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Primary curvature in the Mid-Continent Rift: Paleomagnetism of the Portage Lake Volcanics (northern Michigan, USA)

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Abstract

Rocks of the North American Mid-Continent Rift (MCR) in the Keweenaw Peninsula of northern Michigan display a change in structural trend from east to west, varying in strike from 100° in the east to 35° farther west, before returning to a more east–west trend of 80° near Wisconsin. In general, curvature can be described either as of primary origin, meaning that the arc developed in its present curved state, or as of secondary origin, when the arc formed from an initially straighter geometry. A powerful tool in evaluating the origin and degree of curvature in any deformed belt is paleomagnetism, where coincident change in declination and strike is evidence for secondary curvature. Several paleomagnetic studies have been completed on rift-related sedimentary rocks, as well as lava flows, from the MCR in the Lake Superior region. Paleomagnetic directions for the sedimentary rocks vary much more in declination than in inclination, possibly reflecting a vertical axis rotation. If secondary rotation has affected the sedimentary rocks, then underlying volcanic rocks should also demonstrate a similar rotation.

Thirty-one sites were collected from the Portage Lake Volcanics in the most highly curved part of the Keweenaw Peninsula in the Upper Peninsula of Michigan. Sites were chosen to maximize the variation in structural trend. Thermal demagnetization results showed two components in samples from most sites, a lower temperature A component (<580 °C) as well as a higher temperature B component (>580 °C). Both components were tested for primary remanence using a conglomerate test. The A component, carried by magnetite, passes the conglomerate test at a 95% confidence level, and is therefore considered a primary remanence. The B component, carried by hematite, fails at the 95% level and is considered a secondary magnetization. Most importantly, declination of the primary (A) magnetization between sites shows no correlation with strike, demonstrating that vertical axis rotations cannot explain the curvature of the Mid-Continent Rift. We conclude that curvature in the Lake Superior Region is a primary feature, likely reflecting a pre-existing zone of weakness that was exploited during rifting.

Keywords: Orocline; Paleomagnetism; Portage Lake Volcanics; Mid-Continent rift; Curved belt

1. Introduction

Curvature in mountain belts has been a topic of research for at least one hundred years (Hobbs, 1914) and has become progressively more studied since Carey's (1955) introduction of the orocline concept. An orocline was originally defined as a belt with an initially straight geometry that subsequently was deformed into a curved

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feature (Marshak, 2004). However, the term orocline has also been used for "primary" curved features; that is, arcuate belts that initially formed with a curved geometry. With the inception of plate tectonics, the process by which these arcuate belts form has become increasingly central to the understanding of the kinematic development of deformation belts.

A powerful tool for examining bending of an orogenic belt is paleomagnetism (e.g., Eldredge et al., 1985; Weil et al., 2001). By identifying vertical-axis rotations in a curved belt, it is possible to determine whether, and in some cases when, bending has occurred. A perfectly coincident variation in both paleomagnetic declination and strike of the belt indicates secondary curvature, whereas the absence of any correlation between the two datasets implies primary curvature. Past paleomagnetic investigations of oroclinal bending have primarily focused on thin-skinned fold-and-thrust belts, such as the Apennines (Gattacceca and Speranza, 2002), the Appalachians (Stamatakos and Hirt, 1994) and the Sevier fold–thrust belt (Grubbs and Van der Voo, 1976; Schwartz and Van der Voo, 1984), which all have demonstrated some degree of oroclinal bending. However, vertical axis rotations in thick-skinned belts, defined as regions where the entire crust may be involved, have remained less understood (e.g., Levashova et al., 2003; Johnston, 2004).

The Mid-Continent Rift (MCR) is a dominant feature in potential fields of central North America (Ocola and Meyer, 1973; Fig. 1a). The rift signature extends 2000 km from the Grenville front in southeast Michigan into Lake Superior and its features eventually terminate in Kansas

