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Paleomagnetism of the Powder Mill Group, Michigan and Wisconsin: A Reassessment of the Logan Loop

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The apex and the western arm of the 1.1-Ga Logan Loop, a prominent feature of the North American Precambrian apparent polar wander path, are defined by a large body of data from Keweenawan rocks of the Lake Superior Basin. Until now the eastern arm of this paleomagnetic feature has been largely defined by two data points from the Powder Mill Group of Michigan. A reexamination of this sequence reveals a primary reversed magnetization which plots close to the apex of the Logan Loop. Data from the Mellen Complex in Wisconsin, together with our data from the Powder Mill Group suggest that for steeply dipping volcanic units, the true direction of a pre-folding reversed magnetization is not obtained by simple structural rotation about presently observed strike. Reversely magnetized sites from localities where the Powder Mill volcanics have shallow dips yield a pole (146°W, 46°N, $A_{95} = 9.2^\circ$) on the apex of the loop. A well-defined, stratigraphically continuous, normal to reversed polarity change near the base of the Powder Mill Group is not confirmed. Normally magnetized flows have been found at two localities, only one of which is at the base of the lava sequence. The higher metamorphic grade of normally magnetized sites suggests that normal magnetizations within the Powder Mill Group are secondary and should not be used in definition of the eastern arm of the Logan Loop.

INTRODUCTION

Keweenawan mafic igneous rocks of the Lake Superior Basin and their subsurface equivalents that continue southwards into central North America have been interpreted as the products of an abortive rift [King and Zietz, 1971; Chase and Gilmer, 1973] now known as the Midcontinent Rift system. Most of this wide-spread igneous activity spans a reversed to normal magnetic polarity transition and occurred 1110 ± 10 Ma ago [Van Schmus *et al.*, 1982]. An earlier normal polarity epoch characterizing the initial stages of volcanism has been proposed by Books [1972]. He found the lowermost 120 m of the Powder Mill Group (formerly called the South Range Traps) in Michigan to have a normal magnetization, in contrast to the remaining 3000 m of the sequence which have reversed polarity. The work of Books is particularly important, not only to the magnetic polarity stratigraphy of Keweenawan rocks but also to the definition of the Logan Loop, a term given by Robertson and Fahrig [1971] to the form of the Apparent Polar Wander path during Keweenawan time. The paleomagnetic poles from the Powder Mill Group [Books, 1968, 1972] are the only ones from the Lake Superior region (apart from the Abitibi dike pole, Laroche [1966]) to define the ascending, eastern limb of the Logan Loop. However, Books collected his samples from localities in the Ironwood area (Figure 1) where the dip of the Powder Mill flows is close to vertical, thus increasing the likelihood of significant error in subsequent structural correction of the paleomagnetic data. It was therefore decided to undertake a more extensive sampling program including the more easterly outcrops of the Powder Mill Group where dips are less steep, with the purpose of (1) testing whether the polarity zonation found by Books [1968, 1972] persists along the full outcrop belt of the Powder Mill Group and (2) ver-

ifying that the pole positions reported by Books, which are anomalous with respect to all others obtained from Keweenawan volcanic sequences, are not the result of inadequate demagnetization or an improper structural correction.

GEOLOGICAL BACKGROUND

The Powder Mill Group [Hubbard, 1975a, b] is a sequence of predominantly mafic lava flows about 2500 m thick in the type area near Ironwood but reaching a maximum thickness of about 6000 further west. It rests conformably upon the Bessemer Quartzite (Figure 1), which, in turn, lies unconformably upon Middle Precambrian sedimentary rocks that were deformed during the Penokean orogeny about 1.8 Ga ago. The Powder Mill Group has been divided into two formations by Hubbard [1975a, b]. The lower Siemens Creek Formation comprises about 1300 meters of thin, fine-grained basalt flows. The upper Kallander Creek Formation contains at least 1200 m of a more lithologically diverse assemblage of flows ranging from basalt to rhyolite. The contact between the two formations may be unconformable; although critical outcrops are sparse, there appears to be a northward increase in dip of about 15° across the contact [Hubbard, 1975b]. Unlike other Keweenawan volcanic sequences the Powder Mill Group contains few interflow sedimentary units. West of Ironwood it is intruded by the ≈ 1.1 -Ga old Mellen Complex (Figure 1), a steeply dipping, roughly conformable body containing a variety of igneous rocks ranging from gabbro to granophyre. A diorite sill is reported to extend further east, close to the contact between the Siemens Creek and Kallander Creek Formations, and may be part of the Mellen Complex [Hubbard, 1975b]. Paleomagnetic data [Books *et al.*, 1966] suggest that the Mellen Complex was emplaced after the Powder Mill flows had already been steeply tilted.

Separating the Powder Mill Group from the overlying Portage Lake Volcanic Group is a narrow poorly exposed zone which, in contrast to the volcanic belts on either side, exhibits a subdued aeromagnetic expression. It contains both felsic igneous and clastic sedimentary rocks [Hubbard, 1975b;

