during Portage Lake or Copper Harbor time before much tilting had occurred. The paleomagnetic data are not, however, consistent with the Rb-Sr (rubidium-strontium) age of 978±40 m.y. obtained by Chaudhuri and Faure (1967, p. 1020); if the quartz porphyry were younger than the Nonesuch Shale (see following section), as this Rb-Sr age suggests, the direction of magnetization should be closer to that of the Freda Sandstone and Nonesuch Shale. (See fig. 22, point F–N.)

UPPER KEWEENAWAN

Immediately above the Copper Harbor Conglomerate are the fine-grained siltstones of the upper Keweenawan Nonesuch Shale, which in turn grade upward into the Freda Sandstone; 5,000 feet of the Freda is exposed on the Keweenaw Peninsula (Lane, 1911, p. 40, 604), and 12,000 feet of Freda is estimated in Wisconsin (Tyler and others, 1940, p. 1479). DuBois (1962, table XVIII) calculated a magnetic field direction for the Freda-Nonesuch units (see fig. 22, point F–N), as well as for some of the succeeding sedimentary rock formations.

RHYOLITE INTRUSIONS

The two rhyolite intrusions whose magnetic field directions are shown in figure 23 are included in the upper Keweenawan more on the basis of geologic information than on precise paleomagnetic data, which does not disagree with the geologic interpretation but adds little to it.

The rhyolite intrusion in secs. 24 and 25, T. 56 N., R. 34 W., near Kearsarge, Mich., cuts the Freda Sandstone, which is the youngest formation known to be intruded by igneous rocks in this part of the Lake Superior region. Dip of the Freda near the intrusion is estimated to be about 22° NW., and the paleomagnetic data have been corrected for this dip. The divergence of point a (fig. 23) from the upper Keweenawan magnetic field represented by the Freda direction (point F–N) can be explained by secular variation because the samples collected (6) were of limited extent.

Placement of the rhyolite intrusion in sec. 4, T. 56 N., R. 32 W., near Kearsarge, Mich., in the upper Keweenawan on the basis of paleomagnetic data is somewhat tenuous and requires a more detailed explanation. The rhyolite intrudes middle Keweenawan lava flows whose present dip is near 62° NW., so that in the strictest sense, the paleomagnetic data indicate only that the time of intrusion could have ranged from after structural movement was completed (no dip correction at all—point b, fig. 23) to before structural deformation of the enclosing flows (dip correction of 62° NW.—point c, fig. 23). The geologic evidence, however, suggests that the rhyolite is upper Keweenawan. White (1968, p. 313) stated that "5° to 10° of the total present dip of the top of the Portage Lake Lava Series and about 20° of the dip of the bottom antedates the deposition of the Nonesuch Shale." White believes (written commun., 1970) that the rocks which now enclose the rhyolite intrusion were dipping 15° to 20° during early Freda time. If these dips were subtracted from the present 62° dip of the enclosing flows, the paleomagnetic data would plot at points d and e and would indicate a possible range for the direction of magnetization at the time of intrusion. Note in figure 23 that points d and e are not significantly different from the Freda-Nonesuch unit direction at point F–N.

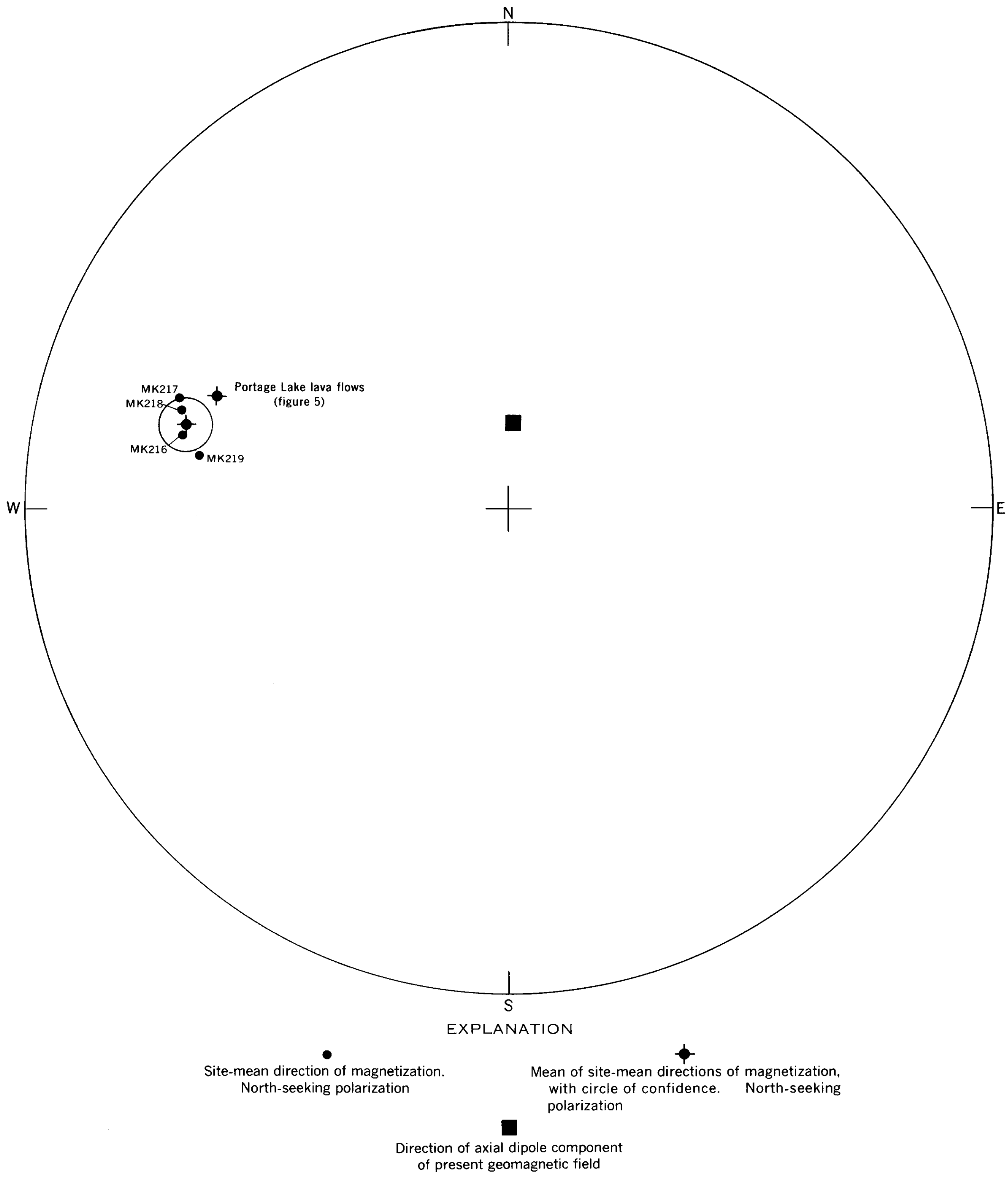


FIGURE 12.—Directions of remanent magnetization for middle Keweenawan lava flows (Portage Lake equivalents) from the Chippewa Hill quarry, Michigan, in sec. 32, T. 49 N., R. 46 W. Data corrected for geologic dip. Equal-area projection, lower hemisphere. See table 10 for site locations.