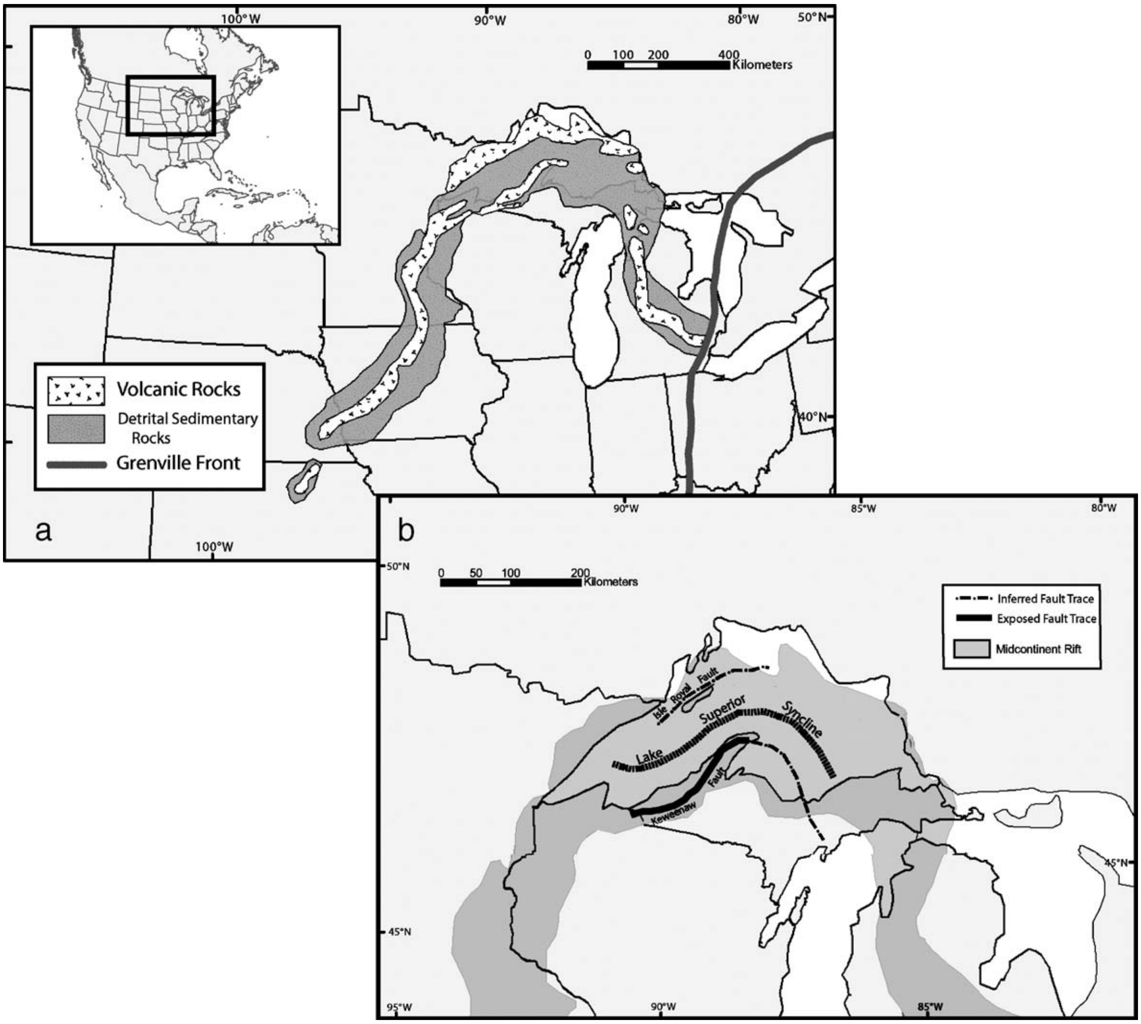

Fig. 1. (a) Outline of the North American Mid-Continent Rift as determined by geophysical methods. Redrawn from Ojakangas et al., 2001. (b) Curvature of rift related structures in the Lake Superior Region. Modified from Hinze et al. (1997).

(Hinze et al., 1997). Rocks of the rift are mostly obscured by the Phanerozoic cover except in the Lake Superior region, where a thick (~ 30 km) sequence of mafic lava flows and associated rift rocks are found. The MCR is unique among continental rifts in that modern analogs, such as the East African Rift or the European Rhine Graben, show no curved segments. The MCR has experienced rift inversion during the post-rifting compressional events of the Grenville orogeny (Cannon, 1994). This shortening of the rift involved thrusting along rift bounding faults and folding in the area. These rift structures show a large degree of curvature in the Lake Superior region (Fig. 1b). The rift related rocks cropping out on the Keweenaw Peninsula vary in structural trend from 100° on the eastern tip of the peninsula to 35° farther west, while returning to a more east–west strike of about 80° in westernmost Michigan and Wisconsin. The curvature in the rift was examined through paleomagnetic investigation of the Portage Lake Volcanics along this section of the Keweenaw Peninsula to evaluate whether all or some of the curvature can be explained through relative vertical axis rotation.

Fault inversion analysis of minor reverse faults of the MCR (Witthuhn-Rolf, 1997) and calcite-twinning analysis of calcite cemented amygdules in basalts and sedimentary rocks (Craddock et al., 1997) shows multiple paleostress directions that were attributed to rift closure. These varying stress directions may be associated with oroclinal bending of the structure, leading to rotation of at least parts of the MCR during rift closure. Previous work has documented that rift-bounding faults in northwestern Lake Superior region may have significant amounts of oblique-slip motion and possible associated counterclockwise rotation of the crust (Witthuhn-Rolf, 1997). This may offer a solution to rotating parts of the MCR if similar structures could be identified elsewhere along the rift margin beneath the Phanerozoic sedimentary cover. This could allow secondary development of at least some of the curvature without disturbing much of the surrounding pre-MCR structures, which do not display any significant curvature.

Further incentive for studying curvature in the Lake Superior region comes from comparing various paleomagnetic studies of the rift-related sediments. The apparent polar wander path (APWP) for Laurentia for ~ 1110 Ma through ~ 1000 Ma is defined using rocks of the MCR. Paleomagnetic data from sedimentary rocks from the western part of the rift in Wisconsin and Minnesota vary much more in declination than in inclination compared to those in Michigan, perhaps indicating a relative rotation between the two areas (Weil et al., 1998). By investigating the volcanic rocks underlying the sedimentary sequences at sites with varying structural trend, it is possible to test whether oroclinal bending of the MCR has occurred in the Lake Superior Region during post-rift deformation. Whereas other curvilinear inverted rift structures are absent elsewhere in the world, intracratonic rotation has been previously observed. Recent paleomagnetic investigation of the Biscotasing dike swarm in Ontario, Canada has revealed that vertical axis rotation of “stable” cratonic elements has occurred in the Canadian shield, despite a lack of obvious structural features that support rotation (Halls and Davis, 2004).

This study thus intends to test whether secondary curvature can be documented in the Mid-Continent Rift. Secondary rotation of the rift sequence would have major implications for intracratonic tectonism, as it requires rotation within a “stable” continental block, presumably involving a large section of the lithosphere.

2. Regional geology

The Portage Lake Volcanics (PLV) represent a series of approximately 200 lava flows that were extruded during the main stage rifting (Li and Beske-Diehl, 1993). Along the Keweenaw Peninsula, the PLV are primarily comprised of tholeiitic flood basalts with minor interbedded conglomerates. The Copper City Flow, near the base of the exposed volcanic pile, has been dated at 1096.2+/−1.8 Ma, whereas the Greenstone Flow, located near the top, was dated at 1094+/−1.5 Ma using U–Pb analyses on zircons and baddeleyite (Davis and Paces, 1990). Livnat (1983) noted that the PLV experienced primarily prehnite–pumpellyite metamorphism and that maximum temperatures only reached 300 °C, which is well below the Curie temperature of most magnetization carriers.

