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Maximum depositional age of the Neoproterozoic Jacobsville Sandstone, Michigan: Implications for the evolution of the Midcontinent Rift

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ABSTRACT

A crucial constraint on the evolution of the ca. 1100 Ma Midcontinent Rift (MCR) in North America comes from the Jacobsville Sandstone, Bayfield Group, and other equivalent sedimentary rocks (JBE) that overlie the volcanics and sediments deposited in the MCR basin near Lake Superior. The MCR began extending ca. 1120 Ma and failed—ceased extending—at ca. 1096 Ma, although volcanism continued for ~10 m.y. The JBE's age is poorly constrained, with proposed ages ranging from ca. 1100 to ca. 542 Ma (i.e., youngest Precambrian). It has been proposed that the JBE were deposited shortly prior to or during the time when the MCR failed due to regional compression occurring ca. 1060 Ma as part of the Grenville orogeny (1300–980 Ma). However, the JBE are not conformable with the youngest rift-filling strata and differ compositionally from them. We present an analysis of 2050 new detrital-zircon ages showing that the JBE are younger than 959 ± 19 Ma. Thus, the JBE and the compression recorded in them that inverted the basin postdate the Grenville orogeny and are unrelated to the rift's failure. The JBE may be significantly, perhaps ~200–300 m.y., younger than the maximum age from zircons and may have been deposited shortly after a Snowball Earth event.

INTRODUCTION

One of the most prominent features on gravity and magnetic maps of North America is the Midcontinent Rift (MCR), composed of an extensive band of buried igneous and sedimentary rocks that outcrop near Lake Superior (Fig. 1A). To the south, the rift is deeply buried by younger sediments but is easily traced because the igneous rocks are dense and highly magnetized (King and Zietz, 1971; Hinze et al., 1992; Merino et al., 2013). The western arm extends at least to Oklahoma, and perhaps Texas and New Mexico, as evidenced by similar-age diffuse volcanism (Adams and Keller, 1994, 1996; Li et al., 2007; Loewy et al., 2011; Bright et al., 2014). The east arm goes through lower Michigan and extends southward to Alabama (Keller et al., 1982; Dickas et al., 1992; Stein et al., 2014).

Although the MCR was previously thought to have formed by isolated midplate volcanism and to have failed due to Grenville compression (Gordon and Hempton, 1986; Cannon, 1994; Swenson et al., 2004), recent data and analyses show that a more plausible scenario is that it formed as part of the rifting of Amazonia from Laurentia and became inactive once seafloor spreading was established (Stein et al., 2014). The rifting is shown by a cusp in Laurentia's apparent polar wander (APW) path near the onset of MCR volcanism, recorded by the MCR's volcanic rocks. Cusps in APW paths arise when continents rift apart and a new ocean forms between the two fragments.

The best record of the MCR's evolution comes from the Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE) of seismic-reflection studies across Lake Superior (Green et al., 1989; Hinze et al., 1992, 1997). As shown in Figure 1B, the volcanics (up to ~20 km thick) and overlying synrift and postrift sediments (~6 km) of the Oronto Group lie within a synclinal basin below the lake. Both the volcanics and Oronto Group rocks dip and thicken toward the basin center, with older units dipping more steeply, indicating that they were deposited as the basin subsided.

Structural modeling of these data shows an initial rift phase starting perhaps as early as ca. 1120 Ma, later than the onset of regional volcanism at ca. 1150 Ma (Heaman et al., 2007). Starting at ca. 1109 Ma (Paces and Miller, 1993; Vervoort et al., 2007), flood basalts filled a fault-controlled extending basin. In the later postrift phase, after extension ceased, starting at ca. 1096 Ma, volcanics and sediments (Oronto Group) were deposited in a thermally subsiding basin (Stein et al., 2015). Hence, volcanism continued for ~10 m.y. after the rift failed, i.e., extension ended. Much of the synclinal structure arose from synrift and postrift subsidence rather than later compression recorded by thrust faults that inverted the basin (White, 1966, 1968; Huber, 1975; Ojakangas and Morey, 1982).

