# Age and deformation of Early Proterozoic quartzites in the southern Lake Superior region: Implications for extent of foreland deformation during final assembly of Laurentia

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## ABSTRACT

**Bedrock mineral cooling dates in the southern Lake Superior region establish a sharp ca. 1630 Ma thermal front that separates basement having typical post-Penokean (1750–1700 Ma) cooling ages to the north from basement having thermally reset (≤1630 Ma) ages to the south. The thermal front coincides spatially with an apparent deformational front in overlying post-Penokean quartzites. Subhorizontal quartzite north (Barron, northwest Wisconsin) and west (Sioux, Minnesota) of the front and highly folded quartzite south of the front (Flambeau, northwest Wisconsin) all yield ion microprobe (single-grain, single-spot) $^{207}Pb/^{206}Pb$ detrital zircon ages as young as 1750 Ma (but none younger than 1714 Ma). The new detrital zircon dates and the thermal-deformational front together with other geologic information suggest that these quartzites were all deposited between 1750 Ma and 1630 Ma. This study provides the first good structural evidence that deformation accompanied the long-recognized but enigmatic 1630 Ma low-grade, thermal-metamorphic event in the southern Lake Superior region. We interpret the strong compressional deformation exhibited in the Early Proterozoic quartzite bodies throughout much of Wisconsin to reflect foreland deformation associated with the assembly of southern Laurentia during the ca. 1650 Ma Mazatzal orogeny.**

## INTRODUCTION

The final formation of Laurentia involved rapid accretion and growth of continental crust along its southern margin between 1800 and 1600 Ma (Nelson and DePaolo, 1985). Accretion during this period resulted in the formation of a wide collage of orogenic provinces that is proposed to have spanned the length of the North American continent from California to Labrador (Van Schmus et al., 1993). Intense interest in these rocks (collectively called the Transcontinental Proterozoic provinces by Van Schmus et al., 1993), especially in the southwest United States (Bowring and Karlstrom, 1990; Williams and Karlstrom, 1996), has yielded considerable insight (and controversy) into processes of Proterozoic tectonic assembly and evolution from initial accretion to final cratonization.

Postaccretion (i.e., post ca. 1850 Ma) stabilization in the southern Lake Superior region resulted in deposition of locally thick successions of Early Proterozoic mature red quartzites throughout Wisconsin and southern Minnesota. Their age of deposition and the age of the deformation that caused widespread folding of many of the quartzite units has long been a matter of considerable importance and controversy (Dott, 1983). This paper provides new evidence for both the maximum and minimum age of these quartzites. We also document the spatial coexistence of a thermal front in the crystalline basement with a deformational front in the overlying quartzite units. The age of the front suggests to us that significant post-Penokean shortening of the Penokean province is probably related to the final stages of formation of the Laurentian supercontinent at ca. 1650 Ma.

## TECTONIC SETTING

The bulk of Laurentia (northern United States and Canada) formed by rapid aggregation of Archean continents ca. 1900–1800 Ma during the Trans-Hudson and Penokean orogenies (Fig. 1; Hoffman, 1989). Subsequent accretion of juvenile crust along the southern margin of pre-1800 Ma Laurentia formed the Transcontinental Proterozoic provinces, which consist broadly of a northern 1800–1700 Ma inner accretionary belt and a southern 1700–1600 Ma outer tectonic belt (Fig. 1). Van Schmus et al. (1993) suggested that the Penokean province could be included as an older part of the inner accretionary belt. Much less is known about the buried eastern portion of these belts (Central Plains orogen of Sims and Peterman, 1986) than the commonly exposed western portion (Reed et al., 1993), although they are considered equivalents, on the basis of similarities of, e.g., rock type, ages, and age of deformation.

The transition zone between the two tectonic belts of the Transcontinental Proterozoic provinces represents the region of known pre-1700 Ma rocks metamorphosed and deformed ca. 1650 Ma during formation of the outer tectonic belt. The eastward continuation of this transition zone and of the outer tectonic belt from the central plains is problematic, because no 1800–1600 Ma juvenile crust is present in the entire southern Great Lakes region. However, on the basis of 1680–1640 Ma orogenic deformation and the existence of 1650 Ma batholithic intrusive rocks in Labrador, Van Schmus et al. (1993)