Overlying the PLV is the Copper Harbor Conglomerate, a clast-dominated conglomerate with interbedded lava flows, known as the Lake Shore Traps, near the base of the unit, which represent the last stages of rifting (Ojakangas et al., 2001). The Copper Harbor Conglomerate is conformably overlain by the Nonesuch Shale, which has been assigned a minimum depositional age of 1047+/−35 Ma from Rb–Sr dating of petroleum inclusions (Ruiz et al., 1984). Conformably overlying the Nonesuch Shale is the Freda Sandstone. The Copper Harbor Conglomerate, the Nonesuch Shale and the Freda Sandstone are all part of the Oronto Group. The Jacobsville Sandstone, lying above the Freda, is a slightly arkosic sandstone that is included in the Bayfield Group. The Jacobsville is separated from the rest of the rift fill by the Keweenaw fault, a reverse fault that juxtaposes the PLV over the younger Jacobsville Sandstone. The

Keweenaw fault originated as a rift-related normal fault that was subsequently inverted due to Grenvillian shortening (Cannon, 1994).

The Jacobsville sandstone has been correlated to several units in Wisconsin and eastern Minnesota, including the Fond du Lac Formation, as well as the Middle River and Eileen sections of the Orienta Sandstone. It is for these deposits that the discrepancy in paleomagnetic direction is found. Data obtained by Roy and Robertson (1978) for the Jacobsville Sandstone and by Watts (1981) for the Fond du Lac formation and Orienta sandstone vary much more in declination than in inclination, with some amount of vertical-axis rotation of the MCR perhaps being one hypothesis for the distribution of the declination data.

3. Sampling and methods

Samples were taken from thirty-one sites in the Portage Lake Volcanics along the Keweenaw Peninsula to test for oroclinal bending using paleomagnetic declinations as a marker (Fig. 2). Two additional sites were sampled in intercalated volcanic conglomerate deposits. Sites were chosen to maximize variation in structural trend and each site is located within a single flow. Between six and ten, 2.5 cm diameter cores were collected from each site using a portable gasoline-powered drill. Where drilling was complicated, oriented hand samples were collected for coring in the laboratory. Both cores and hand samples were oriented with a magnetic compass at all sites and, when possible, checked with a sun compass. Bedding attitude determinations of the flows were obtained using the orientation of flow tops. Prior to analysis, the samples were cut into 2.5 × 2.2 cm cylindrical specimens at the University of Michigan's Paleomagnetic Laboratory. The natural remanence magnetization (NRM) was measured and then subsequently stepwise thermally demagnetized in a magnetically shielded, low-field room using an Analytical Service Co. (ASC) thermal demagnetizer and measured using a three-axes cryogenic 2G Enterprises Model 755 Superconducting rock magnetometer. Stepwise demagnetization was used over a range of 100 °C to 680 °C until the specimen's intensity was less than 2% of the NRM.