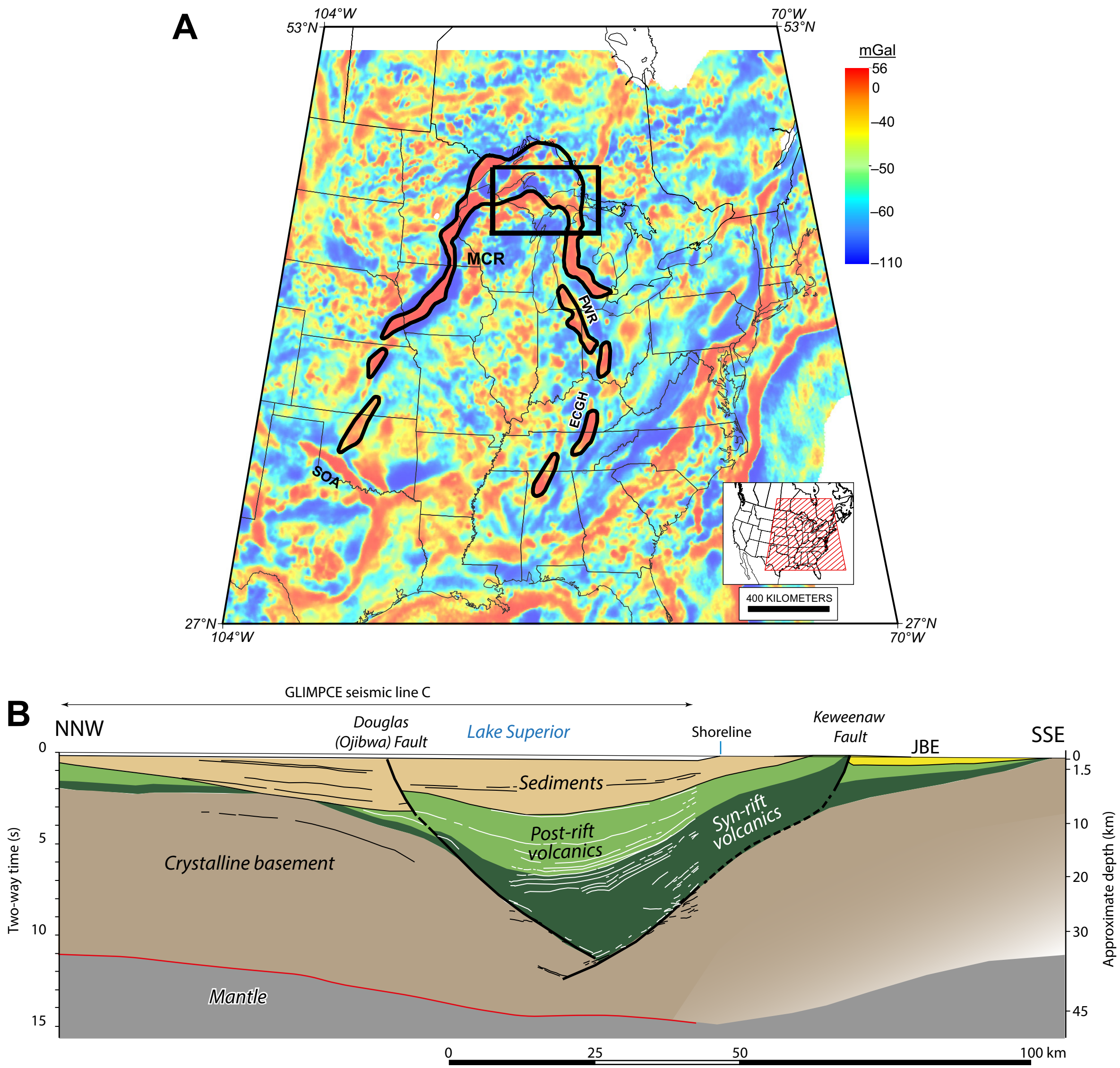

Figure 1. (A) Location of Midcontinent Rift (MCR) and its extensions, the Fort Wayne Rift (FWR) and East Continent Gravity High (ECGH), computed by upward continuing complete Bouguer anomaly (CBA) data to 40 km and subtracting result from CBA (Stein et al., 2014). Box shows location of Figure 3A. (B) Interpreted seismic section across Lake Superior, after migrated profile C (Green et al., 1989) slightly modified and complemented with land data (Stein et al., 2015). JBE—Jacobsville Sandstone, Bayfield Group, and other equivalent sedimentary rocks.

The MCR formed during the Grenville orogeny, the sequence of events occurring from ca. 1.3–0.98 Ga culminating in the assembly of Rodinia. In northeastern Laurentia, the orogeny involved discrete contractional phases, including the Shawinigan from ca. 1200 to ca. 1140 Ma, Ottawan from ca. 1090 to ca. 1030 Ma, and Rigolet from ca. 1010 to ca. 980 Ma (Carr et al., 2000; Gower and Krogh, 2002; Hynes and Rivers, 2010; Rivers, 2012; McLelland et al., 2013) (Fig. 2A). MCR extension began after the Shawinigan phase and ended before the Ottawan phase began and so was not ended by Grenville compression. MCR volcanism continued until ca. 1086 Ma (Davis and Paces, 1990), within the Ottawan, whereas subsidence probably continued beyond the Ottawan.

