Paleomagnetism of the Early Proterozoic Sioux Quartzite, Southwestern Minnesota—Implications for Correlating Quartzites of the Baraboo Interval

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Chapter N

Paleomagnetism of the Early Proterozoic Sioux Quartzite, Southwestern Minnesota—Implications for Correlating Quartzites of the Baraboo Interval

By VAL W. CHANDLER and G.B. MOREY

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Paleomagnetism of the Early Proterozoic Sioux Quartzite, Southwestern Minnesota—Implications for Correlating Quartzites of the Baraboo Interval

By Val W. Chandler[1] *and* G.B. Morey[1]

Abstract

Paleomagnetic studies were conducted on the Early Proterozoic Sioux Quartzite, one of the so-called "Baraboo interval" red-bed sequences of the Lake Superior region. A total of 158 samples were collected from 17 sites scattered across four basins (Cottonwood County, New Ulm, northern Pipestone, and southern Pipestone) in southwestern Minnesota. Alternating-field and thermal demagnetization studies indicate that the magnetization is dominantly single component, and that the magnetic carrier is hematite. Hematite occurs both as a diagenetic mineral whose long paragenetic history began shortly after deposition and as veinlets that formed during a strain event possibly related to regional tilting. The magnetization is tentatively interpreted to have occurred before regional tilting, although a definitive fold test is difficult because dips are low. Measured paleomagnetic directions at both site and basin levels show good clustering, and the average directions obtained from each of the four basins are not significantly different at the 95 percent confidence level. The good clustering at all levels of sampling indicates that the Sioux Quartzite was magnetized either within a short time interval or during a period of subdued apparent polar wander.

The structurally corrected paleomagnetic directions from the four basins yield a combined paleopole location at 101° W. and 16° N. (k=65, alpha 95=11°). Dated paleopoles for Early Proterozoic rocks in North America and age dates of rocks interpreted to underlie the Sioux Quartzite imply that its age is 1,700–1,650 Ma. This interval corresponds in part with the age of 1,800–1,630 Ma of the Central Plains orogen, which lies some 200–300 kilometers south of the Sioux Quartzite outcrop. Thus, the paleopole and inferred age of the Sioux Quartzite may reflect a tectonic pulse related to the Central Plains orogen.

Preliminary paleomagnetic data on Baraboo-interval quartzites from Wisconsin indicate that the Sioux paleopole cannot be distinguished at the 95 percent confidence level from that of the Barron Quartzite, but that it differs from that of the Baraboo Quartzite, which on the basis of existing apparent polar wander data could be as much as 100 million years older. The paleomagnetic data support previously raised cautions that some Baraboo interval quartz arenites may have been deposited in separate basins at significantly different times.

INTRODUCTION

The Sioux Quartzite is an Early Proterozoic quartz-arenitic red-bed sequence that crops out over a large area in southwestern Minnesota and adjoining parts of South Dakota, Nebraska, and Iowa (fig. 1). It is one of several red-bed sequences in the southern part of the Lake Superior region; these sequences include the Barron, Flambeau, Baraboo and Waterloo Quartzites, as well as several other smaller and unnamed sequences, all in Wisconsin (Greenberg and Brown, 1984). A sequence, as used herein, comprises a geographically discrete succession of quartzites that were deposited under related environmental conditions. It is impossible to establish a strictly synchronous relationship between the several red-bed units because exposures are discontinuous and fossils or other stratigraphic markers are lacking. Nonetheless, because the red beds are so similar in appearance, it has been assumed with considerable confidence that they are at least broadly correlative (Pettijohn, 1957; Dott and Dalziel, 1972).

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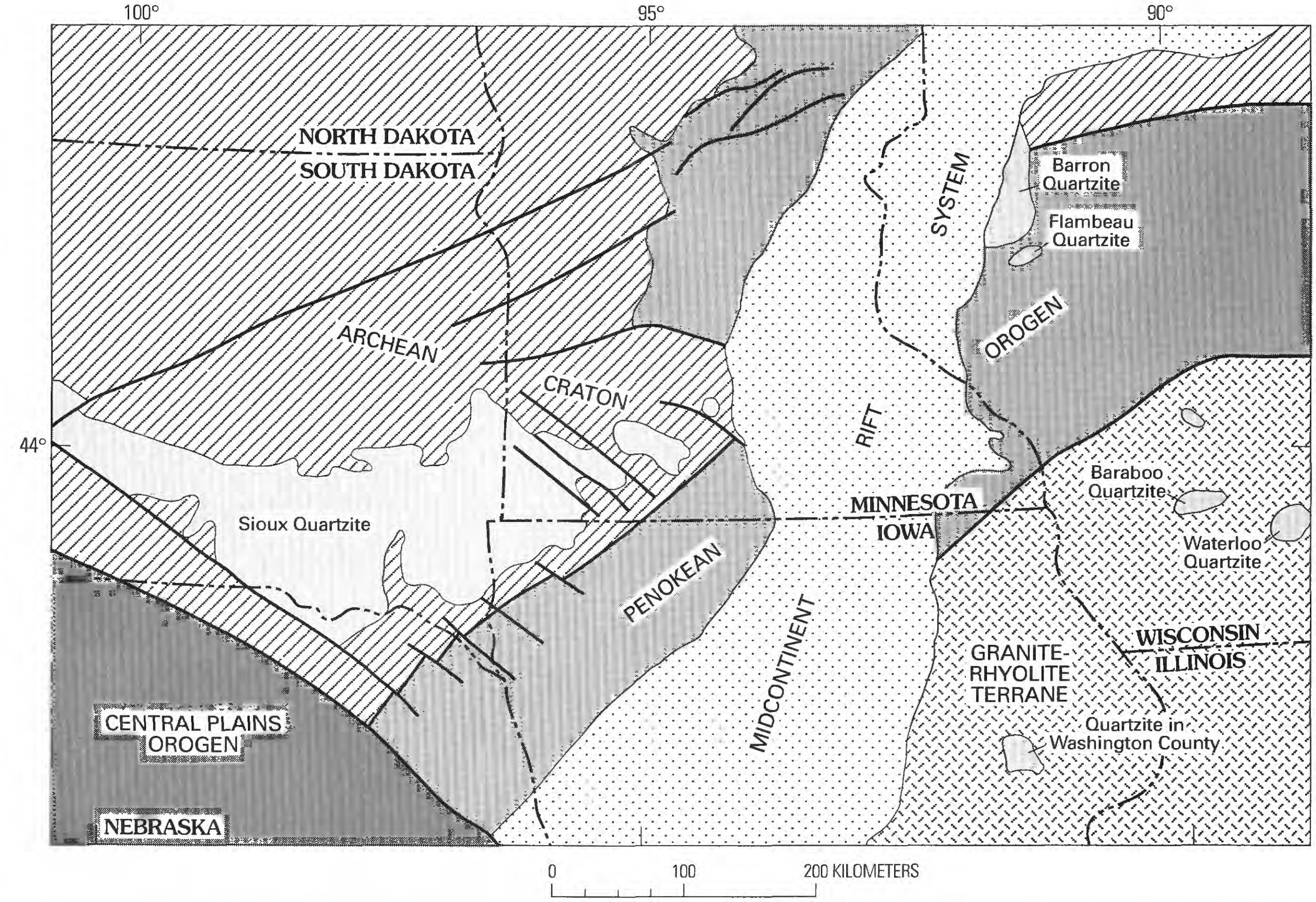


Figure 1. Generalized geologic basement map of southern Lake Superior region and northern Midcontinent showing location of quartz-arenitic red-bed sequences assigned to the Baraboo interval. Heavy solid line, fault; thin line, contact (modified from Dott, 1983; Sims and Peterman, 1986; Southwick and others, 1986; and Chandler and Southwick, 1990).