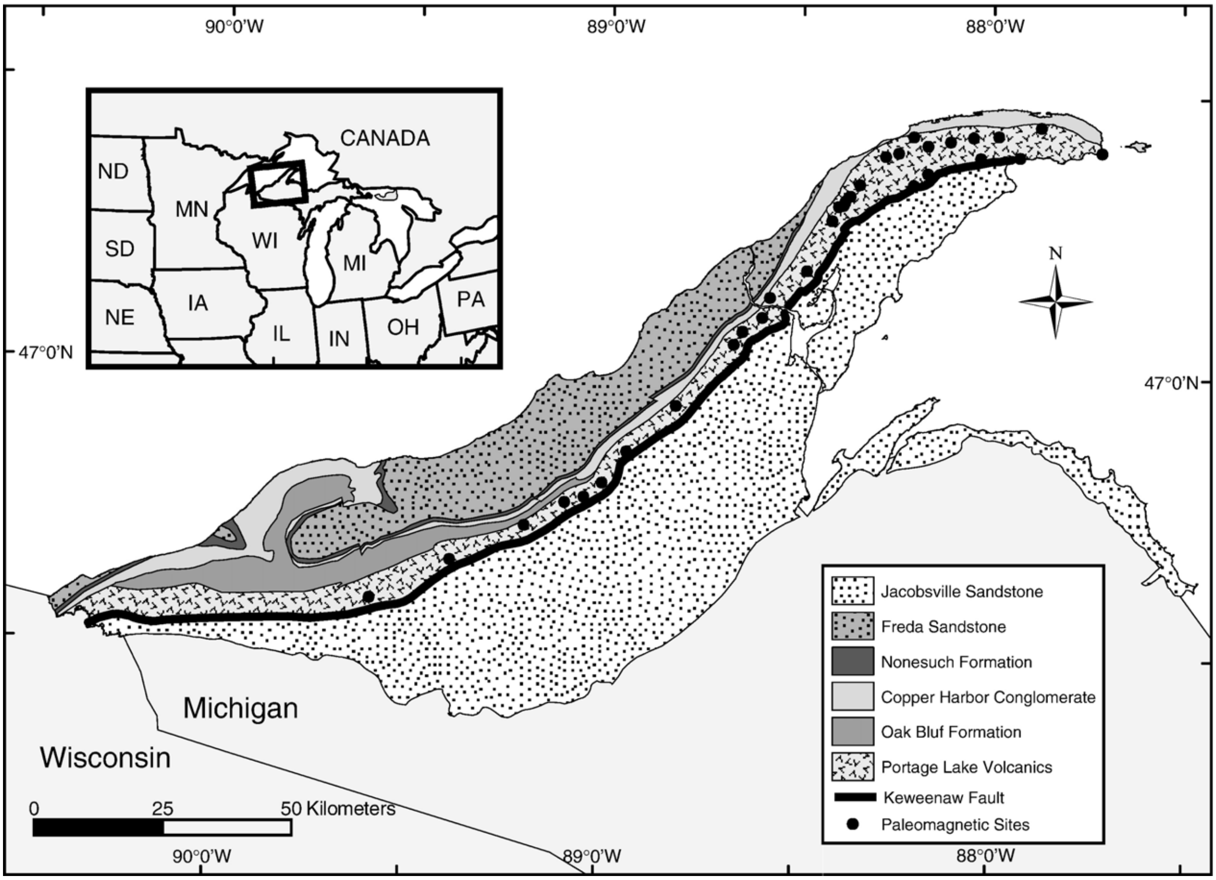

Fig. 2. Geologic map of rift-related rocks in the Upper Peninsula of Michigan showing paleomagnetic sites. Units are shown in stratigraphic order.

Remanence directions were calculated using principal component analysis (Kirschvink, 1980) of linear vectors selected from orthogonal projection demagnetization plots (Zijderveld, 1967) with the SuperIAPD software package (Torsvik et al., 1999). Individual sample directions were used to determine site means using Fisher's (1953) method. Watson's (1956) test for randomness in the cobbles of intercalated conglomerate beds was performed to establish the relative age of magnetization.

4. Results

4.1. Direction of magnetization

NRM intensities of the PLV ranged from 20 to 9000 mA/m. Stepwise thermal demagnetization revealed two components in the PLV, a lower laboratory unblocking temperature (T_{lab}) A component and a higher T_{lab} B component. Specimen demagnetization trajectories are generally well behaved and tend to display either two components or the appearance of a single component during demagnetization, with the latter being either high or low laboratory unblocking temperature (Fig. 3). The general direction of both magnetization components tend to be similar, being west–northwest and down after structural correction and varying by only a few degrees.

The lower T_{lab} A component was identified in twenty-eight of thirty-one sites. This component decayed progressively during demagnetization up to 580 °C. Magnetite is considered the carrier of the magnetization component, based on its laboratory unblocking temperature. The higher T_{lab} B component was isolated in twenty-one of the thirty-one sites and tended to remain stable up to anywhere between 610 °C and 660 °C, where intensity would then rapidly decay towards the origin, indicating hematite as the carrier of magnetization.

Site 9 shows a magnetization that proved to be irresolvable. In situ sample directions were highly scattered, with orientations distributed throughout the southeast and northwest quadrants. This site is located near the base of the exposed section of the Portage Lake Volcanics, dated at ~ 1096.2 Ma. A paleomagnetic reversal has been previously recognized between 1096.2 Ma to 1097.6 Ma in the Osler Group in eastern Lake Superior (Davis and Paces, 1990). Specimens displayed directions that may be the result of this reversal; however, it is impossible to tell from one site.

Site means for the A component display a Fisherian distribution in situ (Fig. 4a), but structural correction enhances this distribution by decreasing the scatter and gives a corrected mean of $D=291.2°$, $I=31.3°$, $\alpha95=5.6°$ and $k=24.51$ (Fig. 4b; Table 1). This mean direction

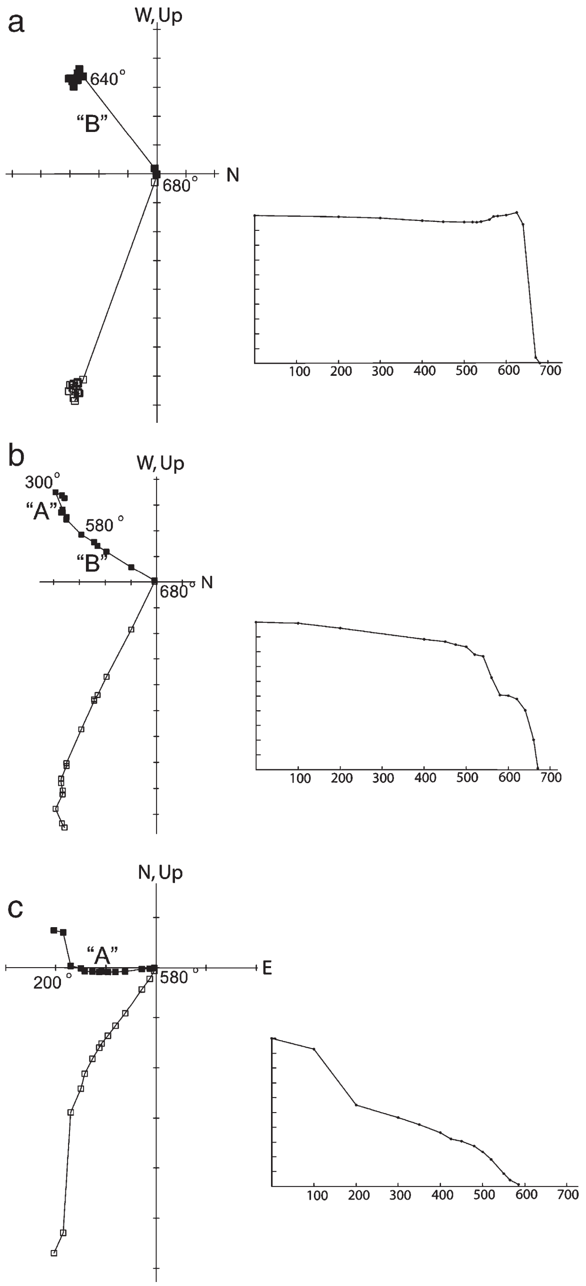

Fig. 3. Representative thermal demagnetization plots of the Portage Lake Volcanics in geographic coordinates and associated intensity plots. Intensity plots show normalized intensity versus temperature in degrees Celsius. In the demagnetization plots, closed (open) symbols represent vector endpoints plotted in the horizontal (vertical) plane. Temperature steps are in degrees Celsius. (a) Plot illustrating the B component carried by hematite. Ticks represent 10 mA/m. (b) Plot that was typical of most samples, showing two components. Note the similarity in the two components. Ticks represent 100 mA/m. (c) Plot of a specimen displaying only the A component carried by magnetite. Ticks represent 100 mA/m.