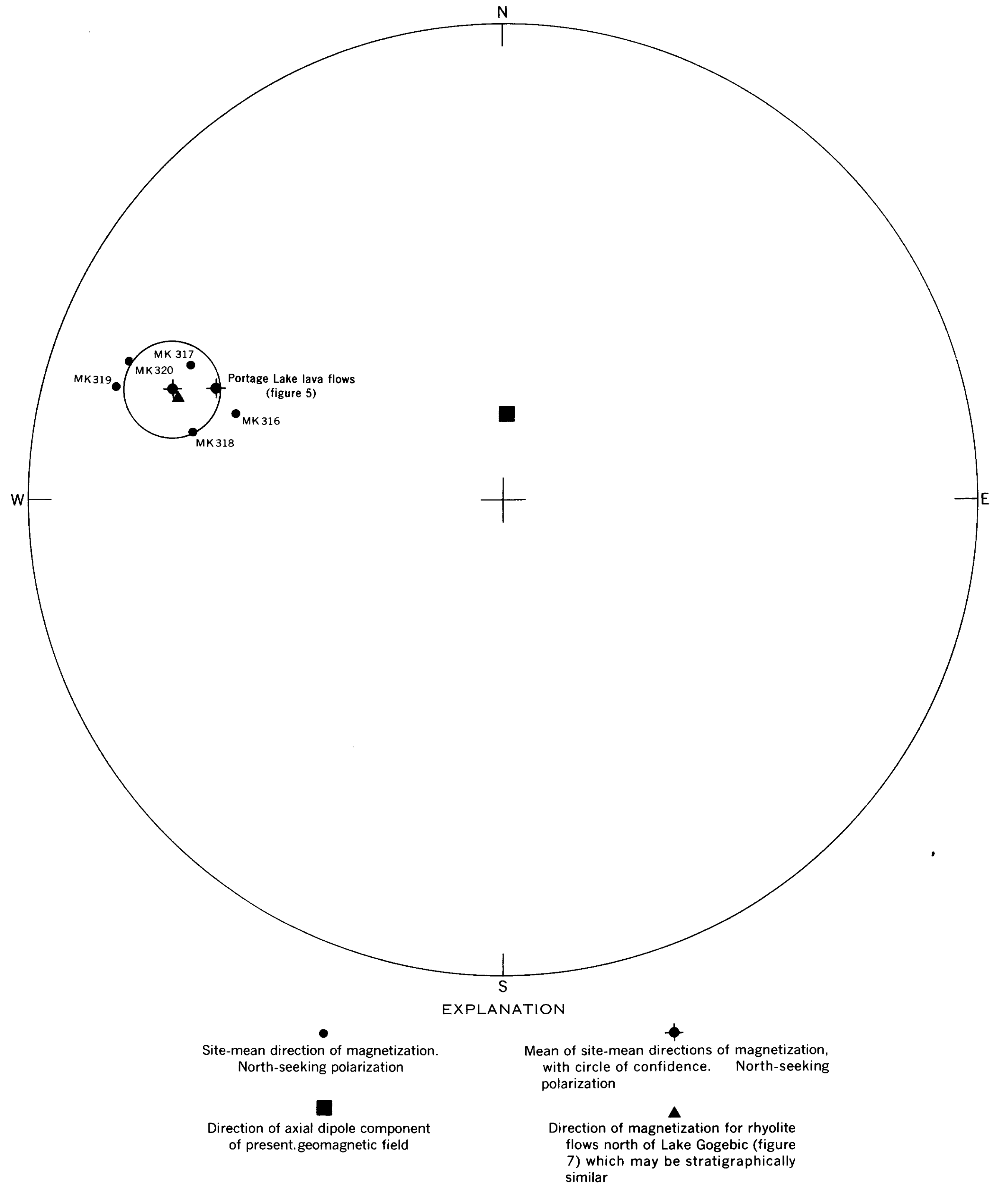


FIGURE 13.—Directions of remanent magnetization for middle Keweenawan lava flows (Portage Lake equivalents) on the Black River near Algonquin Falls, Mich. Data corrected for geologic dip. Equal-area projection, lower hemisphere. See table 11 for site locations.

TABLE 10.—*Paleomagnetic results for Portage Lake lava equivalents at the Chippewa Hill quarry north of Ironwood, Mich.*

[All sites are in sec. 32, T. 49 N., R. 46 W. Flows strike N. 85° E. and dip 40° NW. at all sites. Data are corrected for geologic dip]

Site No.	Number of samples (*N*)	Mean direction of magnetization at collecting site		Remanent intensity (emu/cm³ ×10⁻⁶)	Location from northwest corner of section
		Declination, *D* (degrees)	Inclination, *I* (degrees)		
MK216	5	282.6	30.9	698	2,600 ft south, 1,300 ft east.
217	5	283.0	28.1	825	2,620 ft south, 1,320 ft east.
218	5	286.3	29.4	586	2,640 ft south, 1,320 ft east.
219	5	279.4	35.0	732	2,680 ft south, 1,350 ft east.

TABLE 11.—*Paleomagnetic results for Portage Lake lava equivalents on the Black River near Algonquin Falls, Mich.*

[All sites are in sec. 29, T. 49 N., R. 46 W. Lava flows strike N. 80° E. and dip 30° NW. at all sites. Data are corrected for geologic dip]

Site No.	Number of samples (*N*)	Mean direction of magnetization at collecting site		Remanent intensity (emu/cm³ ×10⁻⁶)	Location from northeast corner of section
		Declination, *D* (degrees)	Inclination, *I* (degrees)		
MK316	5	287.8	39.5	836	1,200 ft south, 1,200 ft west.
317	4	929.9	28.5	1,110	1,500 ft south, 900 ft west.
318	4	282.0	32.6	1,130	1,750 ft south, 850 ft west.
319	4	275.0	29.1	305	2,200 ft south, 1,100 ft west.
320	4	273.4	31.9	471	2,200 ft south, 1,300 ft west.

SUMMARY AND CONCLUSIONS

The directions of magnetization in all the Keweenawan units sampled by the author (table 15) and others fall into three significantly different groups. The groups have polarities that are alternately normal, reversed, and normal.

In the oldest normal polarity group are sedimentary and igneous rocks in the Ironwood, Mich., area and some of the lower sedimentary rocks of the Sibley Series on Sibley Peninsula in Ontario. In the Ironwood area, this group includes the basal quartzite unit and approximately 400 feet of immediately overlying lava flows in the lowermost exposures of South Trap Range rocks.

In the reversed polarity group are some 6,700 feet of lava flows near Ironwood, Mich., some 4,550 feet of lava flows near Grand Portage, Minn., the northern tongue of the Duluth Gabbro in Cook County, Minn., part of the Sibley Series, part of the lava flows at Gargantua Point and Mamainse Point, Ontario, the lavas at Alona Bay, Ontario, part of the Logan intrusions, the Baraga County dikes, and the Keweenawan Osler Series on the north shore of Lake Superior.

In the youngest normal polarity group are intrusive and extrusive rocks usually considered middle Keweenawan in age including the Portage Lake Lava Series and equivalents to the southwest in Wisconsin, most of the North Shore Volcanic Group, part of the Logan intrusions, the major part of the Duluth and similar gabbros, and many lesser sills and dikes cutting middle Keweenawan and earlier rocks. Also included in this group according to DuBois' (1962, p. 61) results is the upper Keweenawan Copper Harbor Conglomerate.

The paleomagnetic data indicate that many different rock units in the Lake Superior region may have formed within the same magnetic epoch as did the sedimentary Sibley Series (Tanton, 1931) in the Thunder Bay district, Ontario. Tanton (1931, p. 56, 58) found evidence for pre-Osler Series lavas in the red volcanic debris that makes up the greater part of the Sibley Series and the red porphyry pebbles in the basal conglomerate of the Osler Series of Ontario. DuBois (1962) related the Logan sills in Ontario and the lavas at Alona Bay, Ontario, to the lower Keweenawan and suggested a period of intrusive and extrusive activity in the Lake Superior region in early Keweenawan time.

Thus, major igneous activity probably began very early in Keweenawan history and volcanism and sedimentation probably were concurrent in the Lake Superior region. While the basal quartzite and succeeding lava flows were being formed in the Ironwood area, the early Sibley sediments were being deposited in the Sibley Peninsula area. While the Sibley continued to be deposited during the reversal of the earth's magnetic field, volcanism was dominant elsewhere. This reverse-polarization interval probably marked the initial stages of formation of the Duluth Gabbro Complex as well as the Logan intrusions; intrusion took place in such widely separated areas as Baraga County, Mich., and Nipigon, Ontario. Widespread extrusion at this time is represented by some 6,700 feet of lava flows near Ironwood and by lesser amounts across Lake Superior near Grand Portage, Minn., Alona Bay, Ontario, and Gargantua Point and Mamainse Point, Ontario.

By middle Keweenawan time when the earth's magnetic field was again normal, the igneous activity had almost replaced sedimentation, resulting in the bulk of the flows and intrusions found in the Lake Superior region today. During this normal-polarization interval some 20,000 to 30,000 feet of lava flows poured out, and the Duluth Gabbro Complex and major parts of the Logan intrusions were emplaced. Sedimentation again became dominant in Copper Harbor time; only minor igneous activity occurred thereafter.

A tentative correlation chart based on magnetic polarity changes and including all available paleomag-

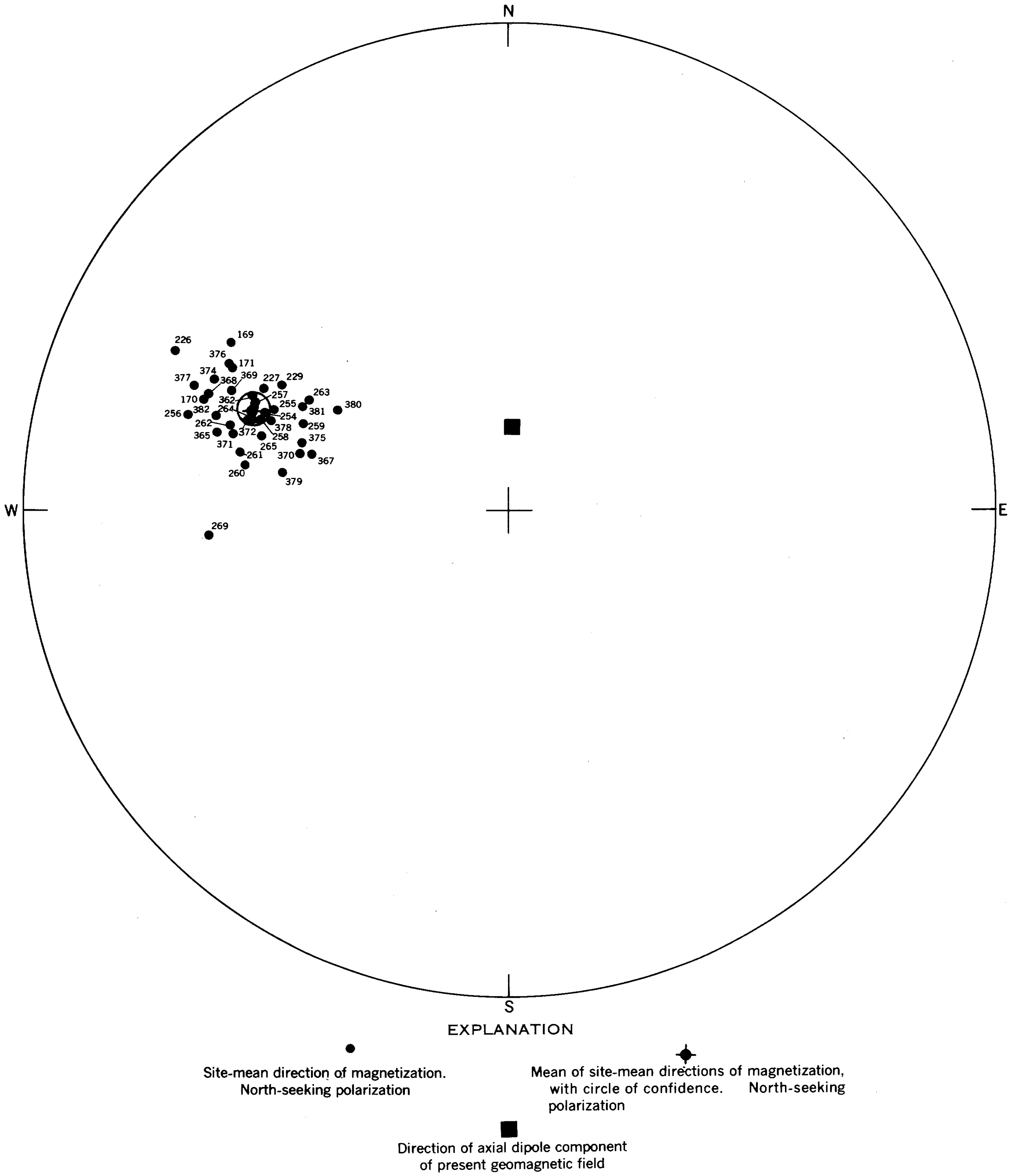


FIGURE 14.—Directions of remanent magnetization for North Shore Volcanic Group from flow No. 33 to flow No. 94 of Grout, Sharp, and Schwartz (1959), between Grand Portage and Tofte, Minn. Data corrected for geologic dip. Equal-area projection, lower hemisphere. See table 12 for site locations.