Until recently, workers quite uniformly assumed that all the red-bed sequences were once part of a continuous blanket of sand deposited in a shallow-water near-shore environment on an east-west-trending, southward-sloping continental shelf (Baldwin, 1949, 1951; Dalziel and Dott, 1970; Austin, 1972; and Dott and Dalziel, 1972). However, Henry (1975, as cited by Dott, 1983) was among the first to realize that, in the absence of fossil evidence, the assumption of continuity is at best tenuous and that the Baraboo Quartzite was equally likely to have been deposited by braided fluvial processes. Dott (1983, p. 140) consequently modified the sedimentological model, suggesting that the red beds could have been deposited as "braided fluvial deposits formed on a sandy coastal plain several hundred kilometers wide* * * that subsequently was submerged during a shallow marine transgression." Even though individual units could be somewhat diachronous in this model, in Dott's view they all were part of a larger sedimentary regime peculiar to the time interval of 1,750 Ma to 1,450 Ma. He termed that period of time the Baraboo interval, after the best studied of the red-bed sequences. Shortly thereafter Greenberg and Brown (1984) redefined the Baraboo interval as that period of time characterized by anorogenic igneous and sedimentary activity between the inferred end of the Penokean orogeny (approximately 1,760 Ma) and the emplacement of major anorogenic plutons in Wisconsin at about 1,500 Ma. Subsequently Morey and Van Schmus (1988) suggested that red-bed sedimentation occurred in the Lake Superior region during the interval from 1,760±10 Ma to 1,630±40 Ma.

Since 1983 most workers have adopted the Dott (1983) model, and a fluvial or a mixed fluvial and shallow-marine sedimentological model has been proposed for the Barron and Flambeau Quartzites (Campbell, 1981, 1986; Johnson, 1985) in Wisconsin and the Sioux Quartzite in Minnesota (Ojakangas and Weber, 1984). In contrast, Morey (1983, 1984) and Southwick and Mossler (1984) found no compelling evidence for a continental margin sequence in southwestern Minnesota and suggested instead that the Sioux was deposited in an intracratonic setting by braided fluvial processes in a series of northwest-trending fault-bounded

Table 1. Site- and basin-average paleomagnetic parameters for the Sioux Quartzite

[AF, alternating field demagnetization; T, thermal demagnetization; BA, basin average, no structural correction; D, declination; I, inclination; SBA, structurally corrected basin average; *N*/No., number of samples used in analysis followed by original number of samples collected at site; for basin average *N* and No. represent total number of sites used and total number of sites sampled, respectively; k, precision parameter; α95=95 percent confidence circle. All paleomagnetic parameters given for sites are not corrected for structure; the structurally corrected basin average for the Cottonwood County basin is based on regional strike and dip values of N. 70° W. - 7° SW., respectively, rather than on local values]

Site No.	Lat ° N.	Long ° W.	*N*/No.	Treat-ment	D deg	I deg	k	α 95 deg	Strike deg	Dip deg
				Cottonwood County basin						
1	44.10	95.10	16/17	AF+T	173.2	61.6	117	3.4	NS	11E
2	44.08	95.11	6/6	AF+T	158.7	75.0	465	3.1	N45W	9S
3	44.08	95.11	6/6	AF+T	162.5	78.4	330	2.4	N50W	5S
4	44.09	95.12	5/5	AF+T	158.4	73.7	142	6.4	N70W	9S
BA	44.09	95.11	4/4	AF+T	164.9	72.3	112	8.7	--	--
SBA	44.09	95.11	4/4	AF+T	173.9	66.1	100	9.3	--	--
				New Ulm basin						
5–1	44.28	94.41	14/15	AF	198.3	71.0	54	5.5	N58W	14NE
5–2	44.28	94.41	5/8	AF	226.4	78.3	111	7.3	N58W	14NE
5–3	44.28	94.41	8/8	AF	192.4	56.2	181	4.1	N38W	17NE
BA	44.29	94.41	3/3	AF	200.4	69.0	42	19.3	--	--
SBA	44.29	94.41	3/3	AF	169.1	82.2	35	21.3	--	--
				Northern Pipestone basin						
8–1	44.01	96.32	16/18	AF	205.2	74.9	85	4.0	N5W	8E
8–2	44.04	96.33	9/10	AF	225.9	60.1	53	7.2	N3W	5E
8–3	44.02	96.33	3/3	AF	223.2	85.2	722	4.6	N15W	9E
BA	44.02	96.33	3/3	AF	219.3	73.6	39	20.1	--	--
SBA	44.02	96.33	3/3	AF	199.9	78.5	30	22.9	--	--
				Southern Pipestone basin						
9	43.85	96.39	5/7	AF	232.7	63.2	12	23.5	N55E	5SE
10	43.88	96.37	10/10	AF	253.6	78.0	13	14.0	N81E	7S
12	43.69	96.20	8/10	AF	213.0	58.8	45	8.4	N69E	5N
13	43.70	96.19	8/10	AF	165.4	71.63	77	6.4	N25E	9NW
BA	43.85	96.31	4/7	AF	215.4	70.3	31	16.8	--	--
SBA	43.85	96.31	4/7	AF	218.0	68.7	75	10.7	--	--

basins. They further suggested that there exists no compelling evidence that sedimentation was ever continuous between the several basins or even contemporaneous.

This report uses paleomagnetic data from 17 quartz arenite sites in southwestern Minnesota (figs. 2–5 and table 1) (1) to evaluate the extent to which diachronous sedimentation occurred in the several Sioux depositional basins, and (2) to test possible correlations of the Sioux Quartzite with the Barron and Baraboo Quartzites of Wisconsin.

ACKNOWLEDGMENTS

This study was supported by the Legislative Commission on Minnesota Resources and the Minnesota Geological Survey. Douglas Bergstrom conducted most of the earlier field and laboratory work; later work was conducted by T.J. Boerboom and B.D. Schaap. We are particularly grateful to several property owners for access, and to the Institute for Rock Magnetism, Department of Geology and Geophysics, University of Minnesota, Minneapolis, for access to their paleomagnetic equipment. Some work also was performed using paleomagnetic equipment at the Minnesota Geological Survey.