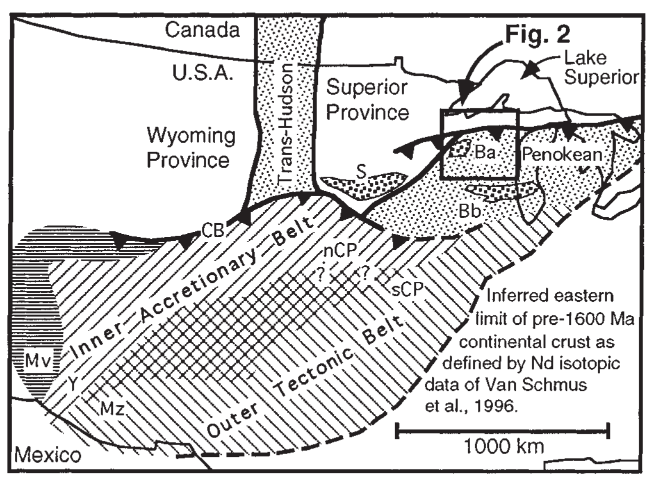


**Figure 1. Proposed distribution of Early Proterozoic crustal provinces in United States prior to formation of Middle Proterozoic igneous and tectonic provinces (modified after Van Schmus et al., 1993). Ba—Barron quartzite; Bb—Baraboo quartzite; CB—Cheyenne belt; Mv—Mojave province; Mz—Mazatzal province; nCP—northern Central Plains orogen; sCP—southern Central Plains orogen; S—Sioux quartzite, Y—Yavapai province. Cross-hachure pattern between inner and outer belts depicts inferred part of inner accretionary belt deformed during main ca. 1650 Ma tectonism of outer tectonic belt (also after Van Schmus et al., 1993).**

**Data Repository item 9885 contains additional material related to this article.**

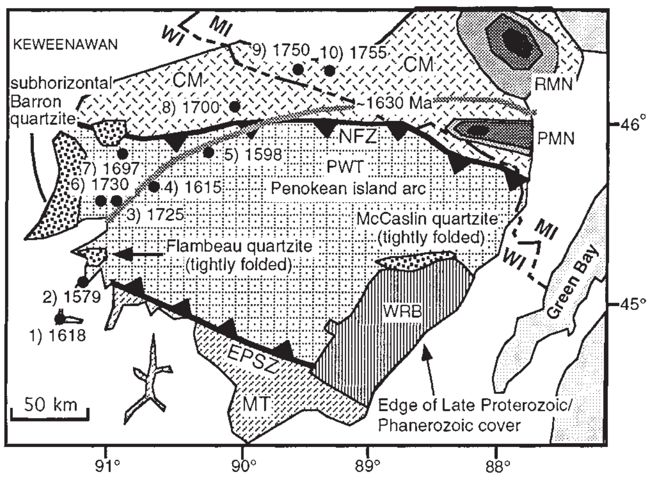


**Figure 2. Simplified tectonic map of southern part of Lake Superior region, northern Wisconsin, and northern Michigan (after Sims, 1992). Ca. 1630 Ma shaded line separates basement having typical post-Penokean (1750–1700 Ma) cooling ages to north from basement having thermally reset (less than ca. 1630 Ma) ages to south. Same line separates regions of subhorizontal post-1760 Ma quartzites to north from highly deformed post-Penokean (both pre- and post-1760 Ma) quartzites to south. CM—continental margin; EPSZ—Eau Pleine shear zone; NFZ—Niagara fault zone; MI—Michigan; MT—Archean Marshfield terrane; PMN—Peavy metamorphic node; PWT—Pembine-Wausau terrane; RMN—Republic metamorphic node; WI—Wisconsin; WRB—1470 Ma Wolf River batholith. Representative dates shown (in Ma) are mica Rb-Sr, K-Ar, and Ar-Ar after Sims and Peterman (1980), Peterman and Sims (1988), Schneider et al. (1996), Romano et al. (1997), and Holm and Henderson (1997). Numbers 1–10 correspond to numbers in Appendix (see footnote 1 in text).**

proposed that the outer tectonic belt was once a single coherent continental arc extending from California to Labrador.

The Penokean orogeny in the southern Lake Superior region involved island-arc-microcontinent collision along the southern passive margin of the Superior Province ca. 1870–1830 Ma (Sims et al., 1989). In northern Wisconsin the south-dipping Niagara fault zone (Fig. 2) represents the main suture, which separates uniformly metamorphosed (upper greenschist–lower amphibolite facies) island-arc rocks of the Pembine-Wausau terrane from deformed continental margin rocks that exhibit a nodal metamorphic pattern imposed during collapse of the orogen (Schneider et al., 1996; Marshak et al., 1997).