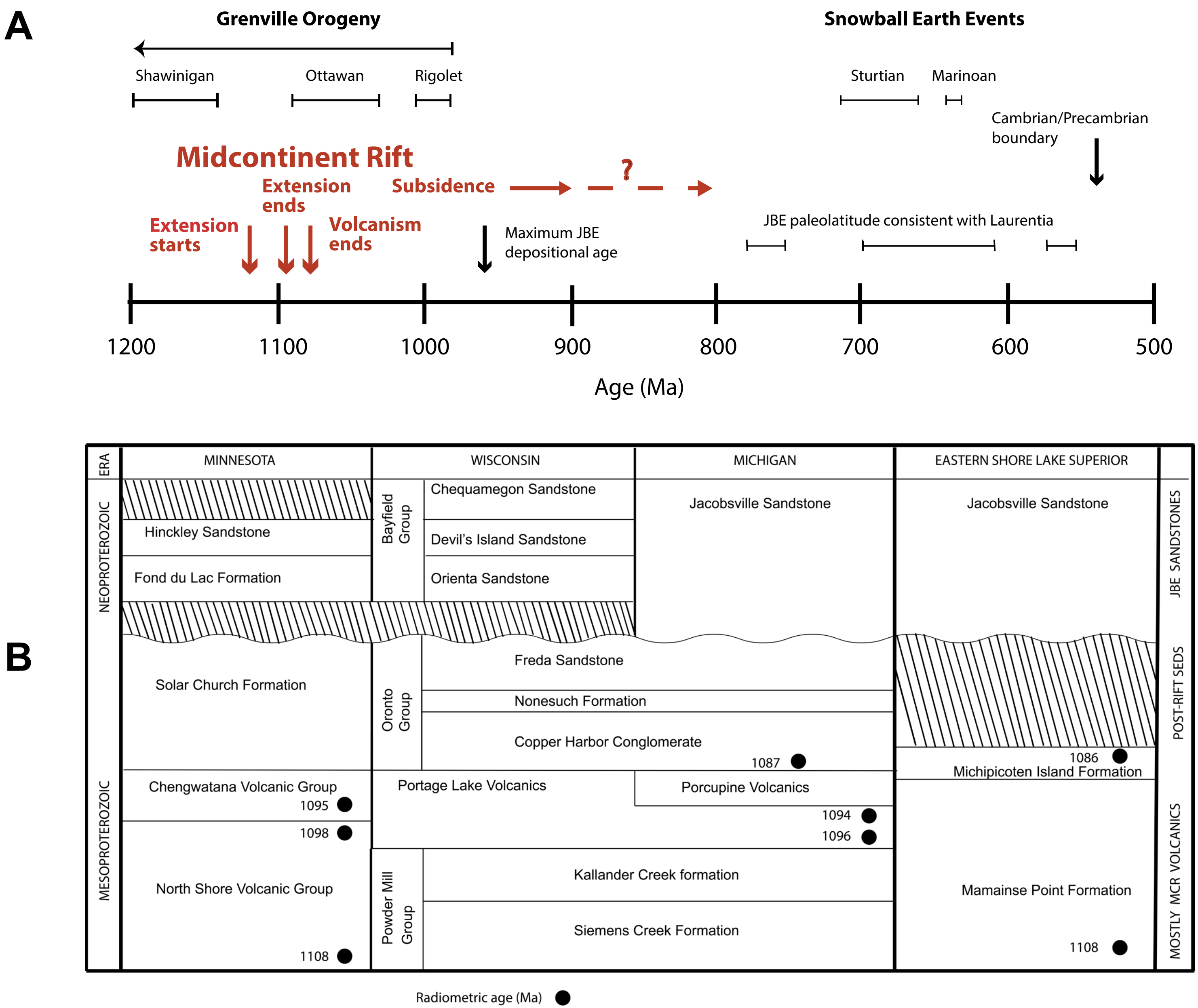

Figure 2. (A) Timeline for key events discussed in this paper. (B) Stratigraphy of Midcontinent Rift (MCR) and younger sediments for the Lake Superior region after Ojakangas and Dickas (2002). Solid circles are radiometric ages of the volcanic rocks. Upper Keweenawan sandstones have different names across the Lake Superior region, including Jacobsville and Bayfield. We propose that these sandstones are Neoproterozoic. JBE—Jacobsville Sandstone, Bayfield Group, and other equivalent sedimentary rocks.

JACOBSVILLE SANDSTONE

The dipping volcanic and sedimentary rocks filling the MCR rift basin are overlain near Lake Superior by the Jacobsville, Bayfield, and other stratigraphically equivalent sandstones such as the Fond du Lac and Hinckley Formation (JBE), the youngest of the Keweenawan Supergroup (Fig. 2B). The names of these sedimentary rock units vary regionally, reflecting both their original names and uncertain time correlations. We use "JBE" for these units collectively, and "Jacobsville" for that specific unit.

The Jacobsville Sandstone is a sequence of feldspathic and quartzose sandstones, conglomerates, siltstones, and shales, mostly from fluvial environments (although some alluvial fan deposits have been noted) (Mitchell and Sheldon, 2016). The Jacobsville Sandstone has a maximum thickness of ~1000 m observed in drill holes, and some geophysical data have been interpreted as suggesting at least double that thickness (Kalliokoski, 1982). Overall there is a lack of basin-wide laterally continuous units or vertical trends; although the Jacobsville west of Lake Gogebic has somewhat lower quartz content and is more poorly sorted than to the east (Hedgman, 1992).

Sparse samples from two long drill-hole sections for the Jacobsville Sandstone show a weak trend of increasing quartz from the lower to the top part of the cores. Quartz/feldspar/lithics ratios from these drill holes overlap those from the Bayfield Group and Fond du Lac and Hinckley Formations, reflecting the similarities of the different JBE units (Ojakangas and Dickas, 2002). Recently, Mitchell and Sheldon (2016) have identified a sequence of lithologically distinguishable pulses within some outcrops of the Jacobsville Sandstone.

Current directions for the Jacobsville Sandstone (Kalliokoski, 1982; Hedgman, 1992; Mitchell and Sheldon, 2016) are generally northerly but vary considerably. In the Fond du Lac Formation–Hinckley–Bayfield Group, directions are mostly easterly (Ojakangas and Morey, 1982; Adamson, 1997). Given the lack of stratigraphic control, whether the different directions result from differences in time of deposition or local topography is unknown.

The age of the JBE is poorly constrained, with reported and/or interpreted ages ranging from ca. 1100 to ca. 542 Ma. MCR volcanic rocks (ca. 1.1 Ga) or older rocks are typically observed below the JBE (Kalliokoski, 1982). A maximum age constraint comes from a drill hole where Jacobsville Sandstone unconformably overlies the Oronto Group (Ojakangas and Dickas, 2002). This unconformity can also be observed directly west of L'Anse, Michigan (Hamblin, 1958). A minimum age constraint comes from the fact that the fossiliferous Late Cambrian Munising Formation unconformably overlies the Jacobsville Sandstone. Because no fossils have been identified in the JBE, they are assumed to be Precambrian.

Provenance studies (Kalliokoski, 1982; Hedgman, 1992) have concluded that the early Proterozoic rocks and Archean rocks to the south (Marquette Range Supergroup in the Gogebic Iron Range) contributed to the Jacobsville Sandstone; although Hedgman (1992) favors an additional source to the north. Recent detrital-zircon ages have shown additional sources including Grenville rocks from the east and the Wolf River Batholith of the 1.3–1.5 Ga Granite-Rhyolite province (Craddock et al., 2013).