GEOLOGIC SETTING

The Sioux Quartzite overlies a regolith developed on an older Precambrian crystalline basement (Southwick and Mossler, 1984). It is a red-bed sequence that was deposited by braided streams flowing over a deeply weathered land surface of moderate relief. Deposition in Minnesota was confined largely to four northwest-trending basins in an

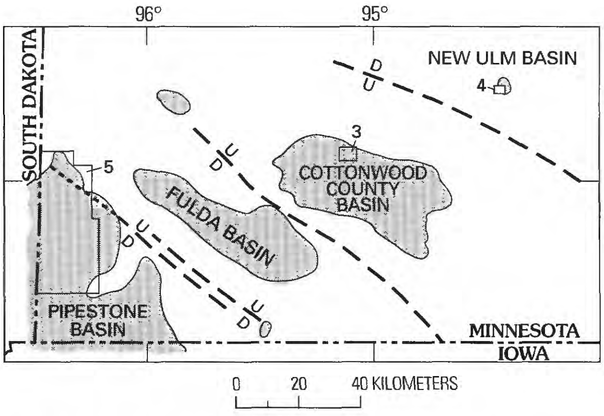


Figure 2. Distribution of Sioux Quartzite in southwestern Minnesota. Rectangular boxes numbered 3–5 represent areas of detailed maps shown in figures 3–5. Dashed line, basement fault; short dashed where inferred; U, upthrown side; D, downthrown side.

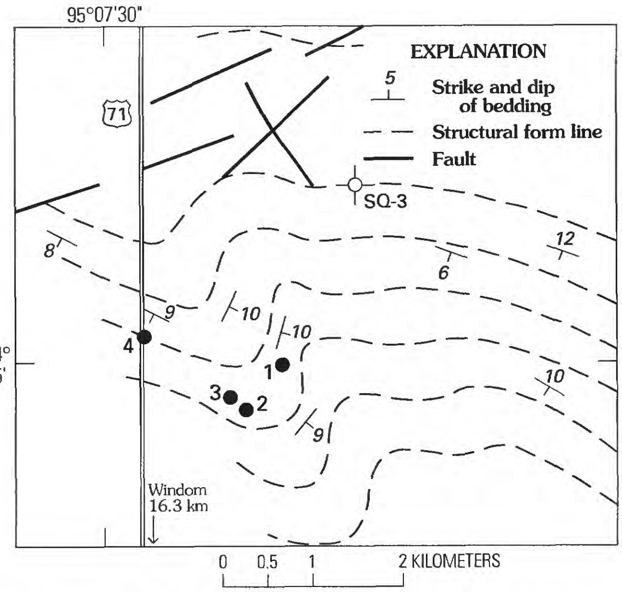


Figure 3. Sample sites 1–4 in the Cottonwood County quartzite basin. Form lines and structural attitudes from Southwick and Mossler (1984). SQ–3 designates drill hole that penetrated 287 m of Sioux Quartzite. Location shown in figure 2.

intracratonic setting. The basins, named in figure 2, are separated from one another by areas where quartz arenite is patchy or absent. The faults were inferred from aeromagnetic anomaly patterns and cataclastic textures in several drill cores along anomaly trends. That differential fault movement controlled sedimentation is likely, and such movement may have continued long after the Sioux was lithified (Southwick and others, 1986).

The basins containing the Sioux Quartzite sequence are erosional remnants, and the total amount of sediment deposited in each of them is unknown. However, approximately 287 m (942 ft) of section was transected by drilling in the Cottonwood County basin (fig. 3), and nearby outcrops represent an additional stratigraphic thickness of about 200 m (660 ft), most of which is stratigraphically above the section cut by drilling (Southwick and Mossler, 1984). Therefore the total documented thickness in the Cottonwood County basin is about 490 m (1,600 ft). This estimated thickness is consistent with the work of Gries (1983), who concluded that the Sioux Quartzite in South Dakota is generally not much more than 305 m (1,000 ft) thick. Both estimates are considerably less than those of Baldwin (1951), who calculated that 610–1,220 m (2,000–4,000 ft) of strata was present in the Cottonwood County basin and that the Sioux in general was 1,600–2,400 m (5,300–7,900 ft) thick.

The Sioux Quartzite is a texturally and mineralogically mature quartz arenite. Sand-size grains consist mainly of monocrystalline quartz, along with rare grains of chert, granular iron-formation, and quartzite. Scattered conglomeratic layers contain lithic clasts that include red quartzite, chert, iron-formation, vein quartz, and rhyolite, together with rare grains of granitoid gneiss. A conglomeratic interval near the base of the formation in the New Ulm basin contains an array of red sedimentary rock clasts including orthoquartzite boulders as large as 35 cm in diameter (Miller, 1961). Clasts of similar sedimentary rocks also occur near the base of the Sioux Quartzite in the southern Pipestone basin, together with cobbles of undeformed rhyolite and welded rhyolite tuff that were apparently derived from a 1,825–1,800 Ma granite-rhyolite terrane reported in eastern South Dakota (Wallin and Van Schmus, 1988).

Other units of conglomeratic quartzite are generally confined to the lower two-thirds of the formation, where they form lenticular layers consisting of pebbles of vein quartz, quartzite, hematitic chert (jasper), and rare laminated oxide-facies iron-formation set in a coarse sand matrix. In contrast the upper third of the Sioux contains thin units of mudstone or claystone (pipestone or catlinite) that consist of very fine grained quartz, sericite, hematite, and diaspore, with smaller amounts of chlorite, kaolinite, and rutile (Morey, 1984; Gundersen, 1982). Beds of true pipestone lack quartz and kaolinite and are rich in some combination of diaspore, muscovite, and trace amounts of chlorite (Gundersen, 1984).

The diagenetic mineral assemblage diaspore-kaolinite-quartz is widely distributed in the quartz-arenitic rocks of the Sioux Quartzite (Berg, 1937, 1938). Textural relationships indicate that the diaspore formed more or less concurrently with an early generation of well-crystallized kaolinite (Southwick and Mossler, 1984; Vander Horck, 1984), and both minerals clearly occupy interstitial voids between sand-size framework grains. The quartz arenitic rocks also contain sand-size clots of sericite and kaolinite. Although their origin is uncertain, they are similar in size and form to residual grains of feldspar heavily modified by sericite and kaolinite that occur in the lower part of the formation.

Much of the quartz arenite is cemented by epitaxial silica, and some of this silica may have been liberated from the interstitial breakdown of feldspar (Southwick and Mossler, 1984). Both Berg (1937) and Vander Horck (1984) observed that hematite occurs as a fine dust at boundaries between detrital cores and overgrowths, as included material within epitaxial overgrowths, and as discrete grains within masses of kaolinite and diaspore. It therefore appears that much of the hematite formed sporadically throughout the diagenetic history of the rock. Some hematite also occurs throughout the formation as sand-size clasts of cherty iron-formation and ferruginous chert or jasper. These grains rarely exceed more than 1 or 2 percent of the framework grain population. Small hematite-bearing veinlets also have been observed in quartz arenitic rocks of the northern Pipestone basin where pyrophyllite occurs in beds of claystone. The quartz arenitic beds have been weakly strained after cementation, as strain shadows and deformation laminae cross grain boundaries into the epitaxial quartz cement. Pyrophyllite also occurs in claystone beds that crop out at Blue Mounds State Park in the southern Pipestone basin. Both localities are near the trace of inferred faults, implying that the pyrophyllite may have formed by burial metamorphic processes and that the strata were uplifted to their present positions by subsequent faulting.