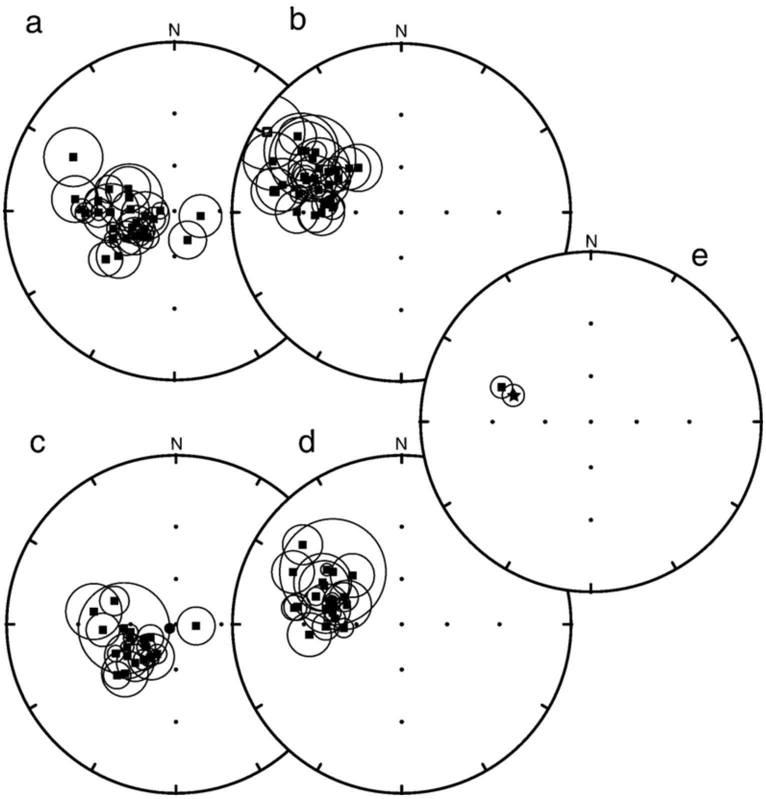

Fig. 4. (a,b) Lower hemisphere equal-angle projections showing distribution of site means and associated confidence circles for the A component both in situ (a) and tilt-corrected (b). This component, carried by magnetite, gives a mean direction of $D=291.2°$, $I=31.3°$, $\alpha95=5.2°$. (c,d) Lower hemisphere equal-angle projections showing distribution of site means and associated confidence circles for the B component both in situ (a) and tilt-corrected (b). This component, carried by hematite, gives a mean direction of $D=288.8°$, $I=38.6°$, $\alpha95=6.0°$. (e) Lower hemisphere equal-angle projection showing the orientations of the magnetization carried by magnetite and hematite. The square represents the magnetite component and the star represents the hematite component.

agrees with previous paleomagnetic studies of the PLV (Books, 1972; Halls and Pesonen, 1982; Browning and Beske-Diehl, 1987). Similarly, the B component also has a low dispersion both before (Fig. 4c) and after structural correction (Fig. 4d). The corrected mean for the hematite-carried component is $D=288.8°$, $I=38.6°$, $\alpha95=6.0°$ and $k=29.22$ (Fig. 4d; Table 1).

The similarity between magnetite and hematite-carried components indicate that these magnetizations were acquired within a relatively short time span of each other (Fig. 4e). The higher T_{lab} B component direction agrees with a similar high temperature component found in the PLV by previous workers (Browning and Beske-Diehl, 1987; Li and Beske-Diehl, 1993).

4.2. Age of magnetization

Samples from fourteen cobbles from two sites were collected from intraformational conglomerates to test the age of magnetization using Watson's (1956) test for randomness. As basaltic cobbles were sporadic and too small for sampling, rhyolitic cobbles were sampled. The source of these cobbles is inferred to be of Keweenawan affinity but has not yet been identified (Ojakangas et al., 2001). As with the Portage Lake samples, specimens from the cobbles were subjected to stepwise thermal demagnetization. The two components identified in the mafic flows were also defined in the rhyolite cobbles.

Thirteen cobbles displayed the lower temperature A component. The critical value of the resultant vector (***R***) for thirteen directions is 5.75 at the 95% confidence level (Table 2). This A component has an ***R***-value of 4.92, less than the critical value, indicating a random distribution of directions at the 95% confidence level (Watson, 1956) (Fig. 5a). Therefore, the A component passes the conglomerate test and indicates a primary magnetization for the component carried by magnetite. The B component was defined in eleven cobbles and,