The age of the JBE is important because it has been unclear whether the JBE should be considered genetically related to the Midcontinent Rift or to have formed much later and unrelated to the MCR. Cannon et al. (1993) proposed that the JBE's age is ca. 1060 Ma, and thus associated with the MCR.

However, the JBE are structurally and compositionally very different from the underlying MCR sediments, suggesting that the JBE are much younger. Here we present new detrital-zircon ages from sampling during the summer of 2015 (Fig. 3); these samples support a younger age and imply that the JBE and the compression evident therein postdate the Grenville orogeny and are unrelated to the rift's failure.

BACKGROUND

Many authors note an angular unconformity between the older Oronto and younger Bayfield Groups (Thwaites, 1912; Myers, 1971; Daniels, 1982; Adamson, 1997). Angular unconformities are observed in some seismic-reflection profiles between the JBE and older rocks (Mudrey, 1986; Milkereit et al., 1990). A strong angular unconformity between the JBE and Keweenaw volcanic rocks was also mapped near the Michigan-Wisconsin border (Cannon et al., 1993). In surface exposures, the JBE are not in contact with the Oronto Group but directly overlie older units (Fig. 2B), consistent with a significant period of erosion removing part of the Oronto Group before JBE deposition (Kalliokoski, 1982). In several locations, the relief of the underlying rocks suggests the JBE were deposited on a paleosurface that is now locally re-exhumed (Kalliokoski, 1982). JBE and Freda sandstones (youngest Oronto Group formation) are observed in stratigraphic contact only in two boreholes located on the southeast shore of Lake Superior 12 km apart (Ojakangas and Dickas, 2002). In most cases, the JBE are in fault contact with the Oronto Group.

Compositional differences between the postrift Oronto Group and the JBE may reflect a time gap between their deposition and/or differences in source region or depositional environment. The JBE are more mature in texture and mineralogy than the Oronto, including the youngest Freda Sandstone (Myers, 1971; Daniels, 1982; Kalliokoski, 1982; Dickas et al., 1989; Adamson, 1997; Ojakangas et al., 2001; Ojakangas and Dickas, 2002). The Bayfield Group Sandstones have better rounded grains and more quartz than the Freda Sandstone (Myers, 1971; Adamson, 1997). The Freda is a lithofeldspathic sandstone, and the younger Jacobsville is a feldspatholithic sandstone, with more quartz and less feldspar and lithics (Adamson, 1997; Ojakangas and Dickas, 2002). The JBE likely formed when weathering rates were higher and/or by transportation from a more distant source (Mitchell and Sheldon, 2016).

The best constraint on the JBE's age comes from detrital-zircon grains within it, whose ages yield a maximum age of the sandstone. Craddock et al. (2013) reported 105 ages for the basal Jacobsville Sandstone near Marquette, Michigan. While the fact that the youngest age was 933 ± 18 Ma is significant with respect to provenance, single dates are considered tenuous for defining a maximum depositional age (Dickinson and Gehrels, 2009). Thus, ten addi-