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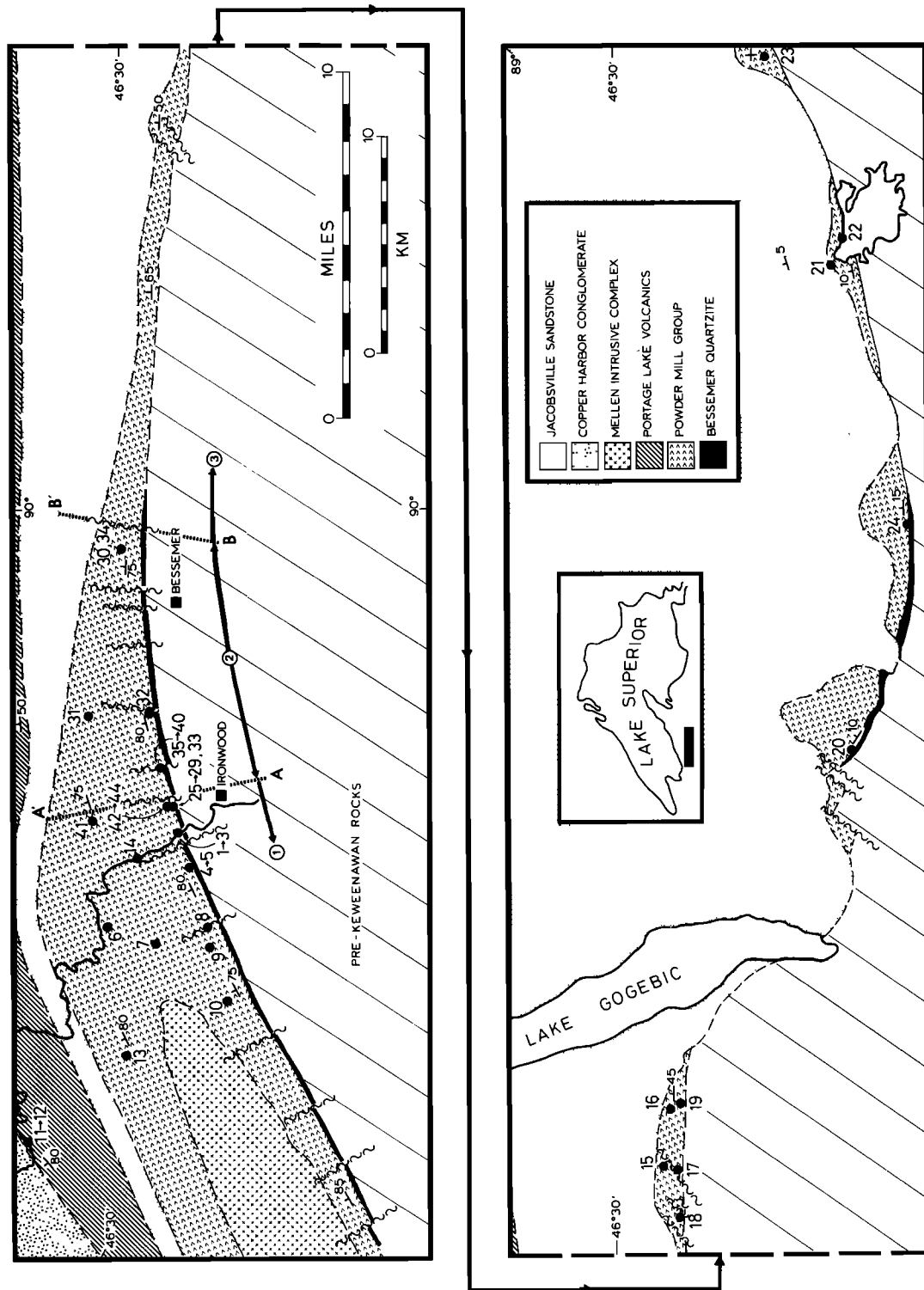


Fig. 1. Geological map showing the location of sampling sites within the Powder Mill Group. Geology is generalized from the maps of Cannon [1978], Hubbard [1975b], Cooper [1973], and Prinz and Hubbard [1975]. Dashed lines A-A' and B-B' separate the outcrop belt into three segments of differing structural attitude.

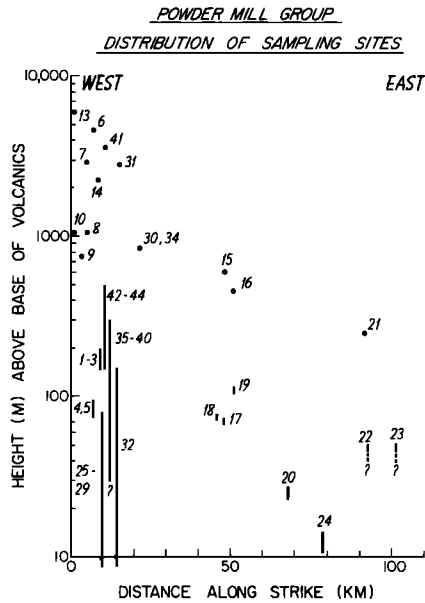


Fig. 2. Stratigraphic distribution of sampling sites within the Powder Mill Group. Vertical bars indicate the stratigraphic interval over which samples were taken at selected sites. Stratigraphic position of each site above the base of the sequence is obtained from outcrop width measurements taken from the maps cited in Figure 1, together with average dips for each stratigraphic interval. At sites 25, 26, 32, and 33, dip was measured from sedimentary bedding; at sites 1-3, 4, 5, 30, and 34, from interflow contacts; at sites 7, 9, 10, 13, 14, 41 and 44, from flow banding or layering of amygdular zones and at site 35, by pillow orientation. A Regional value was assigned at sites 6, 8, 31, 36-40, and 42-43, where local dip information was absent.

Cooper, 1973]. It is interpreted by Hubbard to be a unit sandwiched stratigraphically between the two volcanic sequences, although the northern margin of the zone may not be a stratigraphic contact inasmuch as it lies directly on strike with the Keweenaw fault to the east (see Figure 7).

Toward the east, the northward dip of the Powder Mill Group gradually decreases, ultimately becoming horizontal. A decrease in outcrop width accompanies this change in attitude. This decrease may reflect a progressive covering of the sequence by the unconformably overlying Jacobsville Sandstone or an eastward thinning of the sequence.

PALEOMAGNETIC SAMPLING AND MEASUREMENT PROCEDURES

Four to nineteen field-drilled cores, oriented using both a magnetic and a sun compass, were taken from 42 sites. These sites were distributed along the full length of the Powder Mill outcrop (about 100 km) in flows ranging in attitude from almost vertical in the west to horizontal in the east (Figure 1). We were guided in our selection of sites by the geological maps of Cooper [1973], Hubbard [1975a, b], Prinz and Hubbard [1975], Fritts [1969], and Cannon [1978]. The most samples per site were generally obtained from large outcrops near the base of the Powder Mill Group, across which we expected the change from normal to reversed polarity, as reported by Books [1968, 1972]. The stratigraphic position and range of sampling sites are schematically illustrated in Figure 2. In general, each site is located in a single flow. Two of the more densely sampled sites (8, 32) are possible exceptions, as they include samples collected over several 10's of meters stratigraphically from continuous outcrop across which no definite flow contacts could be established. One site (33) is situated in the Bessemer Quartzite below the flow at site 25 and comprises samples taken 0-6 m stratigraphically from the base of this lowermost flow.