PREVIOUS PALEOMAGNETIC STUDIES OF BARABOO INTERVAL QUARTZITES

The Sioux and Barron Quartzites were included by Runcorn (1964) in a reconnaissance paleomagnetic study of several Precambrian sedimentary rock units of the western United States. Only two sites yielding eight or nine samples each were sampled from each unit, and neither alternating field (AF) nor thermal demagnetization techniques were applied. Their results, however, produced well-clustered directions that yielded paleopoles in the western United States and the eastern Pacific Ocean (table 2). More recently the paleomagnetism of Baraboo interval quartzite has been investigated in Wisconsin by W.F. Kean and co-workers (Kean and Mercer, 1986; Kean and others, 1989; Kean and Schneiker, 1990), and their results with the Barron and Baraboo Quartzites reveal highly stable, predeformational magnetizations, with paleopoles in the same general vicinity as Runcorn's (table 2). A preliminary summary of the work reported here was published (Bergstrom and Chandler, 1987), but this study supersedes that effort.

FIELD AND LABORATORY METHODS

The Sioux Quartzite was sampled at 17 sites throughout southwestern Minnesota (figs. 2–5). Three to 23 oriented

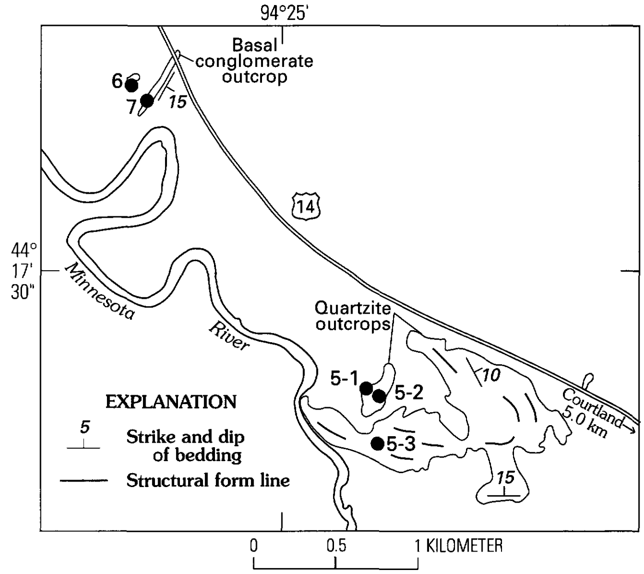


Figure 4. Sample sites in the New Ulm quartzite basin. Location shown in figure 2. Locality 6, granite. Modified from Miller (1961).

samples were taken at each site, either by diamond drilling (10 sites) or by block sampling (7 sites). Of these sites, 10 were natural outcrops and 7 were quarries. As can be seen in figure 5, a major structural discontinuity divides the Pipestone basin into a northern and a southern segment. Morey (1984) has suggested that the northern segment is structurally more akin to the otherwise unexposed Fulda basin. Nonetheless, for simplicity the term "northern Pipestone basin" is used here (fig. 5). One or two core specimens were produced from each sample in the laboratory. These specimens typically have lengths of 2.0–2.54 cm and a diameter of 2.54 cm. At all the sample sites, the amount of correction for tilt was based on regional structural studies (Baldwin, 1951; Webber, 1981; Morey, 1984; Southwick and Mossler, 1984); master-bedding features at the site level were difficult to determine in the extensively crossbedded rocks.

In addition to the 17 quartz arenite sites just mentioned, 2 others were utilized—one in the basal conglomerate (site 7) and one in the underlying granite (site 6) in the New Ulm basin (fig. 4). At site 7, we used a large (0.3×0.3×1.5 m) oriented slab of conglomerate for a preliminary conglomerate test by sawing several clasts from it.

The paleomagnetic attributes of the quartz arenitic rock were examined by the stepwise demagnetization of pilot specimens. In our study we applied AF (alternating field) treatment to 38 specimens and thermal treatment to 32 specimens. Most specimens were characterized by high coercivities with little response to AF demagnetization (fig. 6). Samples that did respond to AF demagnetization were most likely affected by lightning-induced IRM (isothermal remanent magnetization), as evidenced by their high initial intensities and low coercivities (sample 8-2-i, fig. 6). Thermal