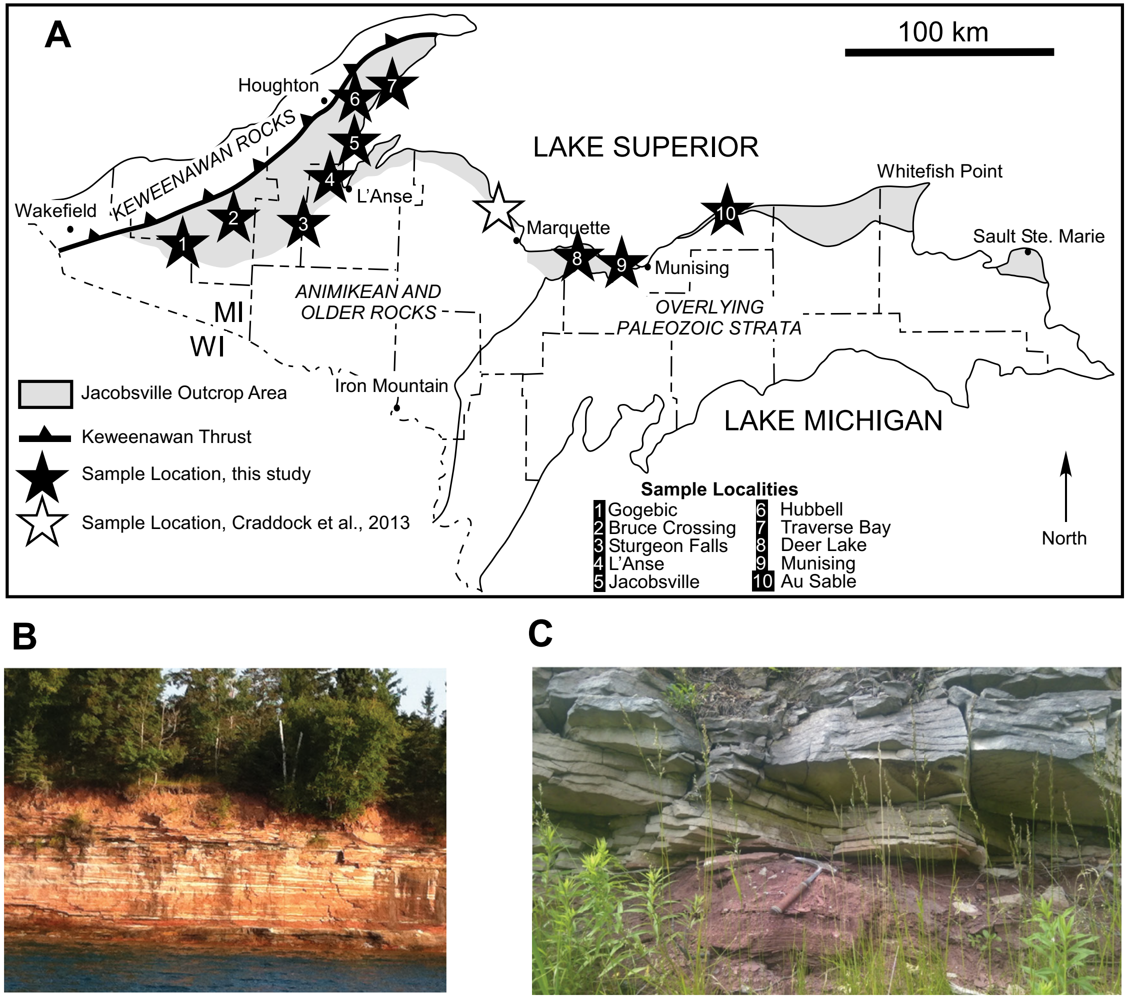

Figure 3. (A) Map of the Upper Peninsula of Michigan showing the outcrop belt of the Jacobsville Sandstone and detrital-zircon sampling localities. Black stars—this study; white star—Craddock et al. (2013). Photographs of the Rabbit Bay (B) and Gogebic (C) sampling localities.

tional sites (Fig. 3) were sampled and analyzed for this study, and 2050 new ages were determined. The details of spatial and temporal Jacobsville provenance evolution will be the focus of a later report. Here we focus only on the age implications of this data set.

METHODOLOGY

Sandstone samples were collected from several locations through the Upper Peninsula of Michigan (Fig. 3), chosen to ensure stratigraphic and geographic coverage. Samples were taken at Au Sable Falls in Pictured Rocks National Lakeshore, Lake Gogebic, Hubbell, Sturgeon Falls, Jacobsville (type section), Bruce Crossing, L'Anse, Deer Lake, Munising, and Traverse Bay. About 10 kg of sandstone were collected from each locality. The samples were crushed and panned by hand. Zircons were extracted from the pan concentrate using heavy liquids and a Frantz magnetic separator.

U-Pb geochronology of zircons was conducted by laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS) at the Arizona LaserChron Center (Gehrels et al., 2006, 2008). The analyses involve ablation of zircon with a Photon Machines Analyte G2 excimer laser equipped with HelEx ablation cell using a spot diameter of 20 microns. The ablated material is carried in helium into the plasma source of an Element2 HR ICPMS, which sequences rapidly through U, Th, and Pb isotopes. Signal intensities are measured with a secondary electron multiplier (SEM) that operates in pulse-counting mode for signals less than 50K counts per second (cps), in both pulse-counting and analog mode for signals between 50K and 4M cps, and in analog mode above 4M cps. The calibration between pulse-counting and analog signals is determined line by line for signals between 50K and 4M cps and is applied to 4M cps signals. Four intensities are determined and averaged for each isotope, with dwell times of 0.0052 s for 202, 0.0075 s for 204, 0.0202 s for 206, 0.0284 s for 207, 0.0026 s for 208, 0.0026 s for 232, and 0.0104 s for 238.

With the laser set at an energy density of ~5 J/cm^2, a repetition rate of 8 Hz, and an ablation time of 10 seconds, ablation pits are ~12 microns in depth. Sensitivity with these settings is approximately ~5000 cps/ppm. Each analysis consists of 5 seconds on peaks with the laser off (for backgrounds), 10 seconds with the laser firing (for peak intensities), and a 20-second delay to purge the previous sample and save files.

Following analysis, data reduction is performed with an in-house Python decoding routine and an Excel spreadsheet (E2agecalc) that determines a "best age" for each analysis, which is generally the 206/238 age for <900 Ma ages and the 206/207 age for >900 Ma ages and provides preliminary filters that highlight analyses with >20% discordance, >5% reverse discordance, or >10% internal (measurement) uncertain. The ages are shown on Pb*/U concordia diagrams and relative age-probability diagrams using routines in Isoplot (Ludwig, 2008).

RESULTS

U-Pb dates for 2050 zircon grains were determined from the ten sampling localities (Fig. 4A). Table 1 shows the U-Pb geochronological data for the youngest 20 grains from this data set. Seven grains yielded ages less than 1000 Ma. The youngest individual grain is 954 ± 29 Ma. The maximum deposi-

TABLE 1. U-Pb GEOCHRONOLOGICAL DATA FOR THE YOUNGEST 20 GRAINS FROM 2050 ZIRCON U-Pb DATES DETERMINED FROM TEN SAMPLING LOCALITIES (FIG. 3A)