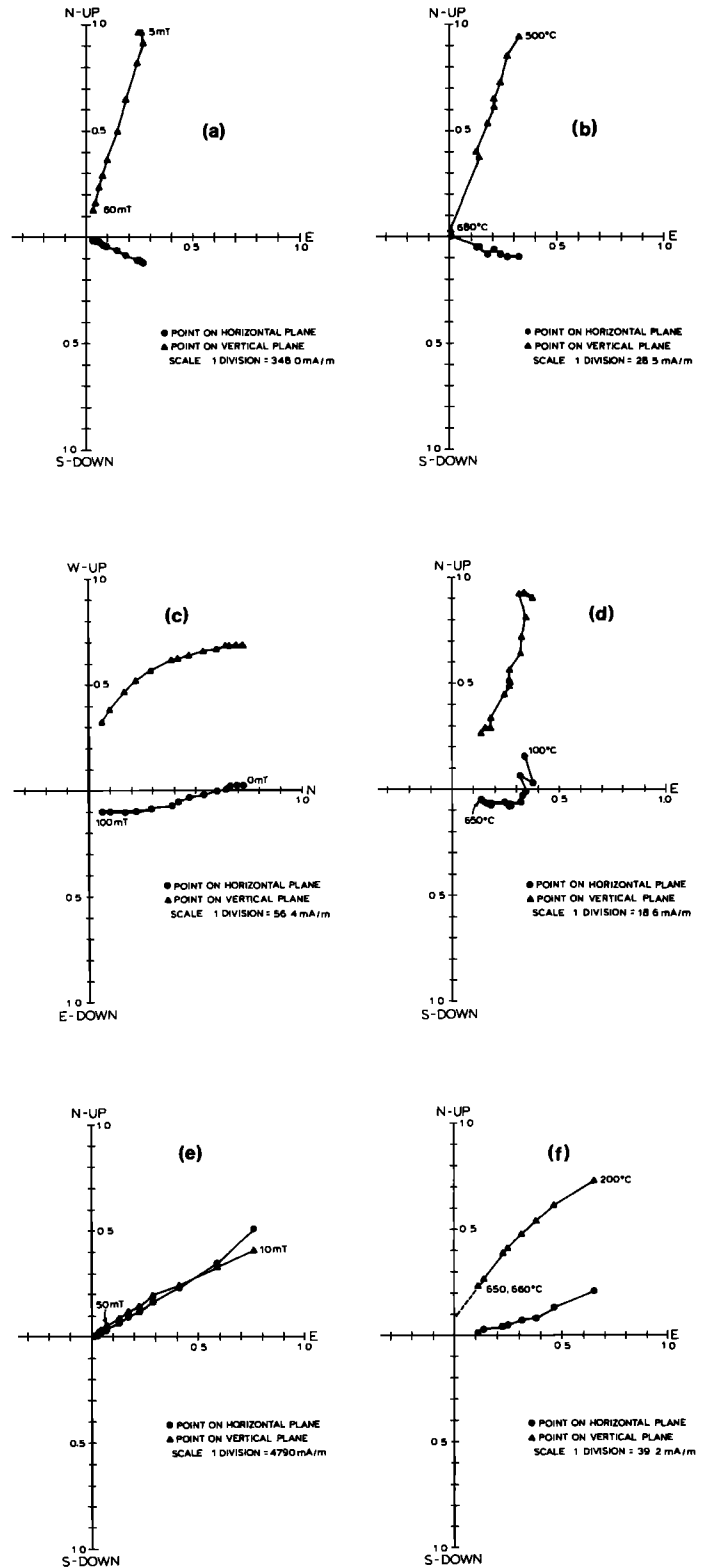


Fig. 3. Orthogonal vector diagrams illustrating the behavior of Powder Mill volcanic samples under AF and subsequent thermal demagnetization. (a) Specimen SR-08-16 after AF demagnetization. (b) Same specimen as in Figure 3a after continued thermal treatment. In order to amplify information near the origin, the NRM data point is not plotted in Figure 3a. (c) Specimen SR-35-07 after AF demagnetization. (d) Same specimen as in Figure 3c after subsequent thermal treatment showing the success of thermal demagnetization in isolating the characteristic component. (e) Specimen SR-28-02 after AF demagnetization. (f) Same specimen as in Figure 3e after subsequent thermal treatment. For this specimen combined demagnetization fails to isolate the characteristic component.

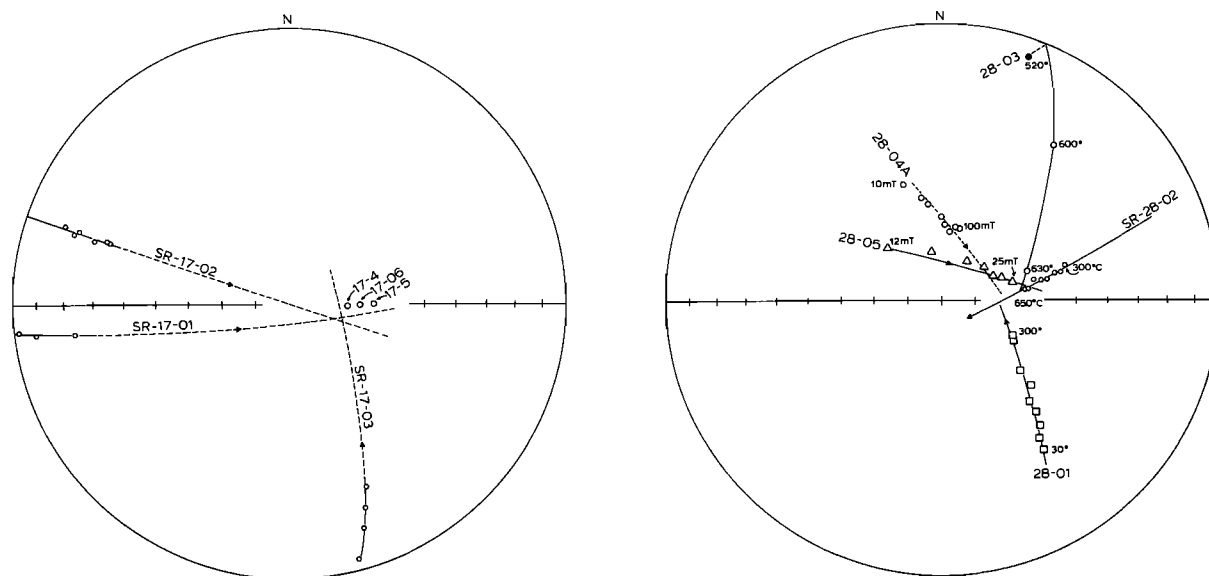


Fig. 4. Remagnetization circle data from sites 17 and 28. In site 17 the site mean is estimated from three stable end points and three circles. In site 28 the site mean is estimated from the intersection of five great circles.

From each field core, at least one standard paleomagnetic specimen core was prepared. At least one polished thin section was examined from the sample set of each site. Odd-numbered samples were studied at the University of Toronto using DIGICO and Schonstedt magnetometers, a Schonstedt GSD-1 alternating field (AF) demagnetizer, and a Schonstedt TSD-1 furnace for thermal demagnetization. Even-numbered samples were studied at the University of Western Ontario using a Schonstedt magnetometer, both three- and two-axis (Schonstedt GSD-5) AF demagnetizers and a Schonstedt TSD-1 furnace.