TABLE 12.—*Paleomagnetic results for North Shore Volcanic Group, between Grand Portage and Tofte, Minn.*

[Flow numbers are from Grout and others (1959). Data are corrected for geologic dip]

Site No.	Number of samples (*N*)	Mean direction of magnetization at collecting site: Declination, *D* (degrees)	Mean direction of magnetization at collecting site: Inclination, *I* (degrees)	Remanent intensity (emu/cm³×10⁻⁶)	Flow No.	Location and attitude of flow
NS254	3	291.1	46.4	103	94	2,800 ft south, 850 ft east of NW. cor. sec. 28, T. 59 N., R. 4 W. Strike N. 43° E., dip 14° SE.
255	4	293.6	47.8	629	91?	500 ft south, 3,300 ft east of NW. cor. sec. 28, T. 59 N., R. 4 W. Strike N. 41° E., dip 14° SE.
256	5	286.6	32.4	800	89	1,650 ft south, 2,850 ft east of NW. cor. sec. 22, T. 59 N., R. 4 W. Strike N. 55° E., dip 12° SE.
263	4	298.3	52.1	2,810	85?	650 ft south, 50 ft west of NE. cor. sec. 14, T. 59 N., R. 4 W. Strike N. 69°, dip 17° SE.
381	5	296.0	51.1	226	82?	750 ft south, 50 ft west of NE. cor. sec. 31, T. 59 N., R. 4 W. Strike N. 59° E., dip 12° SE.
370	5	285.0	54.2	2,890	81?	2,250 ft south, 1,350 ft west of NE. cor. sec. 12, T. 59 N., R. 4 W. Strike N. 59° E., dip 18° SE.
382	3	287.8	37.4	401	80	1,000 ft south, 100 ft west of NE. cor. sec. 31, T. 59 N., R. 4 W. Strike N. 52° E., dip 12° SE.
372	4	288.8	43.3	236	80	1,850 ft south, 1,600 ft west of NE. cor. sec. 12, T. 59 N., R. 4 W. Strike N. 59° E., dip 18° SE.
379	3	279.2	51.9	381	79?	400 ft south, 700 ft west of NE. cor. sec. 31, T. 59, N., R. 4 W. Strike N. 52° E., dip 12° SE.
371	4	285.2	41.6	1,600	79	2,100 ft south, 1,400 ft west of NE. cor. sec. 12. T. 59 N., R. 4 W. Strike N. 59° E., dip 18° SE.
380	3	299.4	57.3	566	78?	10 ft south, 856 ft west of NE. cor. sec. 31, T. 59 N., R. 4 W. Strike N. 52° E., dip 12° SE.
262	5	286.6	40.1	985	78	150 ft south, 1,300 ft west of NE. cor. sec. 34, T. 60 N., R. 3 W. Strike N. 61° E., dip 15° SE.
261	5	282.4	43.4	939	76	2,000 ft south, 1,050 ft west of NE. cor. sec. 19, T. 60 N., R. 2 W. Strike N. 76° E., dip 10° SE.
260	5	279.0	44.8	649	74	4,650 ft south, 1,750 ft west of NE. cor. sec. 17, T. 60 N., R. 2 W. Strike N. 75° E., dip 10° SE.
259	5	292.8	52.8	437	72	3,700 ft south, 250 ft west of NE. cor. sec. 17, T. 60 N., R. 2 W. Strike N. 65° E., dip 10° SE.
258	5	289.1	45.7	10,300	71	2,600 ft south, 1,350 ft east of NW. cor. sec. 16, T. 60 N., R. 2 W. Strike N. 69° E., dip 10° SE.
264	4	289.0	43.9	2,450	68	800 ft south, 2,250 ft east of NW. cor. sec. 11, T. 60 N., R. 1 W. Strike N. 63° E., dip 10° SE.
257	5	292.4	43.6	985	67	1,600 ft south, 2,050 ft east of NW. cor. sec. 6, T. 60 N., R. 1 W. Strike N. 70° E., dip 12° SE.
377	5	291.8	32.1	3,230	64	4,850 ft south, 1,050 ft east of NW. cor. sec. 32, T. 61 N., R. 1 W. Strike S. 87° E., dip 13° SW.
171	4	297.4	37.5	1,220	64	450 ft north, 1,950 ft east of SW. cor. sec. 32, T. 61 N., R. 1 W. Strike S. 85° E., dip 12.5° SW.
170	5	291.1	34.1	1,420	63	450 ft north, 2,000 ft east of SW. cor. sec. 32, T. 61 N., R. 1 W. Strike S. 85° E., dip 13° SW.
169	4	301.3	34.7	2,480	63	500 ft north, 2,000 ft east of SW. cor. sec. 32, T. 61, N., R. 1 W. Strike S. 85° E., dip 13° SW.
376	5	296.9	36.4	3,480	62	4,150 ft south, 3,050 ft east of NW. cor. sec. 32, T. 61 N., R. 1 W. Strike S. 80° E., dip 13° SW.
374	5	294.3	35.2	772	60	3,300 ft south, 2,500 ft west of NE. cor. sec. 33, T. 61 N., R. 1 W. Strike S. 88° E., dip 14° SW.
369	5	294.0	38.5	558	60	3,150 ft south, 1,500 ft west of NE. cor. sec. 33, T. 61 N., R. 1 W. Strike N. 87° E., dip 14° SE.
368	4	291.7	34.9	627	59	2,000 ft south, 900 ft east of NW. cor. sec. 34, T. 61 N., R. 1 W. Strike N. 76° E., dip 15° SE.
265	3	286.0	47.2	2,150	58	600 ft north, 2,700 ft east of SW. cor. sec. 27, T. 61 N., R. 1 E. Strike S. 77° E., dip 11° SW.
367	5	285.5	56.0	244	58?	3,800 ft south, 100 ft east of NW. cor. sec. 26, T. 61 N., R. 1 W. Strike N. 76° E., dip 15° SE.
365	4	285.2	38.7	237	57?	3,000 ft south, 1,200 ft east of NW. cor. sec. 16. T. 61 N., R. 1 E. Strike N. 87° E., dip 14° SE.
362	5	292.9	43.5	2,620	54	2,400 ft south, 2,000 ft east of NW. cor. sec. 13, T. 61 N., R. 1 E. Strike S. 61° E., dip 11° SW.
226	3	295.5	25.7	2,330	50	4,250 ft south, 2,850 ft west of NE. cor. sec. 9, T. 61 N., R. 2 E. Strike N. 86° E., dip 10° SE.
375	5	287.9	53.8	407	49	4,800 ft south, 1,100 ft west of NE. cor. sec. 3, T. 61 N., R. 2 E. Strike N. 84° E., dip 10° SE.
229	3	298.4	46.9	534	47	2,300 ft south, 1,900 ft west of NE. cor. sec. 1, T. 61 N., R. 2 E. Strike S. 71° E., dip 10° SW.
227	5	296.1	43.6	3,660	45	1,300 ft south, 250 ft west of NE. cor. sec. 6, T. 61 N., R. 3 E. Strike S. 77° E., dip 11° SW.
378	5	290.6	47.9	356	42	4,000 ft south, 2,450 ft west of NE. cor. sec. 32, T. 62 N., R. 3 E. Strike N. 90° E., dip 10° S.
269	3	264.5	38.2	257	33	1,950 ft north, 50 ft west of SE. cor. sec. 28, T. 62 N., R. 3 E. Strike S. 87° E., dip 20° SW.