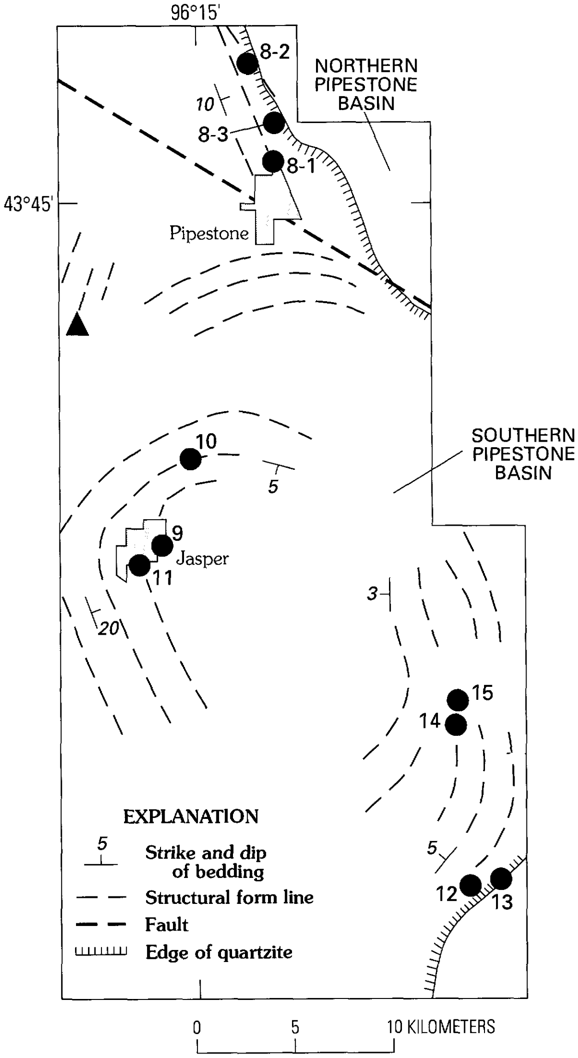


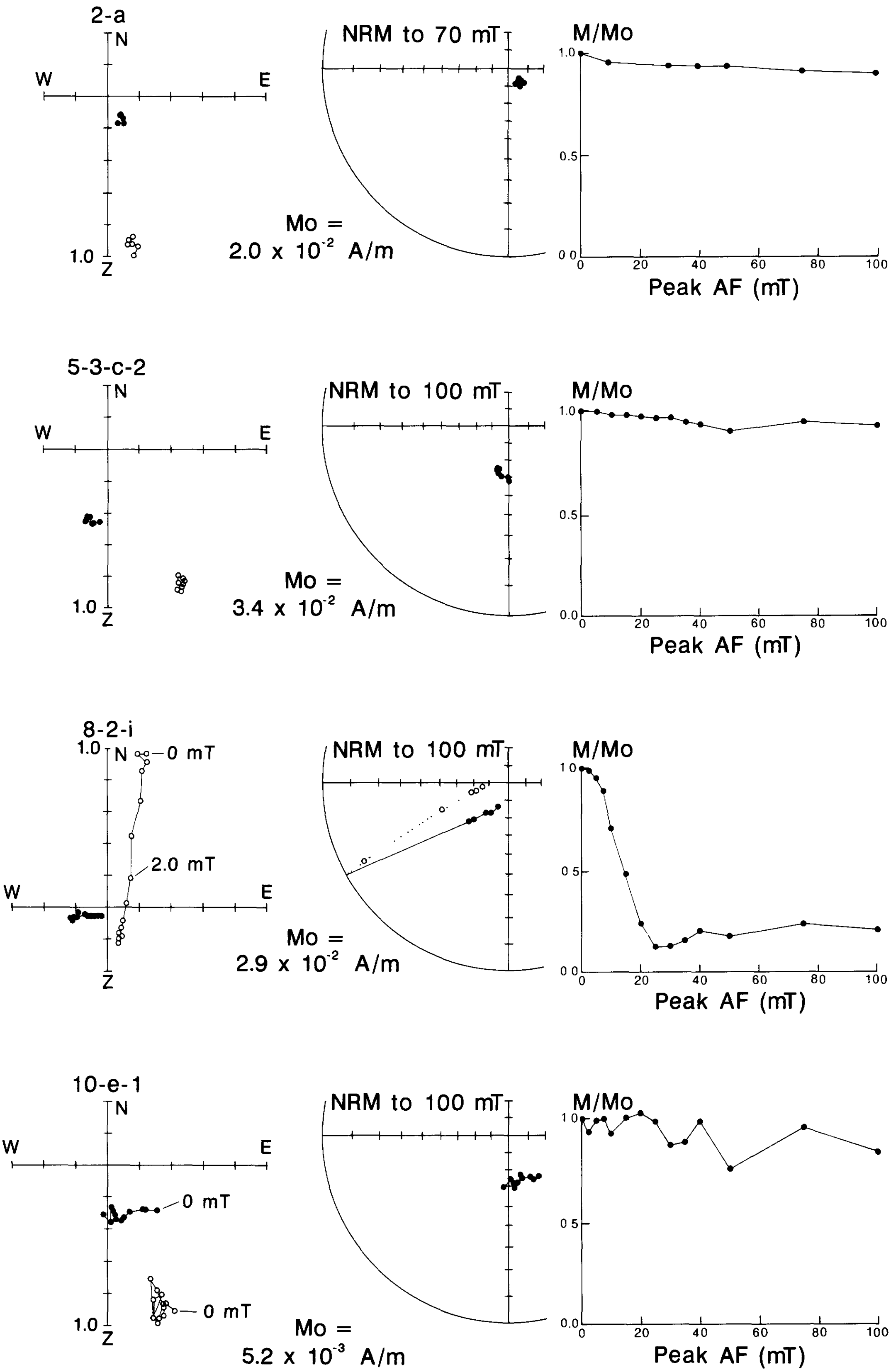
Figure 5. Sample sites in the northern and southern Pipestone quartzite basin. Form lines and structural attitudes from Baldwin (1951) and Morey (1984). Triangle represents sites where rhyolite cobbles in a conglomerate were dated by Wallin and Van Schmus (1988).

demagnetization spectra show generally flat, broad shoulders and a narrow range of high blocking temperatures between 620 and 680 °C (fig. 7). The high coercivities and blocking temperatures displayed by the pilot specimens indicate that hematite is the principal magnetic carrier.

Before reaching stable end points during thermal demagnetization, a few specimens produced short, linear segments on the orthographic projection plots that indicated secondary components (for example specimens 5-3-a-1 and 8-2-b-2 in fig. 7). The presence of secondary components was of particular concern in the Pipestone basin, where the Sioux has been subjected to a low-grade metamorphic event and where small hematite-bearing veins cut both matrix and framework grains. However, principal component analysis (Kirschvink, 1980) of the detailed thermal demagnetization trajectories from nine samples taken from both the northern and southern Pipestone basin produced only components that either are widely scattered or are essentially aligned with the stable end points, which are generally directed steeply to the south or southwest (fig. 8*A*). Thus, we assume that the primary component of the Sioux Quartzite can be adequately isolated by single-step demagnetization at AF levels of 75–100 mT or thermal levels of 600–650 °C.

Single-step AF demagnetization followed by single-step thermal demagnetization of all specimens from sites 1 through 5–1 show that the two procedures yield essentially the same site-average directions. Therefore specimens from the remaining sites were subjected only to single-step AF demagnetization. Three natural outcrop sites (sites 11, 14, and 15, fig. 5) in the southern Pipestone basin show widely scattered directions with no improvement after demagnetization, and were consequently eliminated as most likely being affected by lightning. The two samples taken from a heavily weathered granite below the quartzite (site 6, fig. 4) behaved very erratically upon AF and thermal demagnetization and were eliminated from further consideration. The average paleomagnetic parameters from the 14 remaining sites are presented in table 1. Averaging of paleomagnetic parameters followed a hierarchical order of specimen, sample, site, basin, and formation.

Figure 6 (facing page). Results of progressive AF (alternating field) demagnetization of selected specimens. Each horizontal row of illustrations represents the results obtained from the treatment of a single specimen as labeled at the upper left. The digit(s) to the left in each label designate(s) the site, the lower case letter designates a specific sample, and the digit to the right designates a specimen from the sample (used only if more than one specimen exists for the sample). In each row the change in specimen magnetization during successive levels of treatment is described in three illustrations, which from left to right are: (1) an orthographic plot of the magnetization vector in an east-west vertical plane (open circles) and a horizontal plane (closed circles); (2) a partial stereonet showing direction of magnetization for lower hemisphere (closed circles) or the upper hemisphere (open circles); and (3) a spectral plot of magnetization intensity versus peak alternating field as measured in milliteslas. Units of magnetization in the orthogonal and spectral plots are relative to the initial (untreated) intensity of magnetization (M_0).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Peak AF (mT)

NATURE OF THE PALEOMAGNETISM

We believe that the magnetization of the Sioux Quartzite is a postdepositional phenomenon. The sand-size particles containing iron oxides and hematitic chert are too large for DRM (detrital remanent magnetization), and the extremely fine grained oxides that are typically associated with DRM are not likely to have survived diagenesis (Vander Horck, 1984; Southwick and others, 1986). Furthermore, AF demagnetization of clast specimens from the basal conglomerate at New Ulm (site 7, fig. 4) produces a marked bias in directions obtained from both clasts and matrix toward the direction of the overlying quartz arenite (fig. 8*B*; table 1). Because the conglomerate has not been significantly metamorphosed (Miller, 1961), the most likely source for this bias is secondary hematite along surfaces and fractures of the clasts.

The paleomagnetic attributes of the Sioux are most likely related to diagenetic hematite, which from paragenetic evidence began forming almost immediately after deposition and may have continued to form for a long time (Vander Horck, 1984; Southwick and Mossler, 1984; Southwick and others, 1986). However, the lack of both pronounced streaking and coherent secondary components in the paleomagnetic data, combined with reasonably good clustering at all levels of the sampling hierarchy (table 1), including the basin level (fig. 8*D*), implies that the magnetization was set either within a short time, or during an extended interval of subdued APW (apparent polar wander). Late fracture-filled veinlets of hematite in the northern Pipestone basin apparently either produced no significant magnetization, or produced one that agreed with that of hematite formed earlier.