At least one specimen from each core was subjected to AF demagnetization. For those specimens failing to reach a stable end point (SEP), as judged by examination of plots of the AF treatment data, demagnetization was continued thermally. A few specimens were thermally demagnetized only. Orthogonal demagnetization diagrams [Zijderveld, 1967] and conventional stereoplots were made for all specimens showing more than one magnetization component. Characteristic directions observed on the orthogonal projections were estimated using the Principal Component Analysis computer program of Kirschvink [1980], modified to generate all possible linear segments defined by three or more data points and a mean angular deviation (MAD) of fit less than or equal to 5° . The characteristic directions in the samples from sites 5, 27, and 32 were defined with lower precision and for these sites the MAD angles for acceptance were relaxed to 10° . At several sites the demagnetization data of some or all of the samples generated remagnetization circles without SEP's. These data were combined with or without SEP data to give site mean directions using the method of Bailey and Halls [1984].

PALEOMAGNETIC RESULTS

Reversely Magnetized Sites

In terms of demagnetization behavior, reversed polarity samples from the Powder Mill Group can be subdivided into three main groups. Group 1 samples contain a single remanence component that is partially demagnetized by alternating fields, but which can only be completely removed by thermal

demagnetization to temperatures of 680°C (Figures 3a and 3b). Thermal demagnetization without prior AF treatment causes sharp decreases in remanence intensity at $\sim 580^\circ$ and $\sim 680^\circ\text{C}$, indicating that the component is carried by both magnetite and hematite. After structural correction group 1 samples yield a steep upward magnetization having an E-SE declination. The highest proportion of group 1 samples is found from the eastern sites shown in the lower map of Figure 1. Group 2 samples are characterized by a curved AF demagnetization path from which a linear decay to the origin (corresponding to an SEP) can be achieved only by subsequent thermal demagnetization in the range 500° to 680°C (Figures 3c and 3d). Group 3 samples are similar to those of group 2 except that AF demagnetization to 100 mT followed by thermal treatment to 680°C does not isolate the characteristic component (Figures 3e and 3f). In both groups 2 and 3, demagnetization paths commonly define great-circle planes, the normals to which, after structural correction tend to lie in the SW quadrant of the stereonet with shallow (10° to 30°) upward inclinations. Within many sites, samples tend to exhibit similar great circle paths that approach a stable end point from a north to northwesterly direction. A minority of sites have samples whose great-circle paths show a wide range in azimuth (Figure 4) and which converge towards the characteristic component direction. In some cases these data can be combined with SEP data to provide a joint directional estimate as shown for site 17 in Figure 4; in others, such as for site 28 in Figure 4, great circles must be relied on entirely to provide an estimate for the reversed component direction.

For all reversed sites the magnetization directions (Table 1) are plotted both before and after unfolding in Figures 5a and 5b, respectively. The reduction in dispersion upon structural correction is spectacular proving conclusively that the reversed component was acquired prior to folding. It is interpreted to be a thermochemical remanence produced during initial cooling and high temperature oxidation of the flows.

The precise number and direction of components that comprise the secondary remanence have yet to be determined. Although individual samples commonly display spectacular great-circle paths, corresponding trajectories on orthogonal

TABLE 1. Summary of Characteristic Magnetization Directions for Powder Mill Group

Site Number	After Demagnetization											
	NRM				SEP/Circle							
	<i>N</i>	<i>E</i>	<i>C</i>	<i>D</i>	<i>I</i>	<i>D</i>	<i>I</i>	<i>R</i>	<i>k</i>	α_{95}	θ	ϕ
1-3*	8	11		338°	-64°	066°	-88°	7.966	206	3.9	265°	75°
4	4			346°	-70°	027°	-77°	3.997	1011	2.9	255°	60°
6	6	1		031°	-50°	072°	-56°	5.960	124	6.0	250°	80°
7	6	1		047°	-42°	084°	-41°	5.930	72	8.0	250°	75°
8	11	3		050°	-79°	090°	-66°	10.883	85	5.0	250°	80°
9	5	1		053°	-73°	084°	-54°	4.904	42	12.0	245°	70°
10	7			049°	-50°	089°	-53°	6.946	112	5.7	255°	75°
11†	7			301°	+36°	302°	+34°	6.962	160	4.8	245°	85°
12†	8			312°	+39°	310°	+40°	7.934	106	5.4	255°	78°
13	6			014°	-64°	099°	-74°	5.983	289	3.9	250°	85°
14	7	2		055°	-81°	141°	-76°	6.993	801	2.1	260°	88°
15	5	1		168°	-79°	102°	-63°	4.996	993	2.4	260°	45°
16	6			094°	-77°	116°	-70°	5.991	551	2.9	270°	45°
17	6		3	183°	-76°	098°	-71°		246	5.3‡	270°	45°
18	7			056°	-53°	116°	-64°	6.989	569	2.5	270°	50°
19	6	1		035°	-65°	119°	-67°	5.950	100	6.7	270°	50°
20	8			061°	-26°	091°	-54°	7.942	121	5.1	280°	15°
21	6			060°	-60°	106°	-79°	5.988	414	3.3	270°	12°
22	6			124°	-77°	133°	-77°	5.992	610	2.7	290°	05°
23	5			025°	-63°	091°	-71°	4.983	241	4.9	000°	00°
24	6			148°	+32°	133°	-53°	5.971	171	5.1	270°	10°
25	6			050°	-77°	102°	-74°	5.982	275	4.0	255°	80°
28	5		5	332°	-35°	082°	-69°			7.1‡	255°	72°
29	7		7	079°	-44°	096°	-69°			6.1‡	255°	72°
30	4	4		081°	-68°	108°	-67°	3.967	90	9.7	270°	70°
31	6			035°	-54°	101°	-68°	5.979	241	4.3	265°	90°
32	11	8		312°	-07°	280°	+22°	8.911	5	23.3	255°	72°
33	5		2	340°	-48°	083°	-67°		642	5.0‡	255°	75°
34	5			066°	-66°	065°	-66°	4.987	311	4.3	270°	70°
35	9	4		018°	-56°	102°	-60°	8.959	194	3.7	258°	80°
36	4		3	015°	-32°	109°	-58°			5.0‡	258°	80°
37	5	1		229°	-56°	128°	-62°	4.990	387	3.9	258°	80°
38	8			000°	-48°	129°	-63°	7.962	184	4.1	258°	80°
39	5		5	268°	-53°	076°	-67°			10.0‡	255°	80°
40	5	1		087°	-72°	083°	-66°	4.975	160	6.1	255°	80°
41	6			061°	-76°	072°	-75°	5.995	1082	2.0	255°	75°
42	6			271°	+30°	269°	+32°	5.990	494	3.0	255°	80°
43	5			277°	+34°	271°	+34°	4.988	321	4.3	255°	80°
44	4	3	2	267°	-38°	275°	+31°		38	20.0	255°	80°