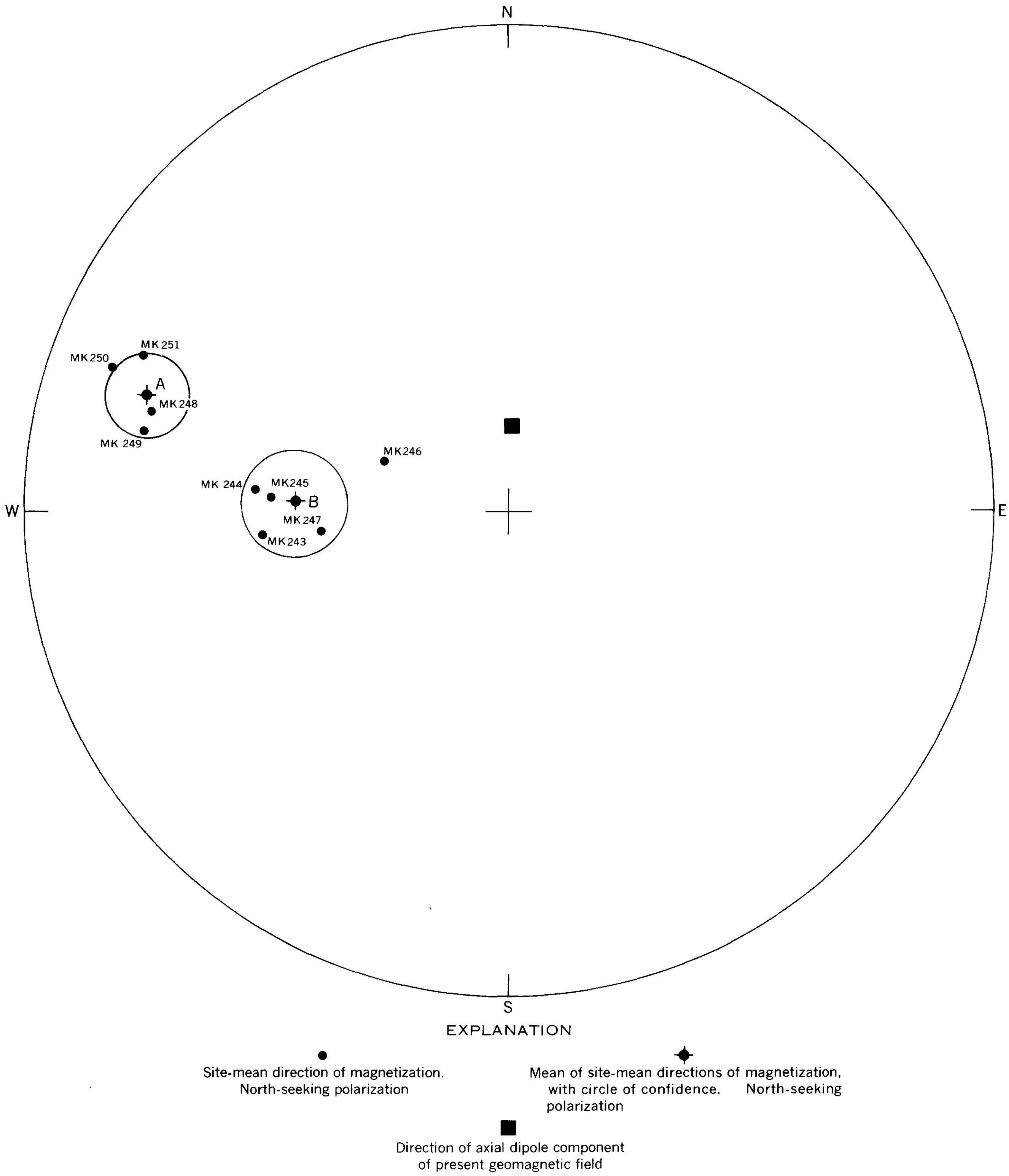


FIGURE 15.—Directions of remanent magnetization for middle Keweenawan lava flows on Isle Royale showing two significantly different groupings (A and B) for adjacent series of flows (see fig. 20 for comparison with the same stratigraphic position in the Portage Lake Lava Series). Data corrected for geologic dip. Equal-area projection, lower hemisphere. See table 13 for site locations.

TABLE 13.—*Paleomagnetic results for middle Keweenawan lavas on Isle Royale, Mich.*

[All sites are located in T. 63 N., R. 39 W. Flows strike N. 60° E. and dip 12.5° SE. at all sites. Paleomagnetic data are corrected for the geologic dip]

Site No.	Number of samples (*N*)	Mean direction of magnetization at collecting site		Remanent intensity (emu/cm³×10⁻⁶)	Location
		Declination, *D* (degrees)	Inclination, *I* (degrees)		
MK243	4	264.4	47.3	2,080	3,100 ft south, 2,600 ft west of NE cor. sec. 1.
244	5	274.1	46.4	7,320	3,100 ft south, 3,000 ft west of NE. cor. sec. 1.
245	5	272.9	49.3	8,450	3,200 ft south, 3,350 ft west of NE. cor. sec. 1.
246	4	290.4	67.1	2,240	3,250 ft south, 3,800 ft west of NE. cor. sec. 1.
247	5	263.7	56.7	4,520	3,300 ft south, 4,200 ft west of NE. cor. sec. 1.
248	5	285.2	25.2	1,710	2,700 ft south, 150 ft west of NE. cor. sec. 1.
249	5	281.9	24.7	3,970	2,400 ft south, 250 ft west of NE. cor. sec. 2.
250	5	289.2	14.1	863	1,200 ft south, 2,400 ft west of NE. cor. sec. 1.
251	6	292.9	29.5	3,240	Section line, 1,700 ft west of NE. cor. sec. 1.

TABLE 14.—*Paleomagnetic results for pre-Keweenawan rocks near Ironwood, Mich., and Grand Portage, Minn.*

[Data are corrected for geologic dip]

Sample No.	Direction of magnetization at collecting site		Remanent intensity (emu/cm³×10⁻⁶)	Location and attitude of bedding
	Declination, *D* (degrees)	Inclination, *I* (degrees)		
Marquette Range Supergroup rocks near Ironwood, Mich.:				
K3111	264.0	46.5	14.5	In the Black River. SE¼sec. 12, T. 47 N., R. 46 W. Strike N. 85° E., dip 55° NW.
2	267.1	48.1	2.64	
4	260.2	57.2	12.1	
6	266.3	40.7	1.28	
Rove Slate near Grand Portage, Minn.:				
K1661	222.9	60.1	52.0	Roadcut on U.S. Highway 61. Center sec. 34, T. 64 N., R. 6 E. Strike S. 66° W., dip 20° SE.
2	246.0	66.0	37.0	
3	187.4	54.1	41.0	
4	264.9	52.0	47.0	
5	266.2	40.9	44.0	

TABLE 15.—*Summary of new paleomagnetic data for rock units in the Lake Superior region*

[*N* is the number of sites for which Fisher (1953) analyses have been computed, unless otherwise noted. Magnetization directions are corrected for geologic dip, unless otherwise noted. δ_m and δ_p are semiaxes of the confidence oval about a virtual pole and are respectively perpendicular and parallel to the virtual paleomeridian]

Rock unit	Location of rock unit		Number of sites (*N*)	Mean of site-mean directions of magnetization		Precision parameter (*K*)	Radius of confidence circle (α_{95})	Pole position		δ_m	δ_p
	North lat (degrees)	West long (degrees)		Declination, *D* (degrees)	Inclination, *I* (degrees)			North lat (degrees)	West long (degrees)		
1	47.2	88.6	[1] 6	295.0	22.2	58.1	8.9	25.4	189.3	9.4	5.0
2	47.2	88.4	[1] 8	[2] 275.1	[2] 23.2	8.8	19.8	12.3	173.8	21.1	11.2
3	46.6	89.6	3	298.6	36.0	25.4	24.9	33.9	186.0	29.0	16.8
4	46.7	90.1	5	287.7	26.2	51.5	10.8	22.1	183.2	11.7	6.3
5	46.6	90.1	4	284.2	30.9	332.7	5.0	21.7	178.4	5.6	3.1
6	46.7	89.6	3	287.2	28.0	164.3	9.7	22.5	181.5	10.6	5.8
7	47.3	88.4	22	291.0	34.9	105.5	3.1	28.2	180.0	3.6	2.1
8	47.3	88.4	7	274.5	45.8	72.9	7.1	22.6	162.1	9.1	5.8
9	47.3	88.4	23	289.3	35.1	77.1	3.5	27.1	178.6	4.0	2.3
10	47.4	88.1	17	288.4	36.4	27.2	7.0	27.1	177.1	8.1	4.7
11	47.9	89.2	5	271.8	53.8	60.8	9.9	25.9	155.7	13.8	9.7
12	47.9	89.2	4	287.3	23.4	106.7	8.9	20.6	183.7	9.5	5.1
13	47.7	90.4	36	291.2	43.9	46.2	3.6	32.6	176.9	4.4	2.8
14	46.5	90.1	7	262.5	37.0	28.8	11.4	9.8	160.4	13.5	7.8
15	46.5	90.0	[1] 4	261.2	45.0	88.4	9.8	13.3	155.3	12.4	7.9
16	48.0	89.7	[1] 5	240.9	58.5	14.8	20.6	12.6	133.6	32.2	20.6

[1] Indicates number of samples rather than number of sites.
[2] Data uncorrected for geologic dip.

1. Rhyolite intrusion in sec. 24, T. 56 N., R. 34 W., near Kearsarge, Mich.
2. Rhyolite intrusion in sec. 4, T. 56 N., R. 32 W., near Kearsarge, Mich.
3. Quartz porphyry north of Lake Gogebic, Mich.
4. Portage Lake lavas near Algonquin Falls, Mich.
5. Portage Lake lava equivalents from the Chippewa Hill quarry, Mich.
6. Rhyolite flows north of Lake Gogebic, Mich.
7. Portage Lake lavas above conglomerate No. 15 near Kearsarge, Mich.
8. Portage Lake lavas between conglomerate Nos. 14 and 15 near Kearsarge, Mich.
9. Portage Lake lavas below conglomerate No. 14 near Kearsarge, Mich.
10. Portage Lake lavas northeast of Kearsarge, Mich.
11. Upper lavas on Isle Royale, Mich.
12. Lower lavas on Isle Royale, Mich.
13. North Shore lava flows (Nos. 33 to 94) between Grand Portage and Tofte, Minn.
14. Basal quartzite and lower 400 feet of South Trap Range lavas near Ironwood, Mich.
15. Marquette Range Supergroup sedimentary rocks in sec. 12, T. 47 N., R. 46 W., near Ironwood, Mich.
16. Rove Slate in sec. 34, T. 64 N., R. 6 E., near Grand Portage, Minn.