Table 1
Paleomagnetic results from the Portage Lake Volcanics

Site number	Latitude	Longitude	Strike	Dip	Component	N/N_o	Dec in situ/corr	Inc in situ/corr
PL01	47.28	−88.41	232	43	A	8/10	249.2/302.8	74.9/40.8
PL02	47.30	−88.40	224	33	A	8/8	272.3/291.5	60.9/32.3
PL03	47.31	−88.38	226	31	A	8/9	235.5/274.3	61.9/45.7
					B	8/9	217.8/266.3	61.8/52.2
PL04	47.31	−88.38	218	42	A	7/8	240.4/270.3	53.8/26.7
					B	8/8	226.5/263.5	53.3/32.5
PL05	47.32	−88.38	228	45	A	6/8	260.7/298.2	70.1/32.3
PL06	47.32	−88.37	223	35	A	7/7	295.5/302.6	56.3/22.2
PL07	47.43	−88.21	252	41	A	6/7	288.5/306.4	45.7/15.5
					B	6/7	290.8/308.8	47.5/16.2
PL08	47.19	−88.48	220	41	A	7/8	225.4/276.0	65.0/41.1
					B	7/8	212.2/274.8	66.5/46.7
PL09	47.40	−87.93	274	71	Inconsistent	0/7	–	–
PL10	47.39	−88.03			B	5/7	225.9/296.5	44.5/35.8
PL11	47.34	−88.34	235	35	A	5/6	253.1/291.0	63.6/40.9
					B	5/6	241.9/295.1	71.6/48.6
PL12	47.14	−88.58	215	56	A	5/7	100.9/316.2	72.2/49.8
					B	5/7	94.8/314.7	76.4/45.4
PL13	47.39	−88.27	245	41	A	7/8	231.1/270.0	44.0/39.6
					B	8/8	236.8/281.7	52.2/40.8
PL14	47.43	−87.98	269	32	A	9/10	268.8/288.9	34.5/28.8
PL15	47.42	−88.10	259	33	A	8/8	245.6/280.3	46.5/44.0
					B	8/8	244.0/279.6	46.8/45.1
PL16	47.40	−88.28	233	22	A	8/8	268.8/280.2	41.8/27.0
PL17	47.37	−88.16	242	42	A	7/7	238.3/298.1	66.4/44.3
					B	5/7	217.4/289.5	62.8/52.0
PL18	47.08	−88.64	230	59	Conglomerate	–	–	–
PL19	47.08	−88.64	225	61	A	8/10	237.5/283.1	59.1/18.6
					B	9/10	222.0/279.4	58.4/25.9
PL20	47.43	−88.04	255	33	A	7/7	268.8/290.1	41.5/27.3
PL21	47.41	−88.18	250	35	A	7/7	253.9/285.4	48.7/36.1
					B	7/7	244.8/286.5	54.7/44.3
PL22	47.41	−87.71	281	26	A	5/6	277.6/299.2	41.1/37.6
					B	4/6	278.8/286.9	37.7/37.7
PL23	47.45	−87.87	272	33	A	9/9	271.0/290.5	32.6/27.4
PL24	47.11	−88.58	222	56	A	10/10	271.2/304.9	80.3/26.5
					B	9/10	236.9/306.2	84.9/32.5
PL25	47.06	−88.66	229	64	A	7/8	155.7/310.3	68.7/46.1
PL26	46.93	−88.83	215	55	A	7/8	248.9/279.6	60.1/15.6
					B	8/8	232.6/278.7	65.0/24.5
PL27	46.86	−88.94	231	69	Conglomerate	–	–	–
PL28	46.81	−89.00			B	9/9	243.4/288.8	66.4/42.9
PL29	46.78	−89.05	230	35	A	4/10	286.8/301.5	58.8/26.9
					B	10	260.3/288.0	59.4/33.9
PL30	46.77	−89.10	245	32	A	7/8	298.1/301.0	21.8/−4.5
					B	8/8	253.1/289.5	58.2/43.0
PL31	46.70	−89.23	250	42	A	7/8	234.9/268.0	37.2/36.0
					B	7/8	229.1/268.3	40.6/41.7
PL32	46.66	−89.39	255	51	A	4/8	269.0/301.9	48.7/20.4
					B	7/8	265.6/295.7	43.2/19.1
PL33	46.59	−89.59	261	42	A	7/10	276.9/291.7	28.8/11.4
					B	4/10	265.5/307.3	55.8/35.8
Mean	–	–	–	–	A	28/31	260.6/291.2	56.7/31.3
					B	21/31	243.6/288.8	60.4/38.6

A and B components are discussed in the text. Mean directions are calculated from site means (Fisher, 1953); N/N_o, number of samples (sites) accepted/studied; Dec, declination; Inc, inclination; α95, radius of confidence circle in degrees; ***R***, the resultant vector; *k*, precision parameter (Fisher, 1953). α95 of the mean after (before) structural correction is 5.6° (7.9°) for the A component and 6.0° (7.5°) for the B component. The precision parameter, *k*, of the mean after (before) structural correction for the A component is 24.51 (12.29) and 29.22 (18.93) for the B component.

Table 2
Paleomagnetic results from interbedded conglomerate samples

Cobble	A component			B component		
	Declination	Inclination	α95	Declination	Inclination	α95
PL18-A	147.3	11.5	5.7	300.9	10.9	3.0
PL18-B	352.1	12.2	10.3	–	–	–
PL18-C	281.6	49.8	5.4	–	–	–
PL18-D	272.1	21.7	6.4	276.2	22.0	5.4
PL18-E	2.4	18.1	3.2	4.0	22.0	5.7
PL18-F	284.1	−40.3	4.1	291.8	3.2	6.3
PL27-A	133.0	20.1	3.3	286.1	16.5	17.3
PL27-B	172.2	23.1	3.0	167.2	4.5	17.2
PL27-C	315.6	57.7	9.4	358.3	33.8	11.5
PL27-D	–	–	–	305.5	64.1	1.8
PL27-E	234.7	20.7	1.0	267.3	29.0	17.0
PL27-F	244.3	−3.5	7.0	236.5	−4.3	5.3
PL27-G	357.1	46.6	7.7	245.9	−33.6	7.1
PL27-H	139.9	20.9	1.8	–	–	–
			R=4.92			***R***=6.86

Notation as in Table 1. Resultant vector given for the two components is a result of the mean direction from the 13 (11) samples for the A (B) component.

unlike the A component, has an ***R***-value of 6.86 (Fig. 5b; Table 2), higher than the required 5.29 at the 95% for eleven directions to be random (Watson, 1956). This component also has a dominant west-northwest and down orientation, which is similar in direction to the characteristic magnetization of the Portage Lake Volcanics. The B component, consequently, can be considered a secondary magnetization carried by hematite. The B component is different from secondary components identified in the overlying Copper Harbor Conglomerate, where the remagnetized component has an orientation similar to that of much younger rift-related sedimentary rocks (Palmer et al., 1981; Halls and Palmer, 1981).