		Isotope ratios								Apparent ages (Ma)								
Analysis (sample location)	U (ppm)	U/Th	$^{206}Pb/^{207}Pb$	± (%)	$^{207}Pb/^{235}U$	± (%)	$^{206}Pb/^{238}U$	± (%)	Error correction	$^{206}Pb/^{238}U$	± (Ma)	$^{207}Pb/^{235}U$	± (Ma)	$^{206}Pb/^{207}Pb$	± (Ma)	Best age (Ma)	± (Ma)	Concordance (%)
Au Sable-Spot 190 (10)	101	1.9	14.1070	1.4	1.5899	2.2	0.1627	1.7	0.76	971.6	15.1	966.3	13.7	954.1	29.0	954.1	29.0	101.8
Hubbell-Spot 57 (6)	51	2.3	14.0573	1.5	1.6565	2.6	0.1689	2.1	0.82	1006.0	19.7	992.0	16.3	961.4	29.7	961.4	29.7	104.6
Bruce Crossing-Spot 90 (2)	19	2.2	14.0211	3.0	1.6236	3.7	0.1651	2.3	0.60	985.1	20.7	979.4	23.5	966.6	60.8	966.6	60.8	101.9
L'Anse-Spot 102 (4)	19	1.3	13.9579	2.6	1.7313	2.9	0.1753	1.4	0.48	1041.1	13.7	1020.3	19.0	975.8	52.6	975.8	52.6	106.7
Gogebic-Spot 131 (1)	177	1.0	13.8068	1.5	1.6791	2.6	0.1681	2.1	0.83	1001.8	19.7	1000.6	16.4	998.0	29.5	998.0	29.5	100.4
Hubbell -Spot 43 (6)	145	2.0	13.8067	1.2	1.6572	2.1	0.1659	1.7	0.80	989.8	15.2	992.3	13.1	998.0	25.1	998.0	25.1	99.2
Hubbell -Spot 71 (6)	269	3.7	13.8052	1.2	1.7208	1.9	0.1723	1.5	0.77	1024.7	13.9	1016.3	12.3	998.2	24.9	998.2	24.9	102.7
Bruce Crossing-Spot 63 (2)	46	3.6	13.7895	1.8	1.6945	2.7	0.1695	2.1	0.77	1009.2	19.6	1006.4	17.5	1000.5	35.7	1000.5	35.7	100.9
Hubbell -Spot 33 (6)	56	6.4	13.7707	2.1	1.7598	3.0	0.1758	2.2	0.72	1043.8	20.8	1030.8	19.4	1003.3	42.4	1003.3	42.4	104.0
L'Anse-Spot 7 (4)	17	1.2	13.7455	4.0	1.6997	4.6	0.1694	2.1	0.46	1009.1	19.5	1008.4	29.1	1007.0	82.1	1007.0	82.1	100.2
L'Anse-Spot 107 (4)	90	2.0	13.7134	1.4	1.7672	2.1	0.1758	1.5	0.73	1043.8	14.7	1033.5	13.7	1011.7	29.4	1011.7	29.4	103.2
Bruce Crossing-Spot 216 (2)	63	0.9	13.6623	1.5	1.7134	2.2	0.1698	1.6	0.71	1010.9	14.6	1013.6	14.1	1019.3	31.4	1019.3	31.4	99.2
Jacobsville-Spot 75 (5)	34	1.0	13.6540	2.0	1.7456	3.0	0.1729	2.2	0.73	1027.9	20.4	1025.6	19.1	1020.5	41.0	1020.5	41.0	100.7
L'Anse-Spot 94 (4)	111	1.3	13.6248	1.4	1.7485	2.3	0.1728	1.9	0.80	1027.4	17.7	1026.6	15.0	1024.9	28.0	1024.9	28.0	100.2
Munising-Spot 59 (9)	171	1.6	13.6187	1.0	1.7849	1.8	0.1763	1.5	0.84	1046.7	14.3	1040.0	11.4	1025.8	19.3	1025.8	19.3	102.0
Bruce Crossing-Spot 28 (2)	64	3.7	13.5852	1.6	1.7216	2.7	0.1696	2.2	0.80	1010.1	20.1	1016.6	17.4	1030.8	33.1	1030.8	33.1	98.0
Jacobsville-Spot 54 (5)	29	1.2	13.5745	2.6	1.7763	3.4	0.1749	2.2	0.66	1038.9	21.6	1036.8	22.2	1032.4	52.3	1032.4	52.3	100.6
L'Anse-Spot 85 (4)	20	1.6	13.5547	2.9	1.7641	3.3	0.1734	1.5	0.46	1030.9	14.3	1032.3	21.1	1035.3	58.3	1035.3	58.3	99.6
L'Anse-Spot 15 (4)	244	4.2	13.5546	1.0	1.8579	2.0	0.1826	1.7	0.86	1081.4	16.8	1066.3	12.9	1035.3	20.0	1035.3	20.0	104.5
Jacobsville-Spot 69 (5)	47	2.7	13.5435	1.9	1.7094	2.8	0.1679	2.1	0.74	1000.6	19.1	1012.1	17.8	1037.0	37.5	1037.0	37.5	96.5

Notes: Analyses with >10% uncertainty (1 sigma) in $^{206}Pb/^{238}U$ age are not included. Analyses with >10% uncertainty (1 sigma) in $^{206}Pb/^{207}Pb$ age are not included, unless $^{206}Pb/^{238}U$ age is <400 Ma. Best age is from $^{206}Pb/^{238}U$ age for analyses with $^{206}Pb/^{238}U$ age <900 Ma and from $^{206}Pb/^{207}Pb$ age for analyses with $^{206}Pb/^{238}U$ age >900 Ma. Concordance is based on $^{206}Pb/^{238}U$ age versus $^{206}Pb/^{207}Pb$ age. Analyses with $^{206}Pb/^{238}U$ age >400 Ma and with >20% discordance (<80% concordance) are not included. Analyses with $^{206}Pb/^{238}U$ age >400 Ma and with >5% reverse discordance (<105% concordance) are not included. All uncertainties are reported at the 1-sigma level and include only measurement errors. Uranium concentration and U/Th are calibrated relative to FC-1 zircon standard and are accurate to ~20%. Common Pb correction is from measured ^{204}Pb with common Pb composition interpreted from Stacey and Kramers (1975). Common Pb composition assigned uncertainties of 1.5 for $^{206}Pb/^{204}Pb$, 0.3 for $^{207}Pb/^{204}Pb$, and 2.0 for $^{208}Pb/^{204}Pb$. U/Pb and $^{206}Pb/^{207}Pb$ fractionation is calibrated relative to fragments of large Sri Lanka zircons and individual crystals of FC-1 and R33. U decay constants and composition as follows: ^{238}U = 9.8485 × 10 – 10, ^{235}U = 1.55125 × 10 – 10, $^{238}U/^{235}U$ = 137.88.

tional age (MDA), based on the youngest four grains with overlapping ages, is 959 ± 19 Ma (mean square of weighted deviates [MSWD = 0.29]; Fig. 4B). These results confirm the result of Craddock et al. (2013).