N, number of cores (samples) which contributed to the site mean direction; *E*, number of samples which proved to be unstable or from which characteristic magnetizations could not be resolved; *C*, number of independent samples which yielded great circle data; *D*, *I*, declination and inclination after structural correction, respectively; *R*, *k*, α_{95} , statistical parameters of Fisher [1953]; θ , ϕ , strike and dip of the sampled flows. Sites 5, 26, and 27 are omitted as they were either unstable and highly scattered (5, 27) or too weak to measure (26).

*Sites 1-3 are from adjacent flows but due to the large number of samples rejected, the three sites are combined.

†These sites in the Portage Lake Sequence (Figure 1) were collected during the survey and are included here for completeness.

‡These values are the square root of the product of the minimum and maximum radii of the 95% confidence ellipse as calculated in the work by Bailey and Halls [1984].

vector plots are usually curved, preventing reliable estimates of secondary component directions. The few secondary directions that are obtained, usually after thermal demagnetization in the range 20° to 600°C, form loose clusters centered around 355°/+70° and 350°/+10° prior to structural correction. It is possible that the first direction corresponds to a recently acquired viscous remanence as it lies close to the present earth's field and the second is a composite of this component and the primary one.

Normally Magnetized Sites

Only four sites (32, 42, 43, and 44) in the Powder Mill Group exhibit normal polarity. Site 32 spans the lowermost

150 m of section (Figure 2) and contains samples having natural remanent magnetization intensities varying by 3 orders of magnitude and poorly defined highly scattered SEP's (Table 1). Several of the more strongly magnetized samples were from higher parts of the outcrop and had probably been lightning-struck. Site 32 is located at one of two normal polarity outcrops sampled by Books [1972]; we did not sample at the second outcrop because its topographically lowest part included a diabase dike. The data from site 32 are essential to Books' [1968, 1972] conclusion that the lowest 120 m of the Powder Mill Group are normally magnetized. This interpretation has fostered belief that the normal polarity flows and perhaps the remainder of the Siemens Creek Formation are older than all

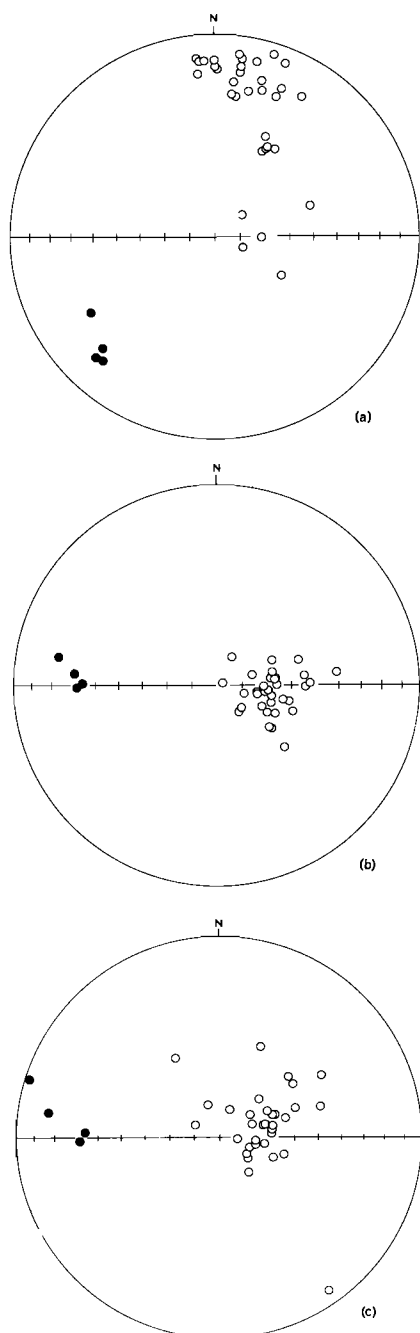


Fig. 5. Equal area projections showing Powder Mill Group site mean directions after optimal AF and thermal demagnetization before (a) and after (b) structural correction. Structurally corrected site means after only 20 mT AF demagnetization are shown to give a direct comparison with the results of Books [1968] (c). Closed (open) symbols indicate positive (negative) inclinations.

other extrusive units within the Keweenaw sequence [Green, 1982]. However, sites 25–29 which like site 32, represent the lowermost flows in observed contact with the Bessemer Quartzite are all of reversed polarity. Between these two basal sections is another (sites 35–40), only 1.5 km west of site 32, which also is entirely reversed. Here, however, the volcanic-sedimentary contact is not exposed; it probably lies within a few meters of the lowest exposed flow (site 35), which is pillowed like the basal flow at site 32. Sites 42–44, of normal polarity, span a 200-m interval beginning 150 m above the

base of the Powder Mill Group and sample a section that is estimated (Figure 2) to overlap the same stratigraphic interval represented by reversed-polarity sites 1–3 and 35–40. Lithologically distinct flows that would have allowed firmer correlation between sections were not found despite detailed petrographic examination. It is conceivable, due to eastward pinching out of underlying flows, that flows at sites 42–44 correlate with those resting on the Bessemer Quartzite at site 32. However, the intervening section represented by reversed sites 35–40 demands gross pinching and swelling of flows along strike for which we have no evidence.