5. Discussion

The twenty-eight sites that displayed the A component, carried by magnetite, were use to test for the presence of oroclinal bending (or secondary rotation) in the Mid-Continent Rift. Because the B component is a secondary magnetization, it is omitted from further analysis for this study. Eldredge et al. (1985) proposed a method to test for oroclinal rotation by evaluating changes in declination as a function of observed deviations in strike for each site. This method was used in this study to assess the possibility of rotation in the Keweenawan rocks. Both strike and declination were normalized to a

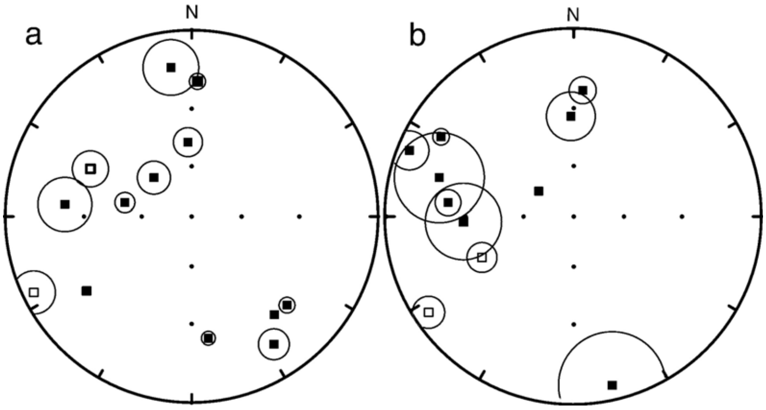

Fig. 5. Equal-angle projections of conglomerate samples for the A component (a) and the B component (b); full (open) symbols are projections onto the lower (upper) hemisphere. Confidence cones represent specimens' maximum angular deviations (MADs). Directions are in tilt-corrected coordinates and are also given in Table 2.

reference strike and declination (S_o and D_o, respectively), so that the best-fit line to the data passes through the origin. The slope of the best-fit line is an indication of the magnitude of oroclinal bending a curved belt has experienced, with a slope of 0.0 representing no rotation and a slope of 1.0 indicating an originally straight belt that has been subsequently bent.

The resulting plot (Fig. 6a) shows a poor correlation between differential strike and differential declination. The best-fit line has a slope of essentially zero (0.004), although the data show high residuals to the trendline. Because the data are from volcanic rocks, which acquire their magnetization relatively quickly, and our sites each come from a singular basalt flow, the individual site-means do not represent a time-averaged direction of geomagnetic field. Therefore, the observed high degree of scatter in declination can be at least partly attributed to secular variation of the geomagnetic field during the