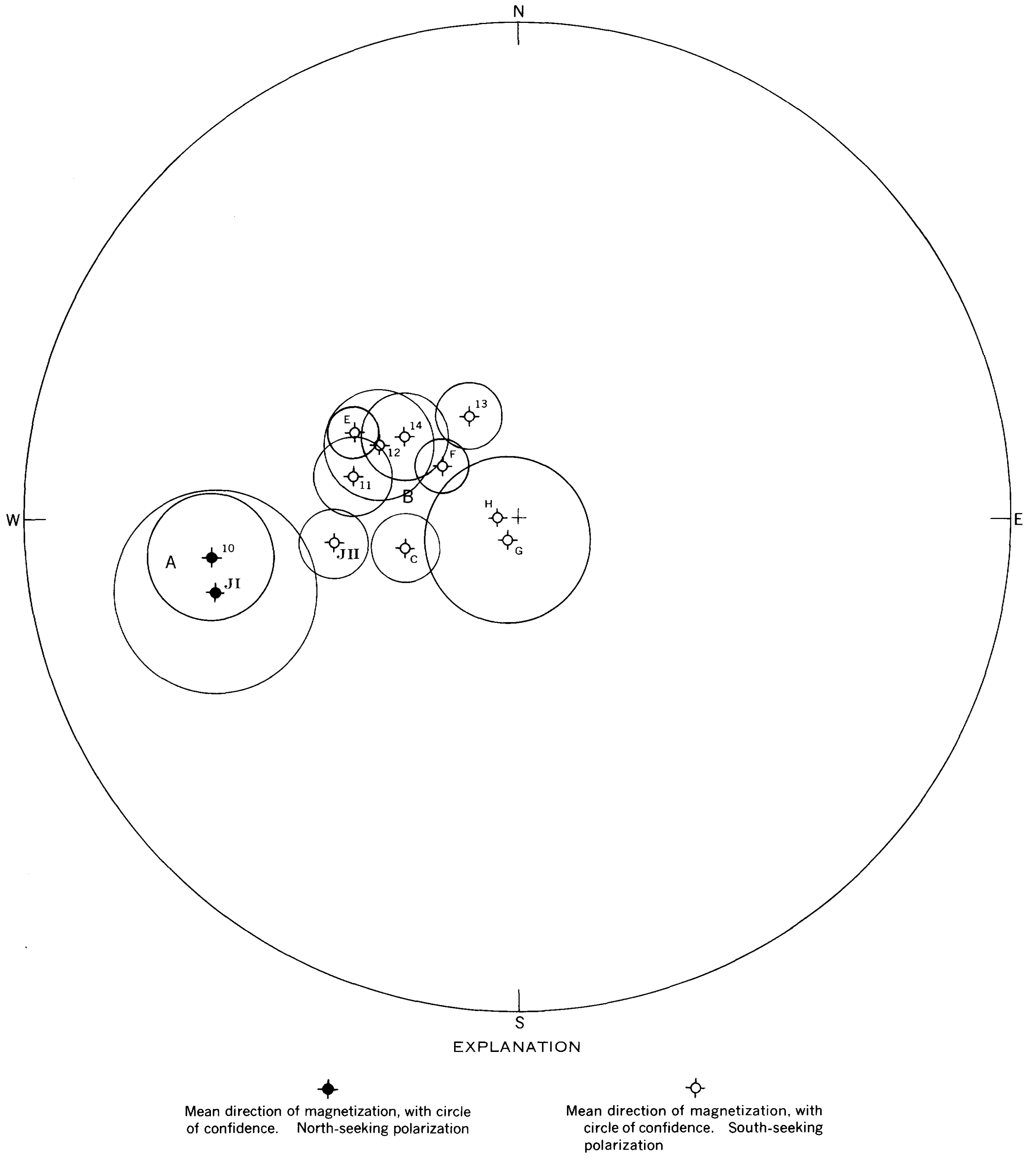


FIGURE 16.—Summary of mean directions of remanent magnetization for lower(?) Keweenawan igneous rock units in the Lake Superior area, showing two groups (A and B) with opposing magnetization. The rock units are: 10, basal quartzite and lower South Trap Range lava flows near Ironwood, Mich.; 11, northern tongue of Duluth Gabbro extension in Cook County, Minn.; C, lower sequence of Keweenawan lava flows at Ironwood, Mich.; E, lower sequence of Keweenawan lava flows at Grand Portage, Minn.; F, Logan sills of Lawson (1893); G, lavas at Alona Bay, Ontario; H, mafic dikes in Baraga County, Mich., circle of confidence not shown; and J (I and II), the Sibley Series of Tanton (1927). The data for point 10, the quartzite and succeeding flows, are new (from fig. 11); data for point 11 are from Beck and Lindsley (1969, table 3); data for points F, G, H, JI, and JII are from DuBois (1962, table 18); data for C and E are from Books (1968, fig. 3); and data for points 12, 13, and 14 are from Palmer (1970, tables 2, 4, and 6). Data are corrected for geologic dip. Equal-area projection, lower hemisphere.

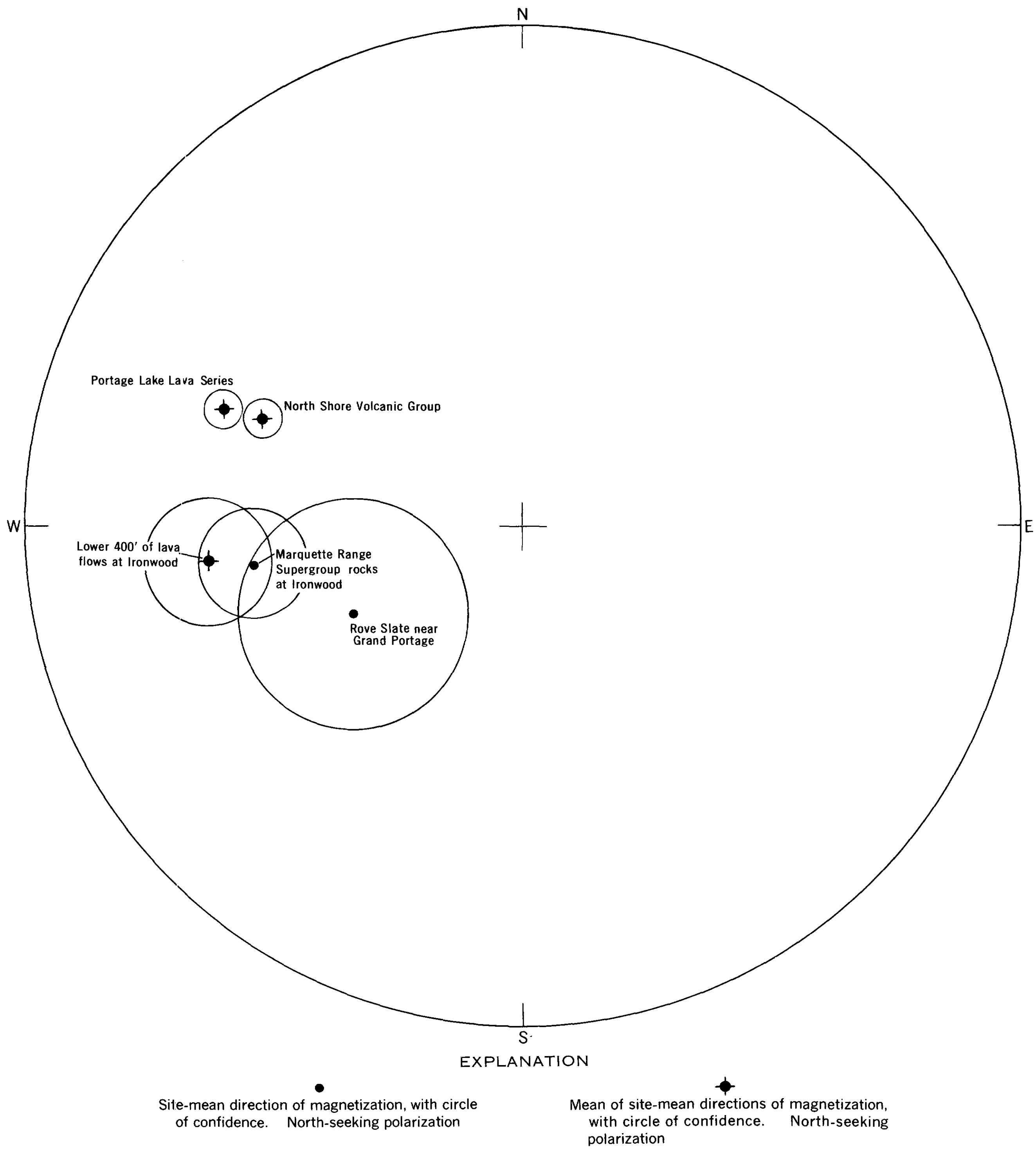


FIGURE 17.—Directions of remanent magnetization for pre-Keweenawan units near Ironwood, Mich., and Grand Portage, Minn., compared to directions of magnetization in lower Keweenawan units. Rock units are: Rove Slate of the Animikie Group near Grand Portage, Minn.; Marquette Range Supergroup sedimentary unit near Ironwood, Mich.; and lower 400 feet of lava flows near Ironwood, Mich. Directions of remanent magnetization for the North Shore Volcanic Group and Portage Lake Lava Series are also shown. Data corrected for geologic dip. Equal-area projection, lower hemisphere. Site locations for Rove Slate and Marquette Range Supergroup unit are given in table 14.