Primary minerals in the Powder Mill Group are plagioclase, clinopyroxene, and Fe-Ti oxides (magnetite, ilmenite, and hematite). Primary textures are intersertal, intergranular and saphritic; a few samples contain phenocrysts of plagioclase. Secondary minerals include chlorite-serpentine, calcite, quartz, sphene, epidote, prehnite and pumpellyite, minerals typical of the prehnite-pumpellyite facies of metamorphism [Hyndman, 1985]. The normally magnetized flows differ from the reversed ones in that they lack pumpellyite and contain an amphibole. At site 32 the amphibole occurs as acicular needles and is found in amygdules and as marginal alteration of clinopyroxene. At sites 42–44 amphibole development is more pervasive, and original igneous texture is partially obliterated. Electron microprobe analyses of four amphibole grains in a polished thin section from site 43 show (Table 2) that they belong to the calcic pargasite-hastingsite compositional series [Leake, 1978, Hawthorne, 1983]. The amphiboles cannot be primary igneous hornblende because of their low potassium and titanium contents; this is in agreement with the textural evidence. This aluminous calcic amphibole is characteristic of medium grades of regional metamorphism and of the hornblende hornfels facies of contact metamorphism [Hyndman, 1985]. It is quite distinct from actinolite which occurs in the outer part of contact aureoles (albite-epidote hornfels facies) and from actinolite which replaces pumpellyite under low-grade conditions of burial metamorphism and which marks the onset of the greenschist facies. This point is emphasized in Table 2, where a comparison is made with amphiboles studied by Graham [1974] and by Moody *et al.* [1983]. In Graham's study the mineral chemistry of the amphiboles in metabasic rocks could be correlated with the classic zone minerals from interlayered metapelites. In controlled hydrothermal experiments, Moody *et al.* have shown that hornblende similar to that in SR-43 (Table 2, D-1-132) marks the transition from the greenschist facies to the amphibolite facies of regional metamorphism. In the two studies cited above, pressures were probably higher than those prevailing in the Powder Mill terrane at the time of alteration. This pressure difference may account for the difference in Mg/Fe at comparable Al_2O_3 contents between the SR-43 amphiboles and those from the regionally metamorphosed metabasites. The amphiboles in the sample from site 43 are most comparable to amphiboles in a sample of slightly altered cumulate gabbro collected from the Annieopsquotch ophiolite by W. R. Church. In this rock the amphiboles occur as small alteration patches replacing clinopyroxene; they range from colorless to blue green and have highly variable Al_2O_3 content (0.4–16.1 wt%). An analysis of one of these, whose color is similar to those in SR-43, is given in Table 2. It exhibits the same high Al_2O_3 , high Na_2O , low TiO_2 , and low K_2O contents characteristic of the amphibole in SR-43. The patchy and limited development of amphibole in the gabbro implies that the alteration resulted from the introduction of heated fluid (brine?) under conditions of low water-rock ratio. It should be emphasized that no amphibole,

TABLE 2. Amphibole Composition From SR-43 and Comparative Amphibole Analyses

	43-1	43-2	43-3	43-5	25,088	25,083	W-1-49	D-1-132	NF79168
SiO ₂	44.21	45.67	42.98	43.84	53.3	43.3	48.09	42.61	42.77
TiO ₂	0.00	0.00	0.01	0.00	0.2	0.3	1.08	1.17	0.00
Cr ₂ O ₃	0.00	0.00	0.00	0.06					0.00
Al ₂ O ₃	12.77	11.49	12.68	13.11	3.3	13.6	7.63	11.90	15.55
Fe ₂ O ₃ *	7.23	6.77	9.17	7.59					
FeO	5.54	4.09	3.18	5.39	10.6†	19.7†	18.38†	21.44†	10.29†
NiO							0.10	0.06	
MnO	0.29	0.22	0.19	0.02	0.3	0.4			0.14
MgO	14.41	16.17	16.02	14.83	16.0	7.5	7.29	7.10	14.55
CaO	10.95	10.96	10.71	10.36	12.6	10.2	12.10	10.97	11.5
Na ₂ O	2.14	2.08	2.39	2.41	0.7	1.5	0.98	1.49	2.91
K ₂ O	0.05	0.07	0.06	0.45	0.2	0.7	0.29	0.18	0.00
Total	97.59	97.52	97.39	98.06	97.2	97.2	95.94	96.01	97.71

Here, 25,088, amphibole from the lower chlorite zone; 25,083, amphibole from the garnet zone of the Scottish Dalradian [Graham, 1974]; W-1-49, 400°C-203 MPa run of *Moody et al.* [1983]; D-1-132, 551°C-405 MPa run of *Moody et al.* [1983]; and NF79168, amphibole from cumulate gabbro in the Annieopsquotch ophiolite (W. R. Church, personal communication, 1986).

*Ferric iron estimated using "midpoint" method of *Papike et al.* [1974].

†Total iron calculated as FeO.

including actinolite, was recognized in any of the reversely magnetized flows.

The occurrence of volcanic rocks possessing two unique features not found elsewhere in the Powder Mill Group, namely, a normal polarity and a significantly higher grade of metamorphism, suggests that the two properties are linked genetically. They can be produced if the volcanics have been locally metamorphosed by intrusive bodies or by hydrothermal vents associated with volcanism during the normal polarity epoch of Keweenaw time. However, rocks of unmistakably intrusive nature have not been found in the vicinity of the metamorphosed flows, although there are nearby tracts of no outcrop, beneath which intrusive bodies could lie. The requirement of a structural correction to yield the normal direction (Figure 5) indicates that the intrusive activity occurred prior to tilting. Unless the diorite sill that locally occurs on top of the Siemens Creek formation represents this activity, the only known intrusives into the Powder Mill Group are those associated with the Mellen Complex and they were emplaced after tilting. A clear coexistence of normal and reversed components in the same sample, which would have immediately demonstrated partial overprinting and the secondary nature of the normal component, was not found. The character of the normal magnetization event is therefore one which is essentially total but areally restricted.

DISCUSSION

The interpretation of the normal magnetization in terms of its primary or secondary origin cannot yet be made unequivocally. However, the former interpretation by *Books* [1972] is now open to considerable doubt. If a flow sequence originally magnetized in a normal field does exist it can neither be followed or confirmed as a stratigraphic unit, despite the existence of three stratigraphically comparable sections that have been studied over a strike length of less than three kilometers. Furthermore, site 32 gives erratic low coercivity characteristic components; none of the 11 specimen cores obtained at this site gave a satisfactory SEP that was comparable in quality to primary normal and reversed components that have been measured in Keweenaw volcanic units elsewhere around Lake Superior [e.g., *Palmer*, 1970; *Halls*, 1974; *Halls and Palmer*, 1981]. In the present study the only results of com-

parable low quality to those from site 32 were obtained from sites 5 and 27. Paleomagnetically, the results of site 32 must be considered a doubtful signature of primary magnetization.