The youngest peak age on the composite frequency plot (all ten sampling localities and 2050 grains) is 1106 Ma. The 1106 Ma age peak is defined by zircons that range in age from 954 to 1200 Ma. This age corresponds with the early phase of MCR volcanism. Many of these younger and older grains that comprise this peak likely come from the overlapping Shawinigan (1200–1140 Ma), Ottawan (1090–1030 Ma), and Rigolet (1010–980 Ma) phases of the Grenville orogeny (McLelland et al., 2013).

Other peaks on the composite frequency plot are 1230 Ma (Elzevirian phase of the Grenville orogeny); ca. 1260–1220 Ma (McLelland et al., 2013); 1356 Ma (mid-continent Granite-Rhyolite Province; Van Schmus et al., 1996); 1455 Ma (Wolf River Batholith; Dewane and Van Schmus, 2007); 1660 Ma (Mazatzal orogeny; Foster et. al, 2006); 1880 Ma (Penokean orogeny; Holm et al., 1998; Schultz and Cannon, 2007); the 2100 Ma Marathon dikes (Halls et al., 2008); and 2660 Ma (Superior Province and areas south and west of the MCR; Bickford et al., 2006). The Jacobsville Sandstone's sources (Fig. 5) are traditionally considered to be local, mostly from the south from the early Proterozoic and Archean, with some from the north (Kalliokoski, 1982; Hedgman, 1992). These older rocks are described by Sims et al. (1989), Van Wyck and Johnson (1997), and Van Wyck and Norman (2004). In contrast, the JBE zircon age distribution from this study and Craddock et al. (2013) includes a large percentage of ages between 1150 and 1300 Ma, indicating an additional source far from the MCR, most likely the Grenville Province to the northeast. The JBE detrital-zircon age distribution in this study and that of Craddock et al. (2013) have similarities to other post-Grenvillian sandstones within Laurentia, along its margins, and some now in Europe (Santos et al., 2002; Rainbird et al., 2012; Spencer et al., 2015).

Frequency plots for individual sites vary considerably and will be the focus of a future detailed study of the provenance evolution of the JBE. However, the 959 ± 19 Ma maximum depositional age shows that the JBE are Neoproterozoic in age and thus are at least slightly younger than the Grenville orogeny.

IMPLICATIONS FOR MCR EVOLUTION

The zircon results showing that the JBE are younger than 959 ± 19 Ma demonstrate that their deposition is unrelated to development of the MCR. Because the shortening that inverted the basin deformed the JBE near the reverse faults, the younger maximum depositional age of the JBE also indicates that this compression occurred more than 100 m.y. after MCR extension and volcanism ended. Hence this compression is not why the MCR failed, as has been previously proposed (Gordon and Hempton, 1986; Cannon, 1994; Swenson et al., 2004). Moreover, because the JBE postdate the major deformational stages of the Grenville orogeny, this compression was not part of the Grenville orogeny proper.

This analysis, like early studies, assumes that although earlier compressional events may have affected the MCR, most of the basin inversion resulted