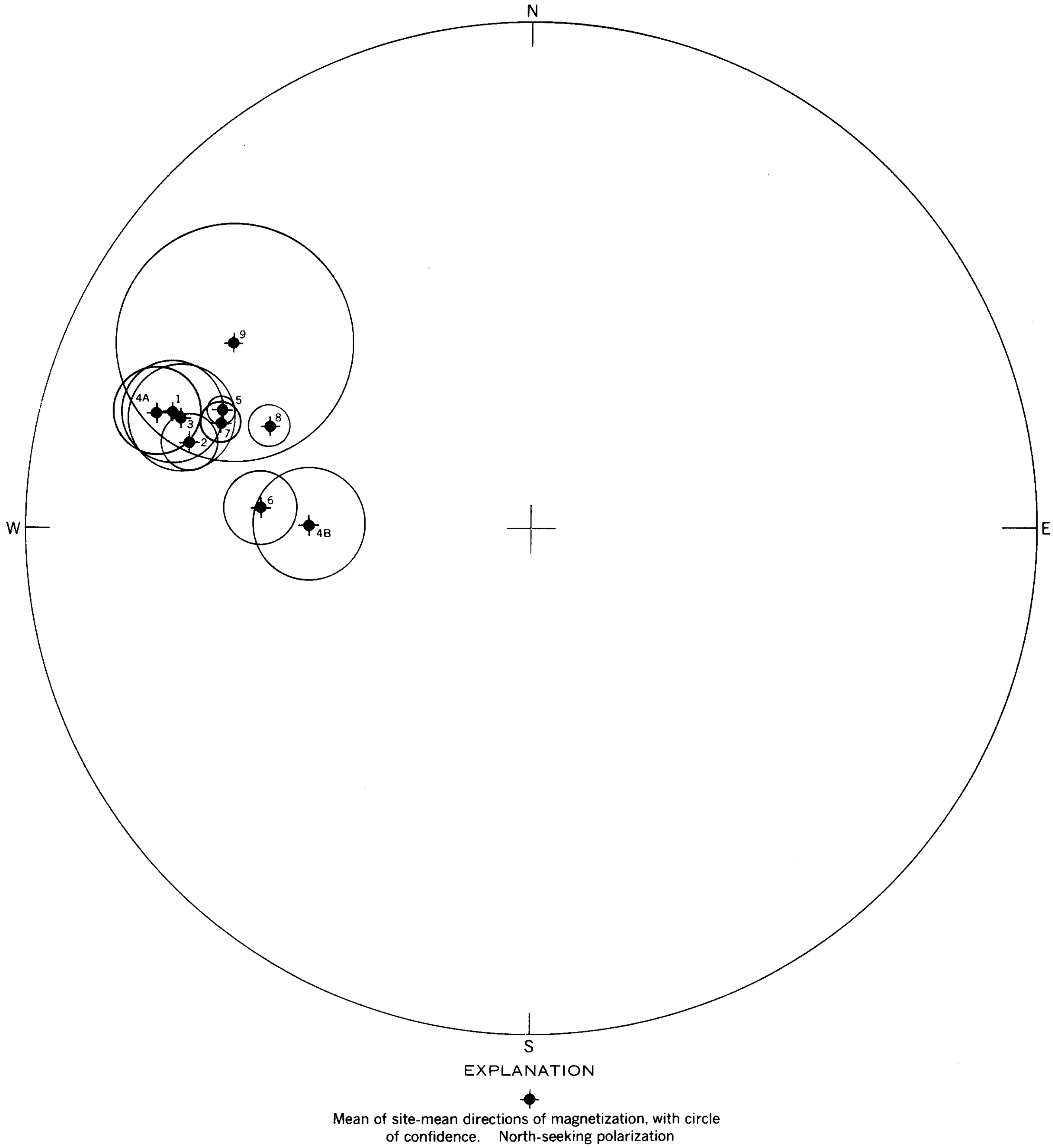


FIGURE 18.—Summary of mean directions of remanent magnetization for middle Keweenawan rock units in the Lake Superior region. The units are: 1, lava flow sequence near Algonquin Falls, Mich; 2, lava flow sequence in the Chippewa Hill quarry, Michigan; 3, rhyolite flows north of Lake Gogebic, Mich.; 4A and 4B, lava flow sequences on Isle Royale; 5, lava flow sequence above conglomerate No. 15 of Portage Lake Lava Series at Kearsarge, Mich.; 6, lava flows between conglomerate Nos. 14 and 15 at Kearsarge, Mich.; 7, lava flow sequence below conglomerate No. 14 at Kearsarge, Mich.; 8, North Shore Volcanic Group; and 9, quartz porphyry north of Lake Gogebic, Mich. Data corrected for geologic dip. Equal-area projection, lower hemisphere.

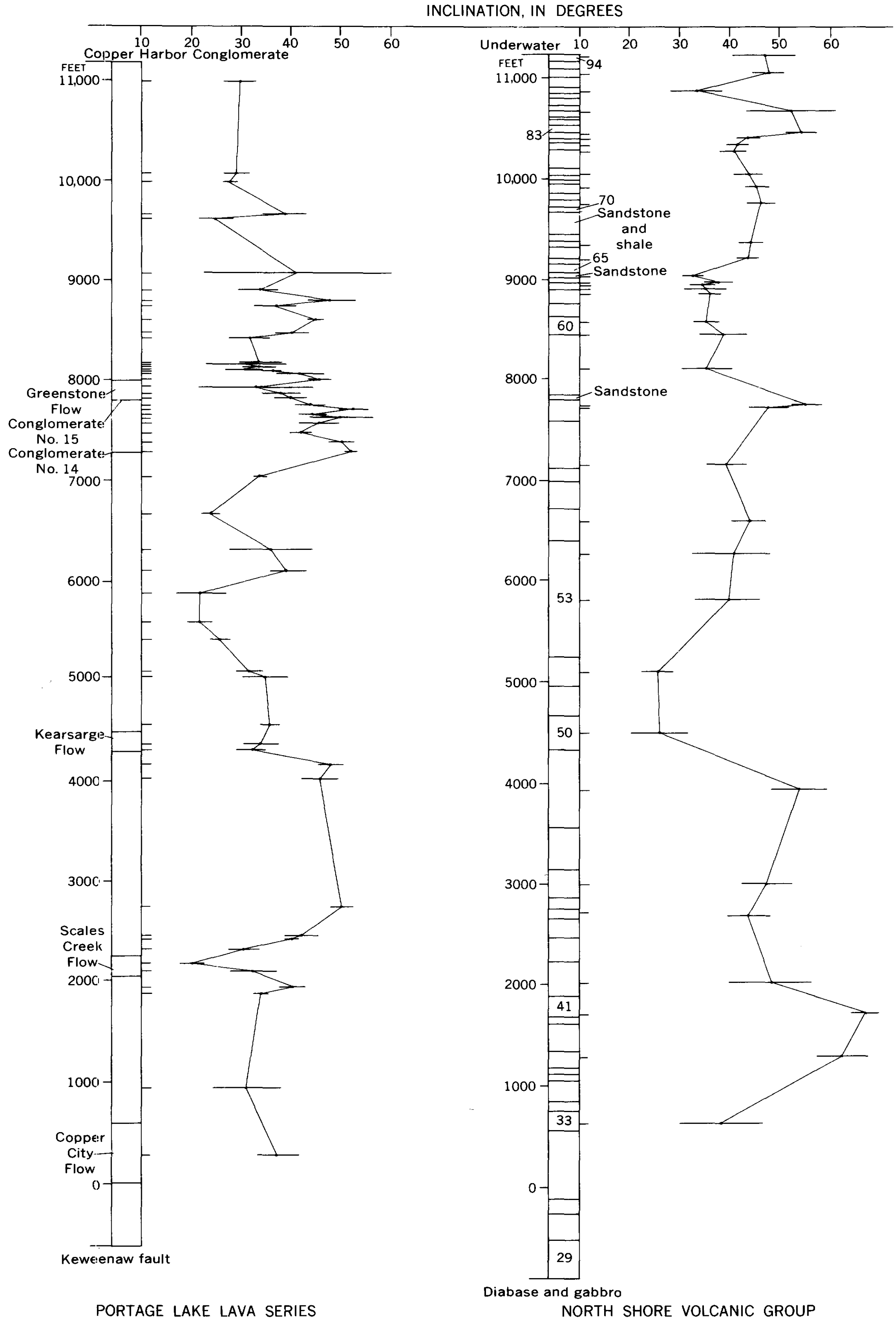


FIGURE 19.—Comparison of chronological movements in inclination of the paleomagnetic fields of the Portage Lake Lava Series and North Shore Volcanic Group. Bars indicate confidence circle radii for a Fisher analysis (Fisher, 1953) of no less than three samples from a single site. Data corrected for geologic dip. Numbers within column are lava flows of Grout, Sharp, and Schwartz (1959).