We prefer the interpretation that the normal magnetization is secondary because amphibole occurs in all normal polarity sites, but no amphibole has been detected at any of the 38 reversed polarity sites. Despite the absence of recognized intrusive or hydrothermal centers that could have caused the metamorphism, there is at least some positive evidence for a

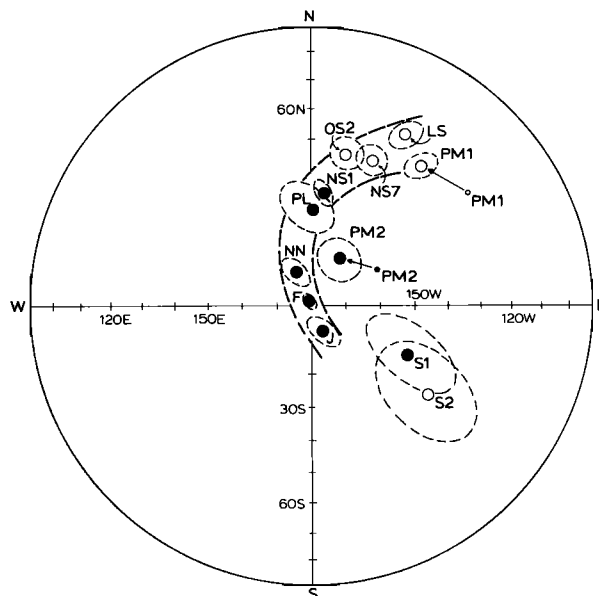


Fig. 6. Equal area projection showing the distribution of Keweenaw poles derived from the stratigraphic control sequence of Table 1 of *Halls and Pesonen* [1982]. Solid (open) symbols are from units of normal (reversed) polarity. Large symbols labeled PM are the reversed (33 sites) and normal (4 sites) polarity poles of this study, whereas the smaller symbols labeled PM are those of *Books* [1968, 1972]. Other symbols are as follows: S1 and S2, Sibley Red-beds; LS, mean Logan sills; NS7, lower North Shore Volcanics; OS2, upper part of Osler Reversed Sequence; NS1, upper North Shore Volcanic Group; PL, Portage Lake Volcanics; NN, Nonesuch Shale; F, Freda Sandstone; J, Jacobsville Sandstone. PM poles of *Books*, together with the Sibley poles S1 and S2, formed the eastern arm of the Logan Loop.

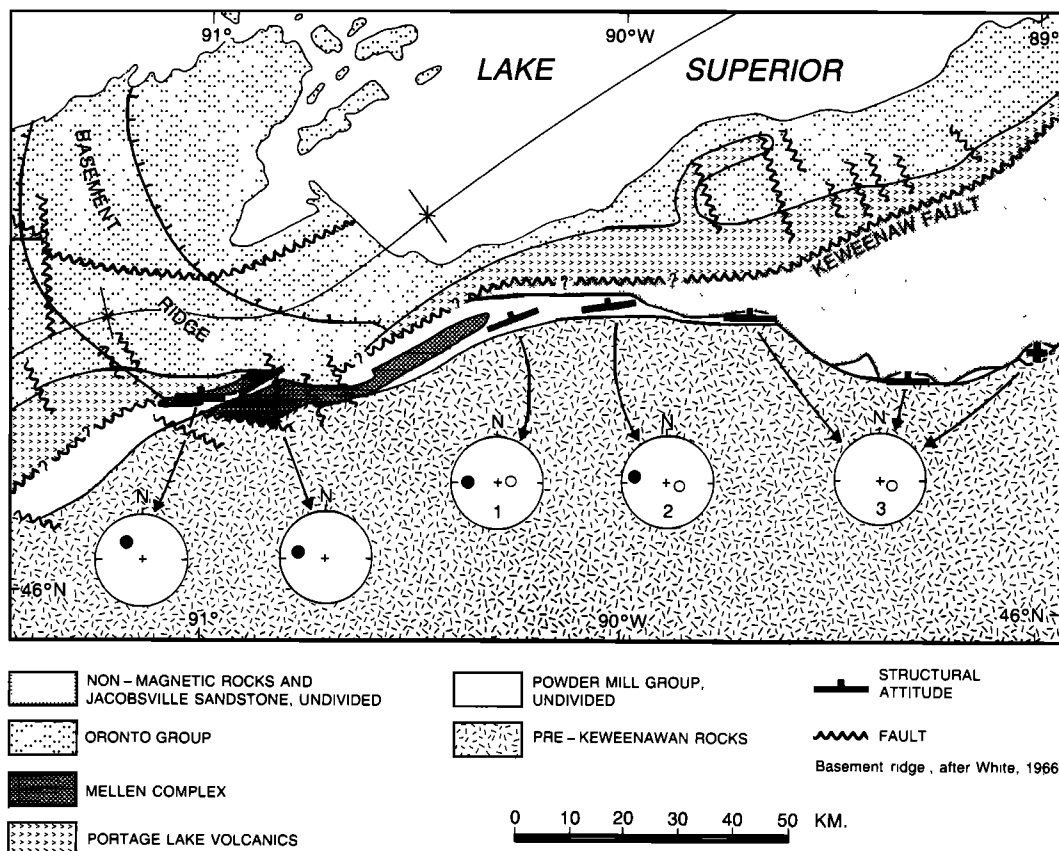


Fig. 7. Mean directions of remanent magnetization from the Mellen Complex and the Powder Mill Group. Powder Mill directions have been dip-corrected by rotation about the line of strike. Data yielding the means are grouped into three segments according to the attitude of the host rocks. Note that the declinations from the E-NE trending segments of both the Mellen Complex and the Powder Mill Group appear to have been rotated about a vertical axis in a counter clockwise sense with respect to declinations recorded from the E-W striking segments. Alternatively, the declination changes may be a consequence of rotation about a subhorizontal axis normal to the local strike. In this model the dividing line between units that have undergone tilting to the NE and SW occurs between the two attitude symbols in the Mellen Complex, approximately at the crest of the transverse ridge postulated by White [1966]. Westernmost sites from the Mellen Complex have been tilted to the southwest, rotating the remanence in a clockwise sense, whereas the eastern sites both in the Mellen Complex and the Powder Mill volcanics have been tilted to the NE resulting in a counter clockwise rotation of the remanence. Measured normal-reversed directions from the Mellen Complex and Powder Mill Group are shown by solid-open dots on the mini stereograms. Directions shown for the Mellen Complex have been obtained by subdividing the data of Books *et al.* [1966]. For simplicity, Chengwatana Group rocks are shown as an extension of the Portage Lake Volcanics west of 91° longitude.

secondary rather than primary origin of the normal-polarity magnetization.

The pole positions (Figure 6) corresponding to the normal and reversed magnetizations of the Powder Mill Group are displaced westward about 10° to 15° compared to those reported by Books [1968, 1972]. These new positions, together with our interpretation that the normal magnetization is the younger, suggest that the poles lie on the apex and descending arm of the Logan Loop rather than on the ascending arm as depicted earlier (e.g., Figure 4 of Halls and Pesonen [1982]). However, both the normal and reversed poles are slightly displaced to the east of the polar track, a possible consequence of an inadequate structural correction of the Powder Mill sequence as is discussed below.