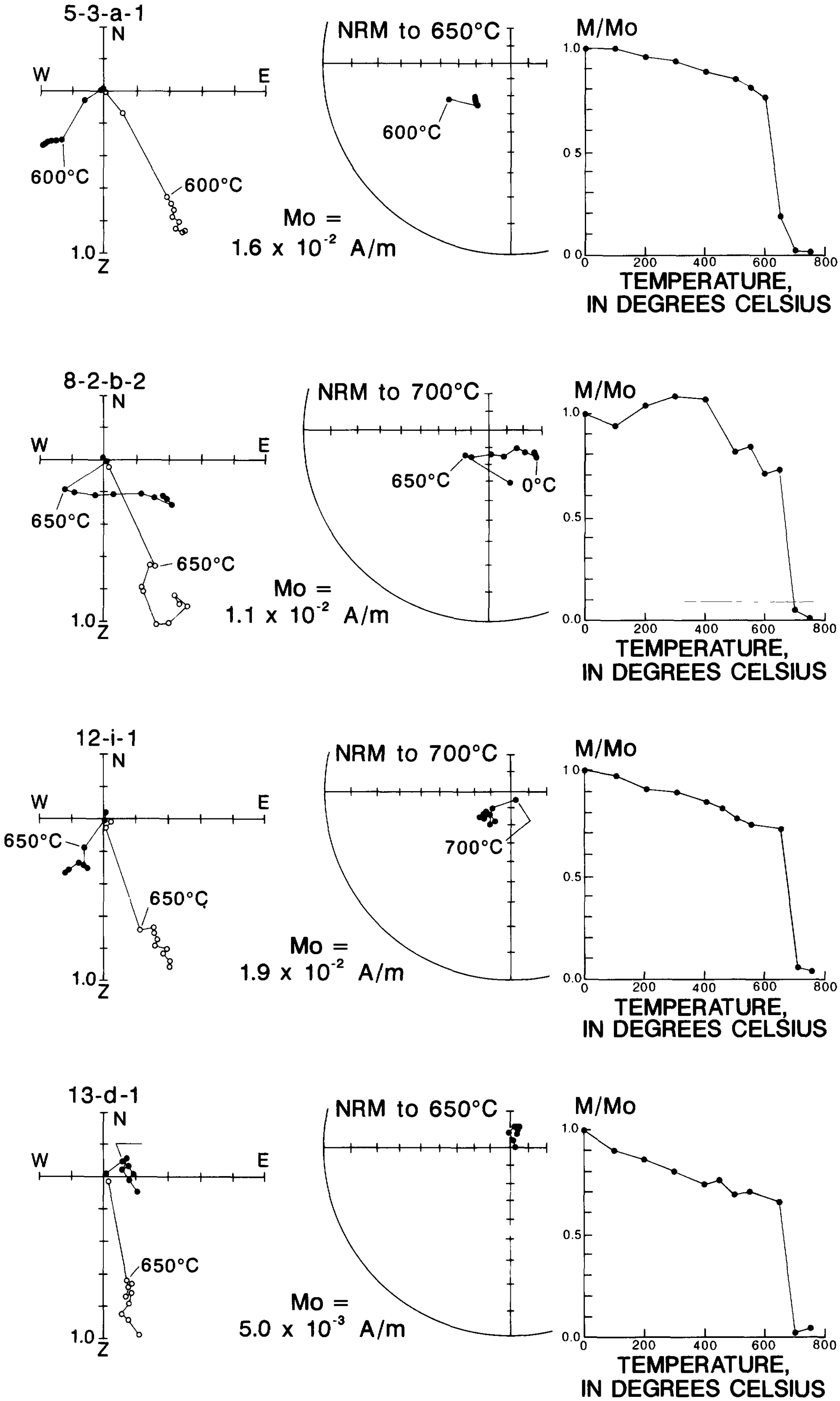
Finally, that the magnetization in the Sioux is the result of a metamorphic overprint that postdates diagenesis is unlikely. With blocking temperatures of 620–680 °C, the quartz arenite would have to have been heated to over 500 °C for more than a billion years for overprinting to occur, according to the theoretical blocking curves of Pullaiah and others (1975). No petrologic evidence exists that supports the idea that the Sioux was ever subjected to temperatures that extreme. According to Walton's (1982) theoretical model, hematite in red beds might be remagnetized at considerably lower temperatures, but field and laboratory data produced by Kent and Miller (1987) indicate that although Walton's model may apply for multidomain magnetites, the model of Pullaiah and others (1975) is more appropriate for single-domain hematite grains that typify most red beds.

A fold test to determine the time of the magnetization relative to tilting is difficult to perform. Tilt corrections for the minor flexure in the Cottonwood County basin (fig. 3) slightly dispersed site-averaged directions (table 1; fig. 8*C*) and imply that magnetization could have followed minor deformation. However, tilt corrections across opposing limbs of the southern Pipestone basin (fig. 5) produce mutually converged site-averaged directions (table 1; fig. 8*C*), which imply that the magnetization formed before the regional flexuring that defines the present basins. The increase of the precision parameter (*K*) from 31 to 75 in the southern Pipestone basin is not significant at the 90 percent confidence level according to the test of McElhinny (1964), but McFadden and Jones (1981) have argued that this type of test may be too stringent. We tentatively favor applying a correction for regional tilting (table 1), although these corrections produce only minor changes in the location of the Sioux paleopole (table 1).

AGE OF MAGNETIZATION AND RELATIONSHIPS WITH THE BARABOO AND BARRON QUARTZITES

If the magnetization of the Sioux Quartzite occurred soon after deposition, the paleomagnetic data can be used to help refine age estimates. Figure 9 shows the structurally corrected Sioux paleopole plotted onto the APW path of Irving (1979), which is one of the more commonly cited Early Proterozoic paths for North America. We recognize that time gaps and dating uncertainties cause considerable ambiguity in constructing an Early Proterozoic APW, making age estimates based solely on such APW's unreliable (Roy, 1983; Buchan and Halls, 1990). However, if we consider new geochronologic data along with the distribution of paleopoles used in constructing the APW in figure 9, we believe that a coarse time interval for the magnetization of the Sioux can be established.

Figure 7 (facing page). Results of progressive thermal demagnetization of selected specimens. Format is the same as described in figure 7, except that peak alternating (AG) field is replaced with peak temperature. In each row the change in specimen magnetization during successive levels of treatment is described in three illustrations, which from left to right are: (1) an orthographic plot of the magnetization vector in an east-west vertical plane (open circles) and a horizontal plane (closed circles); (2) a partial stereonet showing direction of magnetization for lower hemisphere (closed circles) or the upper hemisphere (open circles); and (3) a spectral plot of magnetization intensity versus peak alternating field as measured in milliteslas.