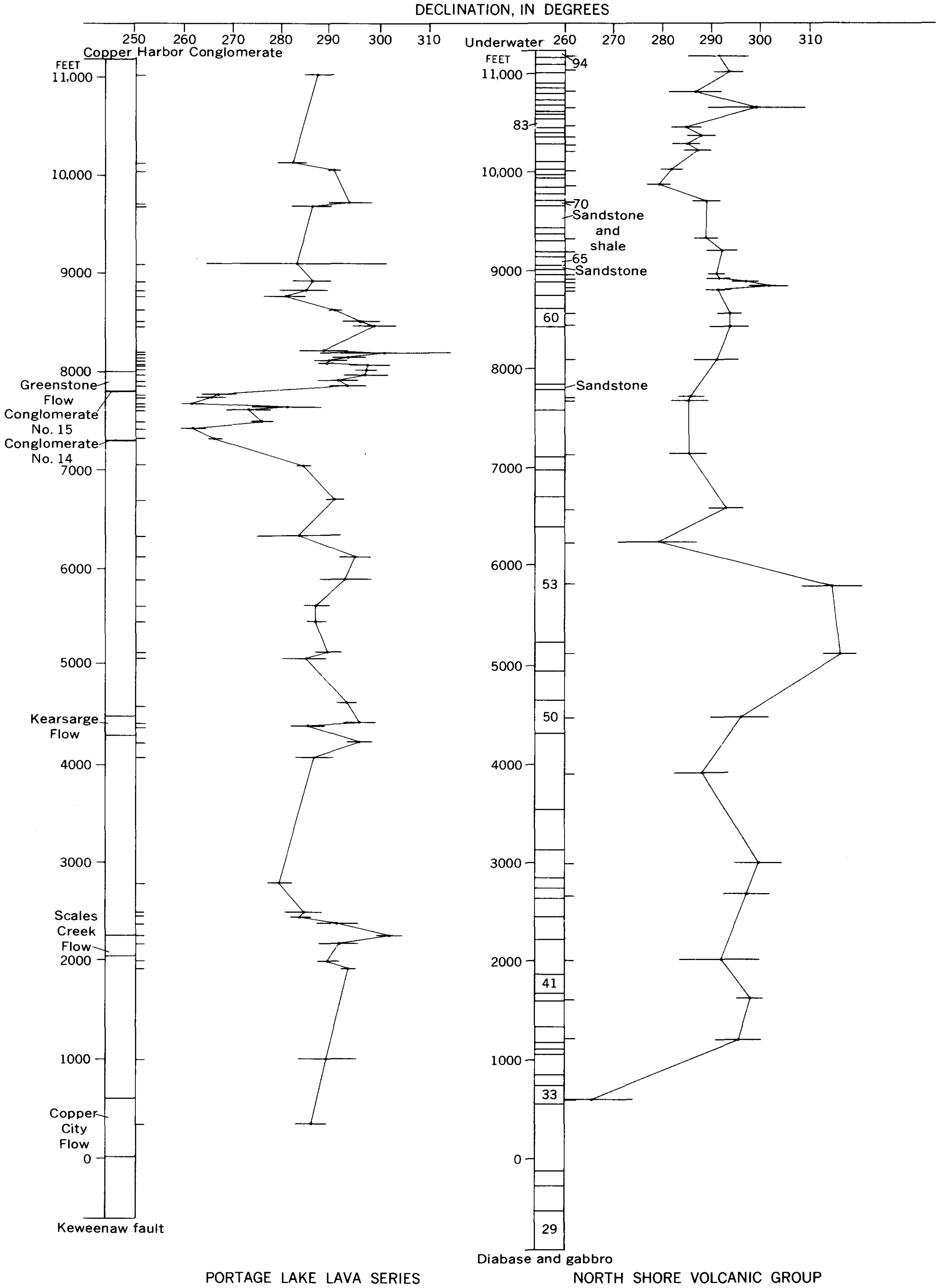
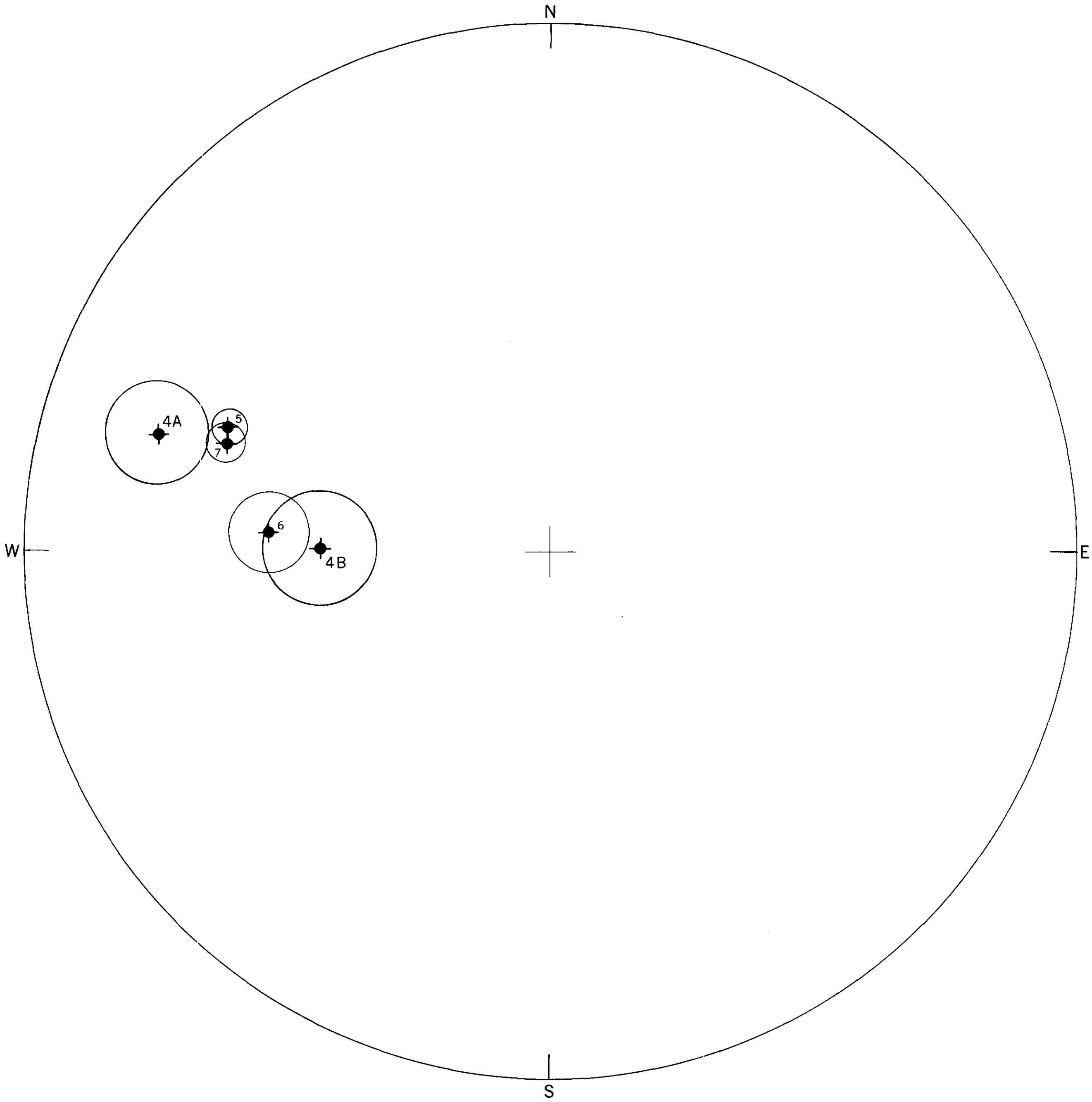


FIGURE 20.—Comparison of chronological movements in declination of the paleomagnetic fields of the Portage Lake Lava Series and North Shore Volcanic Group. Bars indicate confidence circle radii for a Fisher analysis (Fisher, 1953) of no less than three samples from a single site. Data corrected for geologic dip. Numbers within column are lava flows of Grout, Sharp, and Schwartz (1959).



EXPLANATION

Mean of site-mean directions of magnetization, with circle of confidence. North-seeking polarization

FIGURE 21.—Comparison of mean directions of remanent magnetization for Keweenawan lava flow sequences near Kearsarge and on Isle Royale, Mich. Rock units are: 4A, lava flow sequence in the Washington Harbor-Grace Harbor area, Isle Royale; 4B, lava flow sequence above 4A and near Lane's (1911, pl. I) "Greenstone" horizon; 5, lava flow sequence above conglomerate No. 15 near Kearsarge; 6, lava flow sequence between conglomerate Nos. 14 and 15; and 7, lava flow sequence below conglomerate No. 14 near Kearsarge. Data corrected for geologic dip. Equal-area projection, lower hemisphere.