Abundant mica cooling dates from central Minnesota and northernmost Wisconsin and Michigan indicate that collapse and orogenic unroofing occurred at 1750–1700 Ma shortly after an episode of widespread magmatism at 1770–1760 Ma (Holm and Lux, 1996; Schneider et al., 1996). In contrast, Rb-Sr whole-rock isochron and biotite mineral dates (both Ar/Ar and Rb/Sr) in northern and central Wisconsin (Sims and Peterman, 1980; Peterman and Sims, 1988; Romano et al., 1997) are mostly Middle Proterozoic (1600–1100 Ma), and reflect thermal resetting associated with a low-grade ca. 1630 Ma metamorphic event (Van Schmus and Woolsey, 1975; Van Schmus et al., 1975), intrusion of the 1470 Ma Wolf River batholith (Holm and Lux, 1997a), and emplacement of Keweenawan dikes at ca. 1100 Ma (Holm and Lux, 1997b).

## EARLY PROTEROZOIC RED QUARTZITES

Postaccretion rapid stabilization of the inner accretionary belt resulted in the accumulation of thick successions of post-tectonic quartz arenites and pelites in Arizona, New Mexico, Colorado, and the southern Lake Superior region (Van Schmus et al., 1993). Deformed quartzite units in central and southern Wisconsin (Baraboo, McCaslin, and two others; Figs. 1 and 2) yield post-Penokean, single-crystal, detrital zircon $^{207}$Pb/$^{206}$Pb ages (Van Wyck, 1995). The highly folded Baraboo quartzite is depositional on a 1752 Ma granite (Medaris et al., 1996) and contains detrital zircons as young as 1712 Ma (Dott et al., 1997). The minimum age of the quartzite units has been constrained only by the fact that some are intruded by the undeformed 1470 Ma Wolf River batholith, although Dott (1983) and Van Schmus et al. (1993) speculated that they may have been deformed during a 1630 Ma low-grade metamorphic event.

### Flambeau Thermal and Deformational Front

The predominantly Middle Proterozoic mica mineral dates of central Wisconsin contrast sharply with the well-grouped 1750–1700 Ma mica dates obtained from central Minnesota, northernmost Wisconsin, and northern Michigan. The 1750–1700 Ma dates are the oldest mica dates obtained from the internal portions of the Penokean orogen and thus almost certainly reflect primary cooling through mica closure temperatures following Penokean metamorphism. Considering that primary cooling at 1750–1700 Ma was orogen wide, it is likely that the younger mica dates represent thermal resetting. The ca. 1630 Ma age contour of Figure 2 (Peterman and Sims [1988] depicted a similar 1600 Ma age contour based solely on Rb-Sr data) thus separates basement having typical post-Penokean cooling ages to the north (and west, in Minnesota) from basement having thermally reset ages to the south. The eastward extent of the age contour is not precisely located because of discrepancies in mica Rb-Sr and Ar-Ar data (see Van Schmus and Woolsey, 1975; Schneider et al., 1996). However, north of the Flambeau quartzite in northwest Wisconsin, the age contour is sharply defined by Rb-Sr, K-Ar, and Ar-Ar mica dates (Fig. 2, see Appendix[1]).

The Flambeau thermal front in northwest Wisconsin coincides spatially with an apparent deformational front in overlying post-Penokean quartzites. In Minnesota, the subhorizontal Sioux quartzite (Fig. 1; Southwick and Mossler, 1984) is just southwest of Penokean internal zone rocks, which cooled rapidly through mica closure temperatures at ca. 1750 Ma (Holm et al., 1998). In northwest Wisconsin, the Barron quartzite is essentially flat-lying (Rozacky, 1987), and was deposited on basement (including a 1765 Ma granite; Sims, 1992) that has Rb-Sr mica ages between 1730–1700 Ma. South of the thermal front, and only 25 km south of the Barron quartzite, are exposures of steeply dipping Flambeau quartzite (Fig. 2). Here, the quartzite is folded into a moderately west plunging synform (Myers, 1974) similar to the style of deformation exhibited by the Baraboo and McCaslin quartzites (Figs. 1 and 2). The relatively undeformed Barron and Sioux Proterozoic quartzites must either be outside the region of significant post-Penokean deformation, or be younger quartzite packages deposited after significant post-Penokean deformation.