The Powder Mill flows can be divided into three structural segments (Figures 1 and 7) characterized by (1) steep dips, E-NE strike, (2) steep dips, east to E-NE strike and, (3) moderate to shallow dips, east strike. The mean directions from each segment are (1) $D = 86^\circ$, $I = -68^\circ$; (2) $D = 101^\circ$, $I = -66^\circ$; (3) and $D = 110^\circ$, $I = -68^\circ$, respectively. The statistical information associated with these directions is given in Table 3. A

progressive decrease in declination is thus observed as the strike changes from east to E-NE toward the west (Figure 7) where the stratigraphic thickness is greatest. Since there is no evidence from our data (Table 1) of variation in remanence direction with stratigraphic height, the declination change is not caused by systematic variations in paleomagnetic direction up through the sequence.

A similar dependence of remanence declination on strike is seen in the normal polarity directions from the Mellen Complex [Books *et al.*, 1966]. Directions change from $D = 314.7^\circ$, $I = +49^\circ$ ($k = 15$, $\alpha_{95} = 18^\circ$, $N = 6$) in the west where the strike is east to $D = 278.5^\circ$, $I = +44.3^\circ$ ($k = 24$, $\alpha_{95} = 11.4^\circ$, $N = 8$) in the east where the strike is E-NE.

There are three ways in which the observed correlation of declination with strike in both the Powder Mill Group and Mellen Complex might be explained. (1) There is significant magnetic anisotropy that has deflected the remanence into the plane of layering. This interpretation is considered unlikely because in paleomagnetic studies of Keweenawan igneous rocks no cause for invoking anisotropy has ever arisen and flows of the Powder Mill Group seldom exhibit any fabric

TABLE 3. Mean Directions and Poles From the Powder Mill Group

N	R	k	α_{95}	D	I	Paleopole		A_{95}
						Longitude	Latitude	
14 ^a	13.604	33.	7.0	085.6°	−68.1°	136°W	34°N	10.2°
9 ^b	8.880	67.	6.3	101.4°	−65.6°	148°W	39°N	10.0°
10 ^c	9.848	59.	6.3	110.2°	−67.7°	146°W	46°N	9.2°
19 ^d	18.713	63.	4.3	105.9°	−66.7°	147°W	42°N	6.4°
33 ^e	32.242	42.	3.9	097.5°	−67.6°	142°W	39°N	5.8°
4 ^f	3.979	142.	7.7	273.9°	+29.8°	172°W	14°N	6.4°
14 ^g	13.792	62.	5.1	072.9°	−71.3°	127°W	30°N	8.1°
7 ^h	6.792	29.	11.4	262.4°	+37.0°	160°W	11°N	8.7°

^aReversed directions from segment 1, this study.^bReversed directions from segment 2, this study.^cReversed directions from segment 3, this study.^dReversed directions from segments 2 and 3, combined.^eReversed directions from segments 1, 2, and 3, combined.^fNormal directions, this study.^gReversed directions Books [1968].^hNormal directions Books [1972].

anisotropy either at a mega- or microscopic scale. (2) An oroclinal bending of strike has occurred after tilting was completed. This interpretation is consistent with the absence of progressive changes in remanence inclination along strike, but has less appeal because on a larger scale paleomagnetic data suggest that the curvature in axial trend of the Lake Superior Basin is an original feature [Halls and Pesonen, 1982]. (3) The preferred interpretation is that the change in remanence declination arises because there is an unremoved component of tilt, associated with deformation across a basement ridge which according to White [1966], crosses the Lake Superior Basin and emerges in the vicinity of the Mellen Complex where Powder Mill flows are locally thin (Figure 7). It is suggested that this ridge continued to be a positive feature throughout the evolution of the Keweenawan basin even in its later stages when the limbs of the basin were being steepened by late compressional forces. Areas of thick volcanics on either side of the ridge continued to subside isostatically with accompanying tilting away from the ridge during the time the volcanics were being steepened by compression, about an axis approximately normal to the ridge. Inclusion of this component of tilt (less than about 20°) about an axis transverse to the Lake Superior Basin can move the Powder Mill paleomagnetic direction of segment 1 into agreement with that of segment 3 and could also remove the difference in the two magnetization directions found in the Mellen Complex (Figure 7). Manifestations of the transverse upwarping along the ridge may be represented by one or more cross faults in the vicinity of the Mellen Complex (Figure 7). In this tectonic model the presently observed variation in strike along the Powder Mill volcanic belt is considered to have been established early in the deformation history but that much of the ridge-related tilting occurred after the Powder Mill volcanics had already been steeply upturned. This latter requirement is needed to accommodate the Mellen Complex paleomagnetic data.

In view of the uncertainty in structural correction to be applied to those sections of the Powder Mill volcanics that are close to the basement ridge, the most reliable estimate of the Powder Mill pole may be that from segment 3, although a relatively small stratigraphic interval has been sampled, thus increasing the risk that secular variation has not been averaged out.

Neither the normal pole of Books [1968] nor the normal pole of this study are true paleomagnetic poles in that they are based on too few sites to have averaged out secular variation. A comparison of our data with those of Books [1968, 1972] shows that at the 95% confidence level there is no significant difference between the two normal magnetization directions. However, there is a significant difference for the reversed directions, a consequence of the fact that Books [1968] used only AF demagnetization to a maximum field of 20 mT. His results are directly comparable to our site directions plotted after AF demagnetization at 20 mT (Figure 5c), the mean of which (073°, −71°) is within 1° of that obtained by Books (see Table 3).

CONCLUSION

The Powder Mill Group yields normal and reversed poles that lie on the western descending arm of the Logan Loop, rather than on the ascending eastern arm, as previously thought [Books, 1968, 1972]. It appears therefore that only the western arm of the Logan Loop is defined by Keweenawan data. The Logan Loop, as a well-defined entity on the basis of data from the Lake Superior region, remains elusive.

In sharp contrast to Books' conclusion we believe that the normal magnetization in the Powder Mill flows is related to metamorphism produced by intrusions or hydrothermal vents before significant northward tilting of the lava pile. Examination of the polar wander path in Figure 6 suggests that the thermal event occurred before deposition of the Nonesuch Shale, but after or during the waning stages of volcanism as represented by the Portage Lake Group and overlying Copper Harbor Conglomerate.

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