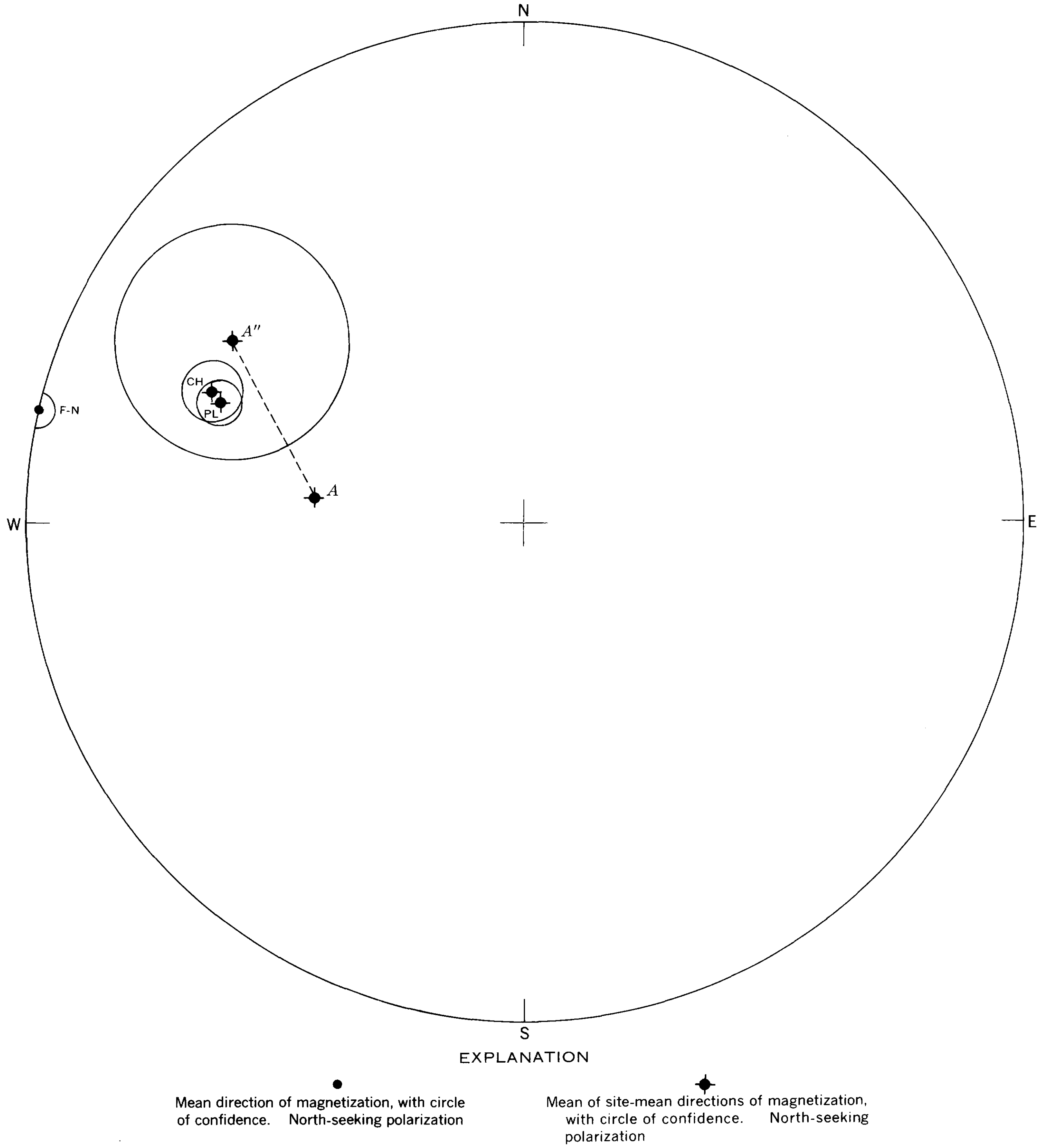


FIGURE 22.—Alternative directions of remanent magnetization for the quartz porphyry north of Lake Gogebic, Mich., before (A) and after (A″) correction for 35° dip of underlying lavas. Other points represent data for: PL, Portage Lake Lava Series; CH, Copper Harbor Conglomerate; F–N, Freda Sandstone-Nonsuch Shale unit. The Copper Harbor and Freda-Nonesuch data are from DuBois (1962, table XVIII); the other data are new. Equal-area projection, lower hemisphere.

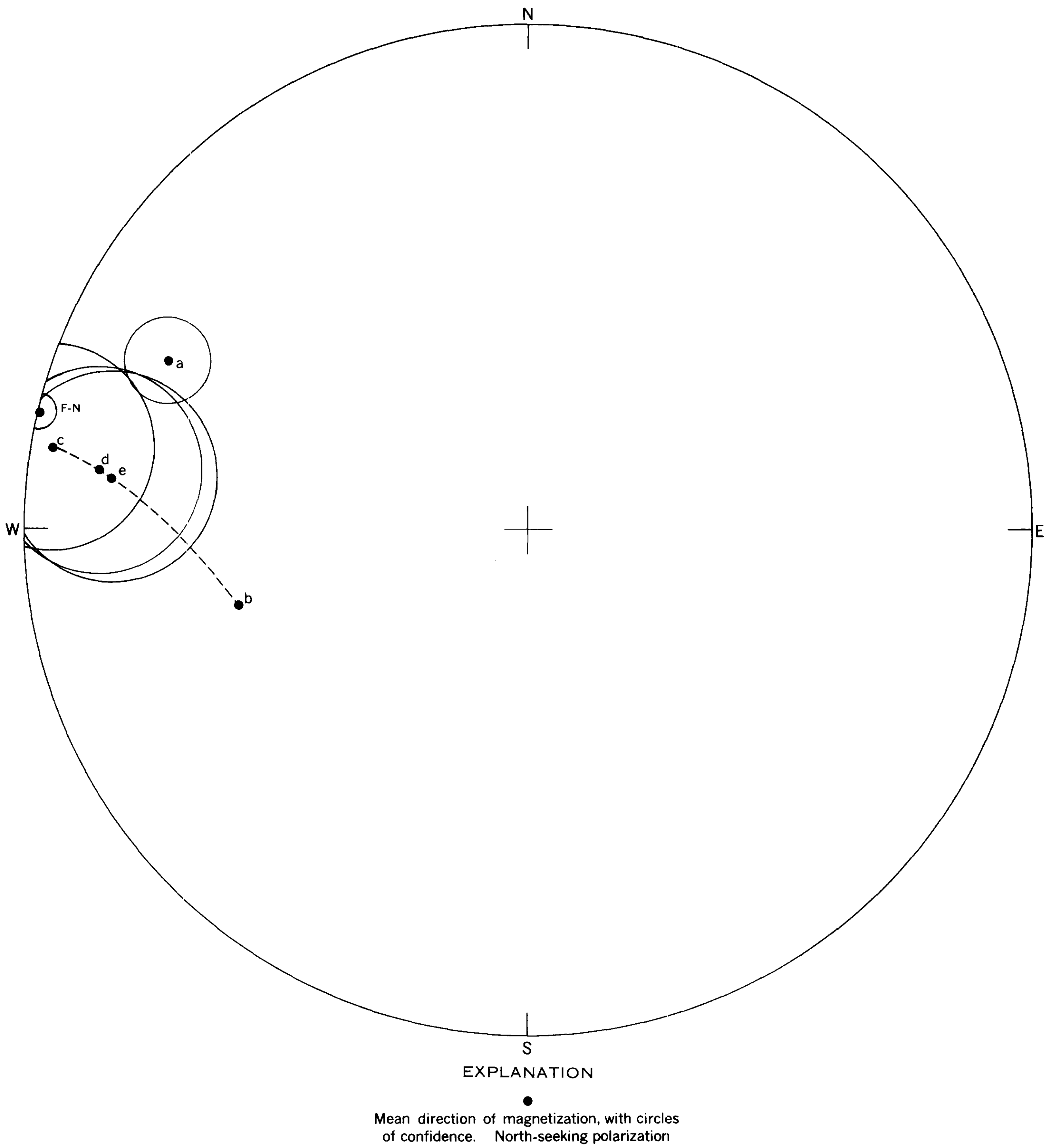


FIGURE 23.—Directions of remanent magnetization for the rhyolite intrusions in T. 56 N., R. 32 W., and T. 56 N., R. 34 W., near Kearsarge, Mich. Directions shown are: a, rhyolite intrusion in secs. 24 and 25, T. 56 N., R. 34 W., after correction for dip of the enclosing Freda Sandstone; and b, c, d, and e, alternative directions based on dip corrections for the rhyolite intrusion in sec. 4, T. 56 N., R. 32 W. Dip corrections for the latter intrusion are: b, no dip correction; e, 42° dip correction; d, 47° dip correction; and c, 62° dip correction. The Freda Sandstone-Nonesuch Shale unit (F–N) direction is from DuBois (1962, table XVIII); the other data are new. Equal-area projection, lower hemisphere.

TABLE 16.—*Tentative correlation chart of Lake Superior Keweenawan units based on magnetic polarity sequences*

[Based on data from this report and from DuBois (1962, table XIX), Books and others (1966, table 1), Books (1968, table 1), Palmer (1970, tables 2, 4, and 6), and Beck and Lindsley (1969, tables 2, 3)]

Polarity sequences	Upper Peninsula of Michigan	Ironwood, Mich., Mellen, Wis., and south shore	Northwest shore	North shore (western Ontario)	Eastern shore
Later Keweenawan polarizations	Jacobsville Sandstone Eileen Sandstone Rhyolites	Chequamegon Sandstone Orienta Sandstone Eileen Sandstone Freda Sandstone and Nonesuch Shale			Jacobsville Sandstone
Upper normal polarizations	Copper Harbor Conglomerate Portage Lake Lava Series Keweenaw fault	Quartz porphyry Keweenaw fault (?) Gabbro at Mellen	Beaver Bay Complex of Grout and Schwartz (1939) North shore lavas, upper flows Major part of Duluth Gabbro Complex Logan intrusions, in part	Logan intrusions, in part	Gargantua and Mamainse Point lavas, in part
Reversed polarizations	Baraga County diabase dikes	Upper 6,700 feet of South Trap Range lavas	North shore lavas, lower 20 flows Northern tongue of Duluth Gabbro Complex Logan intrusions, in part	Osler Volcanic Series Upper Sibley Series Logan intrusions, in part	Gargantua and Mamainse Point lavas, in part Alona Bay lavas
Lower normal polarizations		Lower 400 feet of South Trap Range lavas Basal quartzite Upper part of Marquette Range Supergroup	Rove State (Animikie Group), in part	Lower Sibley Series (?)	

netic data for Keweenawan rocks is presented in table 16. Placement of the geologic units within the several polarity divisions on the chart is somewhat arbitrary because deposition times for the intrusive and extrusive rocks may overlap. It is suggested (Books, 1968, p. D253, and Hubbard, 1968, p. 35) that the top of the reversed polarization sequence be taken as the top of the lower Keweenawan and following DuBois (1962, p. 62), that the base of the Nonesuch Shale be taken as the base of the upper Keweenawan.

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