### Ion Microprobe Detrital Zircon Dates

In an effort to test whether the subhorizontal quartzites are correlatable with the highly deformed quartzites, we obtained U-Pb ages on detrital zircons separated from the Sioux, Barron, and Flambeau quartzites. We obtained single-grain, single-spot $^{207}$Pb/$^{206}$Pb ages using the CAMECA ims 1270 ion microprobe at the University of California, Los Angeles. Ages were determined relative to Keweenawan zircon standard AS3, which yields an age of 1099 ± 1 Ma. Because we are mostly interested in constraining the maximum age of each quartzite, we concentrated our efforts on dating euhedral or subhedral crystals wherever possible. Table 1 is a compilation of Early Proterozoic (<2000 Ma) detrital zircon dates obtained from each quartzite. The high radiogenic component of these analyses means that the ages quoted are insensitive to both the assumed common Pb composition and the poor statistics of the $^{204}$Pb measurements. However, all three quartzites yielded Late Archean and Early Proterozoic zircons older than 2000 Ma, comparable to dates obtained by Van Wyck

[1]GSA Data Repository item 9885, description of bedrock thermochronology and ion microprobe, U-Pb detrital zircon data, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

(1995) for four deformed quartzite bodies in Wisconsin (Appendix, see footnote 1).

All three of the quartzite bodies studied yielded at least three Early Proterozoic concordant or near concordant dates of ca. 1750 Ma (Fig. 3). In making judgments about the data, we disregarded those dates which showed strong normal or reverse discordance. The degree of discordancy in our data appears strongly linked to the %$^{207}Pb^*$ measured (Appendix) and therefore the majority of the data that we consider reliable have $^{207}Pb^*$ near 90% or greater. Finally, in several cases, we measured the same grain twice to check on the reproducibility and reliability of the data. Reliable $^{207}Pb/^{206}Pb$ Proterozoic ages are between 1730 Ma and 1850 Ma for the Sioux (9 grains), between 1714 Ma and 1880 Ma for the Flambeau (9 grains), and between 1750 Ma and 1880 Ma for the Barron (6 grains). These data attest to the fact that all three quartzite bodies post-date the widespread 1760 Ma magmatic event in the Lake Superior region. In addition, a similar range of late Early Proterozoic detrital zircon dates has been obtained from the Baraboo and McCaslin quartzites (Van Wyck, 1995; Dott et al., 1997), suggesting that all five quartzite bodies may be correlatable. There is no evidence to suggest that the subhorizontal Barron and Sioux quartzites are younger than the deformed quartzites found throughout most of Wisconsin.