5-3-a-1
N
W
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600°C
600°C
1.0
Z
NRM to 650°C
600°C
Mo =
1.6 x 10^{-2} A/m
M/Mo
1.0
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200
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TEMPERATURE,
IN DEGREES CELSIUS
8-2-b-2
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650°C
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Z
NRM to 700°C
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Mo =
1.1 x 10^{-2} A/m
M/Mo
1.0
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0.0
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200
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TEMPERATURE,
IN DEGREES CELSIUS
12-i-1
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W
E
650°C
650°C
1.0
Z
NRM to 700°C
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Mo =
1.9 x 10^{-2} A/m
M/Mo
1.0
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TEMPERATURE,
IN DEGREES CELSIUS
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W
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650°C
1.0
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NRM to 650°C
Mo =
5.0 x 10^{-3} A/m
M/Mo
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TEMPERATURE,
IN DEGREES CELSIUS

Table 2. Formation-average paleomagnetic parameters for the Sioux, Barron, and Baraboo Quartzites

Formation	Lat °N.	Long °W.	*N*	D deg	I deg	k	α95 deg	Paleopole Lat	Paleopole Long	dp[2] deg	dm deg	Source[3]	Comments[4]
Barron Quartzite	45.00	92.00	35	273.0	79.0	6	25.0	42°N	122°W	45	47	1	1
Barron Quartzite	45.00	92.00	27	208.0	62.0	21	12.0	2°N	112°W	15	19	1	1
Sioux Quartzite	44.00	94.00	34	243.0	56.0	2	58.0	9°N	141°W	60	83	1	1
Sioux Quartzite	44.00	94.00	35	122.0	79.0	7	25.0	31°N	73°W	45	47	1	1
Baraboo Quartzite	43.50	89.75	12	179.0	46.0	13	17.4	19°S	89°W	14	22	2	2,5
Barron Quartzite	45.50	91.50	6	257.1	67.9	43	10.4	27°N	135°	15	17	2	3
Sioux Quartzite nsc[1]	44.00	95.21	4	200.5	72.5	108	8.9	13°N	106°W	14	16	3	4
Sioux Quartzite	44.00	95.21	4	192.4	74.8	65	11.4	16°N	101°W	18	20	3	4

[1]nsc, No structural correction, all other entries are structurally corrected.

[2]dp, dm, semi-axes of 95 percent confidence; oval about pole position.

[3]1, Runcorn, 1964; 2, Kean and Mercer, 1986; Kean and others, 1989; Kean and Schneiker, 1990 and W.F. Kean, oral commun., 1990; 3, this study.

[4]1, Parameters based on one site average; *N*, number of samples.

2, Parameters based on samples from multiple sites; *N*; number of samples.

3, Parameters based on site averages; *N*, number of sites.

4, Parameters based on basin averages, which in turn were derived from site averages; *N*, number of basins.

5, Parameters based on preliminary results reported in Kean and Mercer (1986). Updated parameters published in abstracts (Kean and others, 1989; Kean and Schneiker, 1990) were rejected because the reported paleopole position was inconsistent with the dec/inc values.

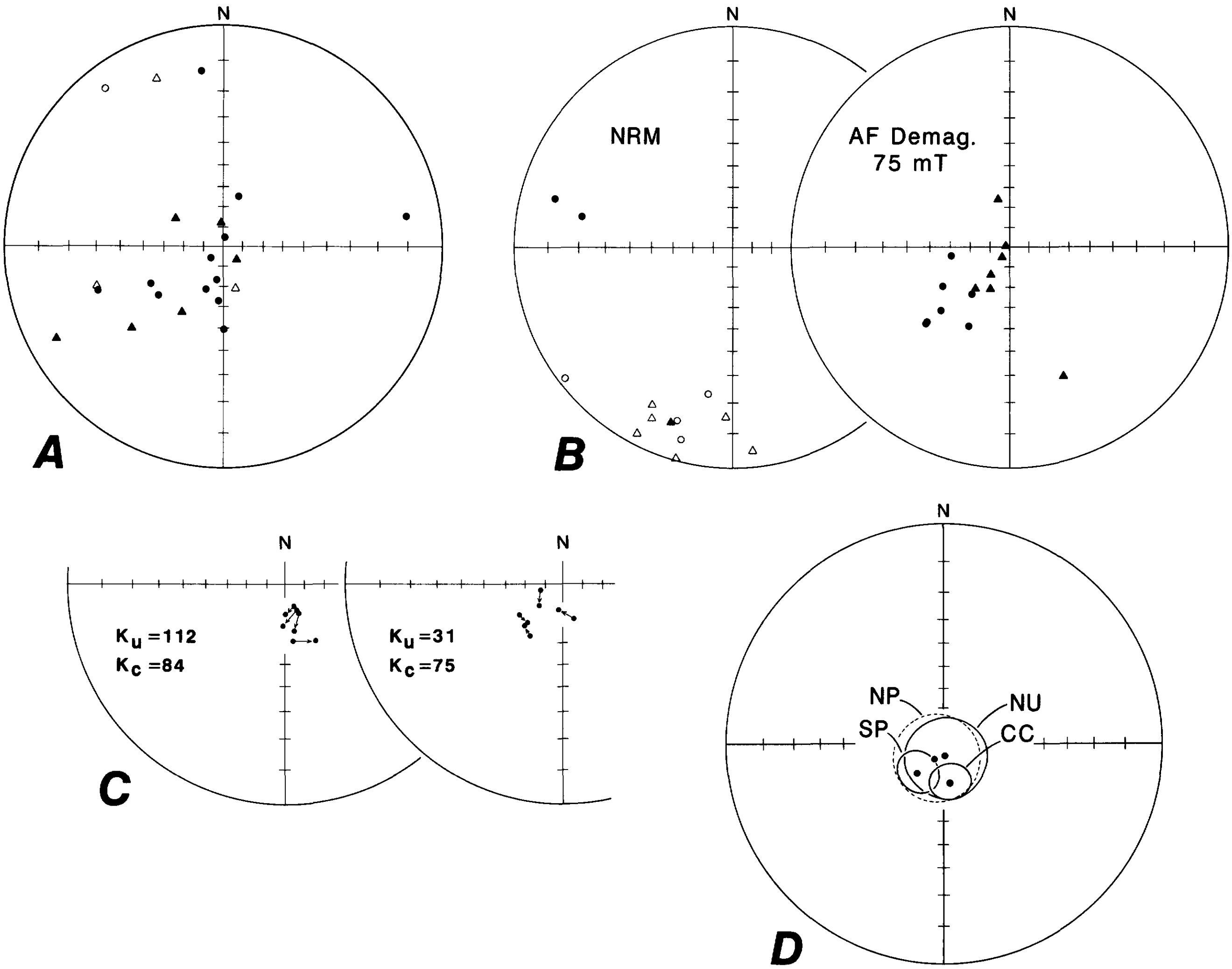

Figure 8. Stereonet plots of various tests conducted on Sioux Quartzite specimens. Open symbol, upper hemisphere; closed symbol, lower hemisphere. *A*, Results of principal component analysis of thermal demagnetization data (Kirschvink, 1980). Based on demagnetization of 10 specimens from sites 8–1, 9, 10, and 12, and using temperatures between 500 and 700 °C in increments of 15–50 °C. Maximum angular deviation allowed, 10°; circles, linear segments; triangles, Hoffman Day directions. *B*, Results of AF demagnetization of the basal conglomerate of the Sioux Quartzite of New Ulm. Circles, clast directions; triangles, matrix directions. *C*, Fold tests of sites from the Cottonwood County and southern Pipestone basins. Ku and Kc are the precision parameters for the structurally uncorrected and corrected directions, respectively. Arrows point from structurally uncorrected to corrected site directions. *D*, Structurally corrected basin-averaged directions and 95 percent confidence circles for the samples from the Cottonwood County (CC), New Ulm (NU), northern Pipestone (NP), and southern Pipestone (SP) basins.