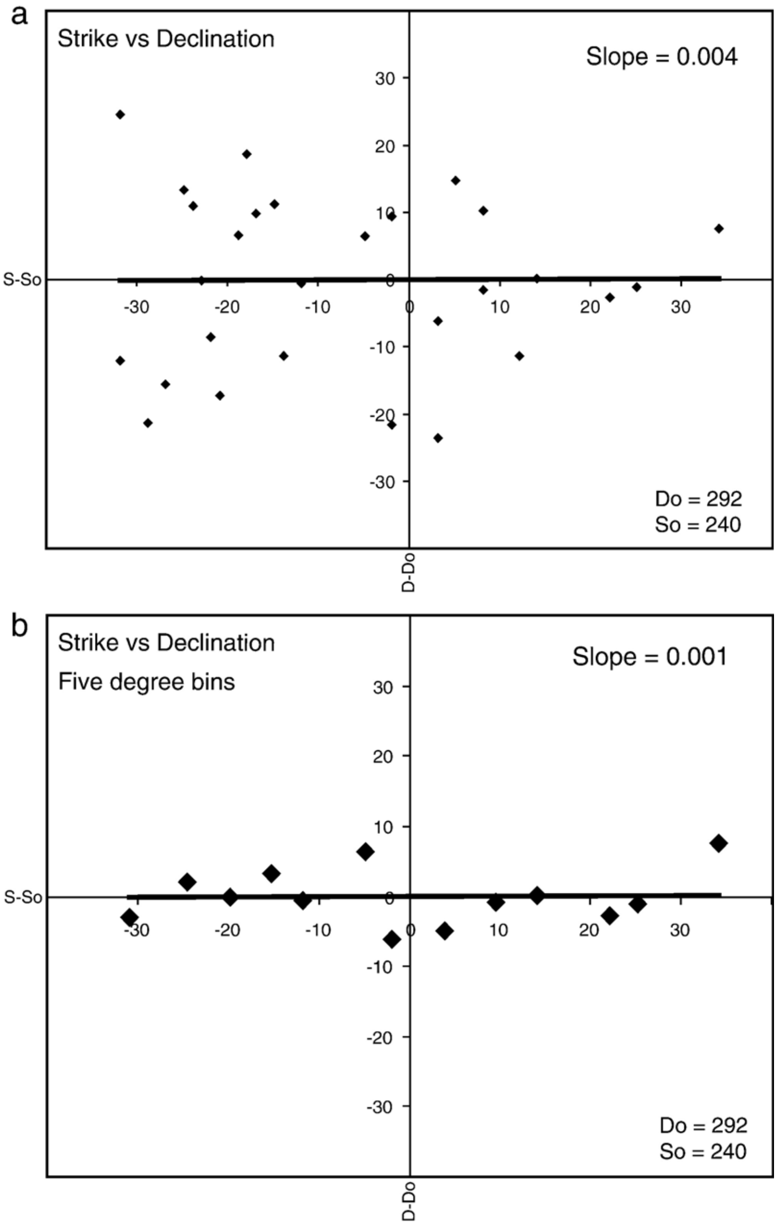

Fig. 6. (a) Declination deviations from a reference declination of $D_o=292°$ for all site means plotted against strike variations from a reference strike of $S_o=240°$. Data are presented so that the "best fit" line plotted for these data passes through the origin. Each site is contained within a single flow. (b) To minimize variations in declination, data are binned into five-degree strike bins and a weighted best fit line is produced. As in (a), $D_o=292°$ and $S_o=240°$.

eruption of the basalts. This has been demonstrated in recent basalts in areas with multiple flows (Herrero-Bervera and Valet, 1999). In order to diminish the effects of secular variation, we chose to bin the data into five-degree intervals of strike values. The declination values within each bin were then used to calculate a mean declination for that five-degree interval and thus average out Mesoproterozoic secular variation. Each mean was then weighted to minimize effects of varying numbers of data points contained within the bins. The resulting trendline is similar to the raw data pattern, showing a slope of essentially zero, and thus no correlation between strike and declination (Fig. 6b). Unlike the unbinned data, the declination data residuals are significantly less, resulting in a better fit to the trendline. The near zero slope and the lack of correlation lead to the clear conclusion that vertical-axis rotations have not affected the mafic flows of the MCR along the Keweenaw Peninsula and, thus, that the curvature of the belt is a primary feature.

Because secondary rotation does not explain the considerable strike variation of the MCR, other sources of curvature have to be considered. Most likely, a pre-existing non-linear crustal feature may have been utilized by the MCR. For example, the MCR in the Lake Superior region has been proposed as being a failed triple junction initiated by a mantle plume (Hinze et al., 1972; Burke and Dewey, 1973; Green, 1983; Cannon and Hinze, 1992), with two of the limbs being the main rift segments and the third arm being an extensive suite of dike swarms extending northward from Lake Superior, known as the Nipigon arm (Cannon and Hinze, 1992). However, the triple-junction hypothesis does not sufficiently explain the gradual strike variation of the MCR. Klasner et al. (1982) suggested that the development of the rift in its present geometry is related to a large gravity low in central Wisconsin. This low has been recognized as the expression of the Wolf River Batholith, a large, late Mid-Proterozoic “anorogenic” granitic pluton that may have diverted rift development around its perimeter. Another possible origin for the curvature is the existence of Penokean (~ 1.85 Ga) crustal fault zones that are roughly parallel to the MCR. The Great Lakes Tectonic Zone (GLTZ) and the Murray fault strike approximately the same as the southwestern and southeastern arms of the rift, respectively (Riller et al., 1999) and zones of Penokean suturing directly adjacent to the rift have been identified in Minnesota (Wunderman, 1988). These planar zones of weakness could have facilitated arcuate development of the Mid-Continent Rift. It is more likely, however, that the arcuate zone of weakness directly responsible for the curvature in the MCR has not been identified or was destroyed during the 25%+ crustal thinning that took place prior to basalt emplacement (Cannon et al., 1989). The most probable scenario is that both arcuate Penokean detachment zones and large, “anorogenic” plutons constrained the MCR to its current curved geometry. During rift inversion in the western Lake Superior region, rift bounding normal faults reversed their sense of motion to accommodate Grenville shortening; however, in eastern Lake Superior, east–west trending thrusts cut across the eastern limb of the MCR (Manson and Halls, 1997). Since inversion in western Lake Superior occurs without any rotation, we can speculate that during post-rift shortening, compression axes responsible for rift inversion must have been sub-parallel to the tension axes that initially formed the rift.

It follows that the variations in declination observed in earlier studies of the late Keweenawan sedimentary rocks (Watts, 1981) cannot be attributed to rotation of the crust. Instead, we speculate that this variation may be due to the poor age constraints of Precambrian sedimentary rocks and therefore apparent polar wander or to errors associated with structural corrections applied to these rocks.

Regardless of the origin, a pre-defined curved zone of crustal weakness is responsible for the arcuate nature of the MCR in the Lake Superior region, rather than secondary rotation. Thus, map-view curvature can form without significant rotations. In many of the world’s other arcuate orogenic belts, at least part of the observed curvature can be explained by secondary rotation of the limbs. However, as shown in this study of Mid-Continent Rift volcanic rocks, secondary rotation is not characteristic of all curvature.

6. Conclusion

Paleomagnetism of mafic flows of the Portage Lake Volcanics of northern Michigan has revealed two remanence components during stepwise thermal demagnetization. The lower temperature component, carried by magnetite, passes the test of randomness on interbedded rhyolite conglomerate clasts and is interpreted to be a primary magnetization. The higher temperature component, carried by hematite, does not show a random distribution of directions, indicating a secondary magnetization. We used the primary component to assess the possibility of oroclinal bending of the Mid-Continent Rift in the Lake Superior Region. The ensemble of declination data shows considerable scatter along the trend of the Mid-Continent Rift. When analyzed using five-degree strike bins to account for secular variation of the paleomagnetic field during the eruption of the flows, the analysis shows no correlation between strike and declination, which leads to the conclusion that no oroclinal bending has occurred in the Mid-Continent Rift. Therefore, the rift's curvature is primary and must be explained by a pre-defined zone of weakness exploited by the rifting process. Post-rift shortening in the area involved rift inversion without resulting in significant rotation.

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