TABLE 1. SUMMARY OF RELIABLE EARLY PROTEROZOIC (<2000 Ma) DETRITAL ZIRCON DATES

| Spot | $^{207}Pb/^{206}Pb$ | Th/U | $^{207}Pb^*$ (%) | $^{206}Pb^*$ (%) | $^{206}Pb/^{238}U$ age (Ma, s.e.) | $^{207}Pb/^{235}U$ age (Ma, s.e.) | $^{207}Pb/^{206}Pb$ age (Ma, s.e.) |
|---|---|---|---|---|---|---|---|
| **Barron quartzite** (total of 28 spots analyzed) | | | | | | | |
| g4sp1 | 0.140 | 0.409 | 73.78 | 96.21 | 1812.0 ± 27.9 | 1787.0 ± 26.5 | 1757 ± 46.4 |
| g11sp1 | 0.121 | 0.594 | 88.04 | 98.51 | 1439.0 ± 41.9 | 1579.0 ± 28.8 | 1772 ± 41.5 |
| g17sp1 | 0.118 | 0.089 | 89.77 | 98.76 | 1864.0 ± 54.4 | 1813.0 ± 40.0 | 1756 ± 62.8 |
| g28sp2 | 0.125 | 0.251 | 84.01 | 97.94 | 1663.0 ± 29.5 | 1702.0 ± 23.7 | 1751 ± 37.6 |
| g6sp1 | 0.128 | 0.542 | 88.48 | 98.49 | 1587.0 ± 47.4 | 1717.0 ± 32.1 | 1880 ± 62.5 |
| g5sp2 | 0.165 | 0.305 | 68.83 | 94.70 | 1212.0 ± 20.9 | 1509.0 ± 26.5 | 1954 ± 44.7 |
| **Flambeau quartzite** (total of 16 spots analyzed) | | | | | | | |
| g2sp1 | 0.113 | 0.176 | 91.65 | 99.02 | 1570.0 ± 14.5 | 1632.0 ± 15.4 | 1714 ± 34.2 |
| g8sp1 | 0.110 | 0.154 | 98.87 | 99.87 | 1749.0 ± 18.8 | 1767.0 ± 11.1 | 1788 ± 13.8 |
| g11sp1 | 0.114 | 0.933 | 93.95 | 99.29 | 1762.0 ± 20.7 | 1762.0 ± 18.4 | 1763 ± 36.5 |
| g18sp1 | 0.112 | 0.238 | 95.87 | 99.52 | 1787.0 ± 17.9 | 1779.0 ± 16.9 | 1769 ± 35.3 |
| g21sp1 | 0.116 | 0.202 | 95.12 | 99.42 | 1592.0 ± 12.8 | 1689.0 ± 14.5 | 1810 ± 30.2 |
| g19sp1 | 0.119 | 0.654 | 96.32 | 99.55 | 1358.0 ± 67.5 | 1577.0 ± 41.0 | 1875 ± 42.3 |
| g30sp1 | 0.114 | 0.336 | 97.37 | 99.69 | 1817.0 ± 20.9 | 1816.0 ± 18.5 | 1812 ± 42.3 |
| g26sp1 | 0.111 | 0.487 | 95.95 | 99.54 | 1820.0 ± 14.7 | 1787.0 ± 13.7 | 1746 ± 40.1 |
| g17sp2 | 0.114 | 0.331 | 94.86 | 99.40 | 1565.0 ± 20.5 | 659.0 ± 18.9 | 1780 ± 42.2 |
| **Sioux quartzite** (total of 19 spots analyzed) | | | | | | | |
| g2sp1 | 0.123 | 0.149 | 89.73 | 98.69 | 1263.0 ± 49.5 | 1493.0 ± 30.9 | 1825 ± 40.2 |
| g7sp1 | 0.111 | 0.023 | 94.50 | 99.37 | 1572.0 ± 28.2 | 1641.0 ± 15.1 | 1729 ± 19.3 |
| g1sp2 | 0.120 | 0.099 | 87.40 | 98.44 | 1361.0 ± 25.0 | 1515.0 ± 21.6 | 1738 ± 39.5 |
| g8sp1 | 0.110 | 0.157 | 97.46 | 99.71 | 1595.0 ± 15.5 | 1670.0 ± 9.0 | 1765 ± 14.0 |
| g20sp1 | 0.110 | 0.058 | 98.46 | 99.83 | 1736.0 ± 15.7 | 1750.0 ± 10.5 | 1767 ± 21.5 |
| g27sp1 | 0.110 | 0.056 | 99.39 | 99.93 | 1737.0 ± 15.1 | 1758.0 ± 9.5 | 1782 ± 12.1 |
| g26sp1 | 0.114 | 0.077 | 93.49 | 99.23 | 1112.0 ± 7.2 | 1353.0 ± 9.4 | 1758 ± 18.9 |
| g6sp2 | 0.110 | 0.071 | 97.44 | 99.71 | 1758.0 ± 18.8 | 1755.0 ± 13.3 | 1751 ± 23.2 |
| g13sp2 | 0.119 | 0.072 | 88.82 | 98.63 | 1501.0 ± 19.1 | 1612.0 ± 23.4 | 1757 ± 50.1 |

Note: g4sp1 is grain 4, spot 1, etc. s.e. is ± standard error.

## DISCUSSION AND IMPLICATIONS

Determining the age of deposition and deformation of Early Proterozoic mature red quartzites in the Lake Superior region is critical for understanding the cratonic evolution of North America in the Proterozoic. Because some of the quartzites display a high degree of deformation and have fold attitudes similar to those of Penokean-age folds in underlying basement rocks, some researchers have proposed that the quartzites were deposited prior to the Penokean orogeny. However, this study (and those of Van Wyck [1995] and Dott et al. [1997]) indicates conclusively that the quartzites are post-Penokean in age, the majority being younger than ca. 1750 Ma. Folding of the quartzites must therefore also be post-Penokean in age.