The Sioux paleopole lies within a diffuse cluster of poorly dated paleopoles between 1,900 and 1,600 Ma (Irving, 1979; Buchan and Halls, 1990). This cluster may be divisible into two groups on either end of a 1,850–1,700 Ma loop (fig. 9), which is largely based on paleopoles from Slave province rocks some 2,200 km north of the Sioux outcrops (Irving and McGlynn, 1981). Recently derived geochronometric relationships would place the Sioux Quartzite in the group at the younger end. The undeformed nature of 1,900 to 1,800 Ma rhyolite cobbles at the base of the Sioux Quartzite in the northern Pipestone basin (Wallin and Van Schmus, 1988) implies that they and the enclosing Sioux were not involved in the Penokean orogeny, which peaked at about 1,870–1,850 Ma (Van Schmus and Bickford, 1981). These cobbles were most likely derived from a terrane of 1,825 Ma rhyolites and 1,810–1,800 Ma granophyric granites in eastern South Dakota (Wallin and Van Schmus, 1988). Moreover, 1,850–1,750 Ma intrusions of varying size and composition cut nearby Archean and Penokean orogen rocks (Morey and Van Schmus, 1988; Wallin and Van Schmus, 1988), but high-resolution aeromagnetic data (Chandler, 1989) yield little evidence of any intrusive rocks

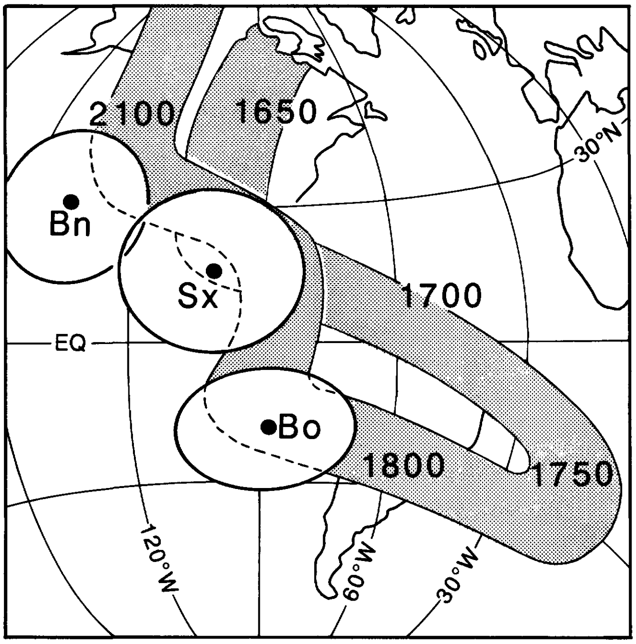

Figure 9. Structurally corrected paleopole for the Sioux Quartzite (Sx). APW (shaded) path from Irving (1979). Approximate ages presented along APW in Ma. Barron (Bn) and Baraboo (Bo) paleopoles from Kean and others (1989), Kean and Schneiker (1990), and W.F. Kean (oral commun., 1990).

cutting the weakly magnetic quartzite, implying that it postdates these intrusions. Thus, the 1,700–1,650 Ma segment of Irving's (1979) APW path (fig. 9) is the most consistent with existing geologic constraints, and this time interval is tentatively accepted for deposition of the Sioux Quartzite. Further refinements must await more geochronologic work and much-needed improvements in the Early Proterozoic APW path for North America.

Our paleomagnetic analysis, in conjunction with the APW position (fig. 9), implies that the Sioux Quartzite could be younger than the Baraboo Quartzite, but may be about the same age as the Barron Quartzite (Kean and Mercer, 1986; Kean and others, 1989; Kean and Schneiker, 1990). Furthermore, the preliminary paleomagnetic data of Kean and his colleagues imply that the Baraboo Quartzite may be as much as 100 m.y. older than the Barron Quartzite, an observation consistent with the conclusion of LaBerge and Klasner (1989) that Baraboo Quartzite probably was deformed during the Penokean orogeny.

No geologic evidence exists that would suggest that the Barron and Sioux Quartzites were ever connected. Nonetheless, a correlation between them is supported by the fact that they, unlike the Flambeau, Baraboo, and Waterloo Quartzites, are essentially undeformed and unmetamorphosed. Both, moreover, were deposited in southward-flowing braided-stream systems; both contain thin layers of quartz-deficient and alumina-rich claystone (pipestone, catlinite) in their upper parts; and both contain large clasts of previously lithified red and purple quartzite (Southwick and others, 1986; Campbell, 1981, 1986; Johnson, 1985; Morey, 1983; Gundersen, 1982, 1984). Although the source of the quartzite clasts has not been established, their presence is consistent with the possibility that more than one quartz-arenitic red-bed sequence exists in the southern part of the Lake Superior region, as briefly discussed by Greenberg and Brown (1984).

CONCLUSIONS

Paleomagnetic studies of the Early Proterozoic Sioux Quartzite in southwestern Minnesota have revealed a highly stable, single-component magnetization that is primarily carried by diagenetic hematite. A definitive fold test is difficult because of low dips, but the magnetization is tentatively interpreted as having preceded regional tilting. Measured paleomagnetic directions at both site and basin levels show good clustering, and the average directions obtained from each of the four basins are not significantly different at the 95 percent confidence level. Clustering also implies that magnetization in the Sioux was completely established before any appreciable APW occurred.

On the basis of isotopic ages and existing Early Proterozoic APW data for North America, the structurally corrected Sioux paleopole, located at 101° W. and 16° N. (k=65, $\alpha95$=11°), implies a diagenetic age of 1,700–1,650 Ma for the Sioux. In discussing the tectonic evolution of the Sioux Quartzite, Southwick and others (1986) noted the alignment of the Sioux basins with en echelon basement faults that were oblique to an east-trending passive continental margin, as proposed by Dott (1983). They also noted that the Sioux basins and their bounding faults were more or less parallel to the trend of the Central Plains orogen (fig. 1) as discussed by Sims and others (1987) and Sims and Peterman (1986). According to Sims and colleagues, this as yet poorly understood orogenic event occurred during the interval 1,800 Ma to 1,600 Ma. Although outcrops of the Sioux Quartzite in southwestern Minnesota are some 200–300 km north of rocks clearly involved in the Central Plains orogen, the paleomagnetic data are consistent with the Sioux Quartzite having been deposited in pull-apart basins related to transcurrent faulting during that tectonic event.

We propose that the Baraboo and possibly the Flambeau and Waterloo Quartzites in Wisconsin may be related to the Penokean orogeny, whereas the Sioux and possibly the Barron Quartzites are related to the younger Great Plains orogeny. Because at least two temporally distinct red-bed sequences appear to exist in the southern part of the Lake Superior region, the term "Baraboo interval" no longer has any paleogeographic continuity.

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