The results of new thermochronologic data in the Lake Superior region have allowed us to make a simple but important first-order observation that provides the first direct structural evidence that the quartzites were deformed during a low-grade ca. 1630 Ma event in the Lake Superior region. We note that subhorizontal post-Penokean quartzites consistently overlie crystalline basement that has primary post-Penokean cooling ages, whereas highly deformed quartzites everywhere overlie crystalline basement that has secondary (i.e., thermally reset) cooling ages. This suggests that the quartzites were all deposited prior to 1630 Ma, and that the relatively undeformed Barron and Sioux quartzites occur outside the region of significant post-Penokean deformation. We are fortunate that the proximity of the deformed Flambeau quartzite to the subhorizontal Barron quartzite in northwest Wisconsin allows us to fairly precisely locate this deformational-thermal front. An age of 1650–1630 Ma for the deformation seems reasonable, given that cooling ages south of the deformational front probably postdate the deformation somewhat. Although younger Middle Proterozoic mica ages are preserved farther south in central Wisconsin, they probably reflect partial or complete disturbances related to intrusion of the 1470 Ma Wolf River batholith and to Keweenawan activity at 1100 Ma.

The trace of the thermal front, based on mica cooling dates, extends eastward across northern Wisconsin and into northern Michigan, the geology of which is dominated by gneiss domes and classic nodal metamorphic isograds. No Early Proterozoic post-Penokean quartzites are known north of the McCaslin quartzite (Fig. 2). However, it is interesting to note that the Republic metamorphic node located north of the thermal front is concentric, whereas the Peavy metamorphic node located south of the thermal front is elongate east-west. It is tempting to speculate that the Penokean isograds of the Peavy metamorphic node have been shortened north-south, and may therefore be yet another structural manifestation of the 1630 Ma deformational event. If our interpretations are correct, then the similar orientation of post-Penokean folds and Penokean-age folds (north of the front) requires that caution be used when attributing basement structures south of the front to Penokean deformation.

The rocks of the Transcontinental Proterozoic provinces were subjected to a major magmatic event during the Middle Proterozoic from 1500 to 1300 Ma. The undeformed Wolf River batholith in central Wisconsin is surrounded by and locally intrudes the deformed quartzite bodies, leading some to suggest that quartzite deformation was caused by Middle Proterozoic epeirogenic doming and igneous intrusion (Greenberg

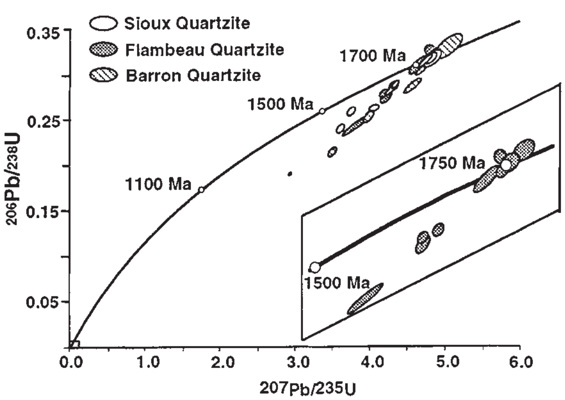


**Figure 3. U-Pb concordia plot showing analyses of Early Proterozoic detrital zircons (Table 1) from Barron, Sioux, and Flambeau quartzites. Error ellipses are shown at 2σ level. Inset shows enlarged version of only Flambeau quartzite data.**

and Brown, 1984). However, the existence of the Flambeau deformational front (located more than 100 km from exposures of the batholith) shows that the degree of deformation does not wane away from the batholith. Rather, the abrupt nature of the front is characteristic of tectonic, not intrusion related, deformation.

The low-grade ca. 1630 Ma metamorphism has been perhaps one of the most poorly understood events in the Lake Superior region. Although it has long been speculated upon that the quartzites may have been deformed during this event (Dott, 1983; Van Schmus et al., 1993), until now there has been no direct evidence of any intrusive or deformational event of that age, and some have even questioned its existence. We believe that the data presented and summarized here provide the missing structural link to that event. The timing and the strong approximately north-south shortening style of post-Penokean deformation are consistent with the event being the result of foreland deformation associated with emplacement of the outer tectonic belt onto the southernmost margin of Laurentia during the 1650 Ma Mazatzal orogeny (Van Schmus et al., 1993). Although no rocks of Early Proterozoic age (>1600 Ma) occur due south of Wisconsin, Nd isotopic data of Middle Proterozoic granite-rhyolites in that area indicate that they are underlain by older Early Proterozoic rocks (Van Schmus et al., 1996). This study lends credence to the seminal model of Dott (1983) that attributed post-Penokean deformation of the quartzites in Wisconsin to Early Proterozoic (1700–1600 Ma) plate tectonic collision from the south and supports the hypothesis of Van Schmus et al. (1993), that the 1700–1600 Ma outer tectonic belt was a single coherent belt extending from California to Labrador.


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