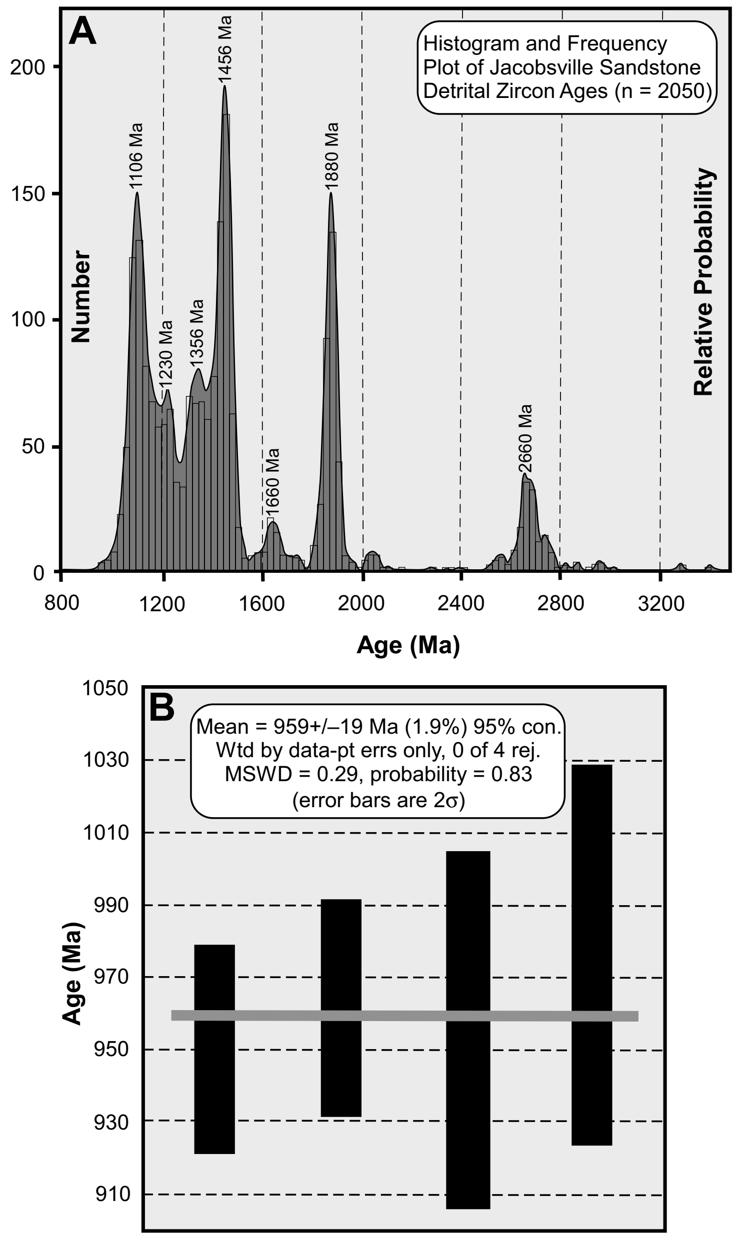

Figure 4. (A) Histogram and frequency plot of Jacobsville Sandstone detrital-zircon ages. (B) Age and measurement uncertainty of the four youngest detrital-zircon ages with overlapping uncertainties.

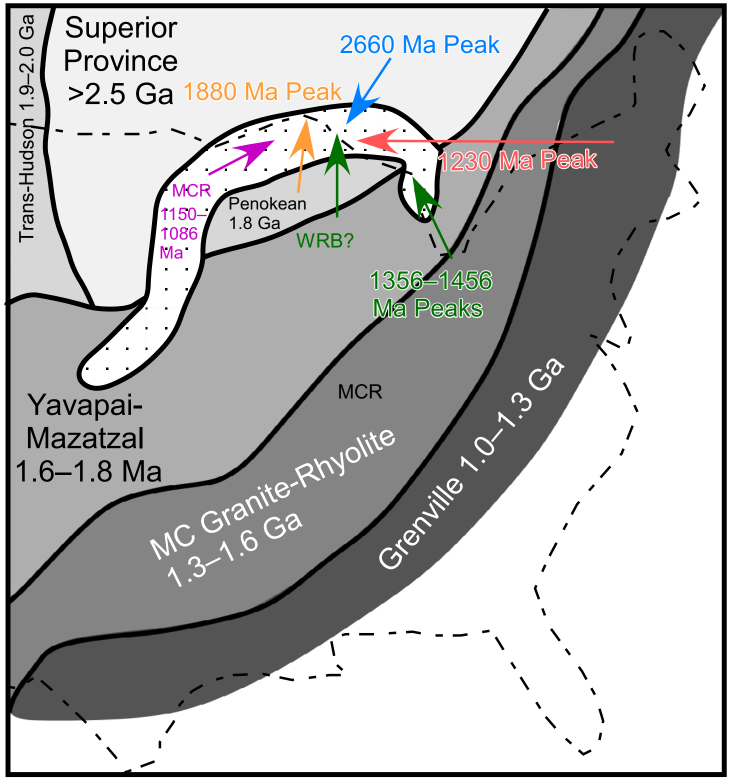

Figure 5. Generalized map of basement terranes in North America (modified from Whitmeyer and Karlstrom, 2007). The Jacobsville Sandstone received sediment from various source areas as indicated by the different arrows. MC—mid-continent; MCR—Midcontinent Rift; WRB—Wolf River Batholith of northern Wisconsin.

from the reverse faulting recorded in the JBE. What caused this compression is unclear. Since the Grenville orogeny, Laurentia has been subject to many collisions. Reconstructions (Li et al., 2013) for times after the Grenville orogeny to the end of the Precambrian do not indicate significant collisional events. However, collisions along Laurentia's margins may have caused compression in the Lake Superior region but not be recognized because their locations later rifted from Rodinia. Some deformation may be early Paleozoic, associated with compression along eastern North America and the present Arctic (Hadlari et al., 2014).

Much of the motion on the reverse faults may be from the late Paleozoic collisions that formed the Appalachian and Ouachita orogens and gave rise to recognized deformation of the distal foreland (Craddock and van der Pluijm, 1989; Craddock et al., 1993; van der Pluijm et al., 1997). The Midwest United States contains many compressional features of this age, including structures within the Illinois and Michigan Basins and the west arm of the MCR (the Ashland syncline and Nehama ridge) (McBride and Nelson, 1999; Marshak et al., 2000). Faulting and folding of Paleozoic limestones and the underlying Jacobsville Sandstone suggest that some slip on the Keweenaw fault might have occurred at this time (McGovern et al., 1993; Craddock et al., 1997).

This paper focuses on the Lake Superior region, where rocks are best exposed and the best seismic-reflection data exist. We have conducted detailed structural modeling (Stein et al., 2015) and have the new age data presented here. Other parts of the rift system may have evolved somewhat differently, especially after extension ended (Baranoski et al., 2009).

AN EVEN YOUNGER JBE?

Several lines of complementary—although not definitive—evidence suggest that the JBE may be significantly younger than 959 ± 19 Ma. First, the absence of any zircon grains younger than 959 ± 19 Ma within the JBE allows (but does not require) their depositional age to be much younger (even up to Cambrian). Because both the Late Cambrian Munising Sandstone that overlies the Jacobsville Sandstone (Craddock et al., 2013) and other early Cambro-Ordovician quartz arenites in the midcontinent (Konstantinou et al., 2014) lack zircons younger than ca. 1000 Ma, it appears that the upper midcontinent region did not receive sediment from late Neoproterozoic rifting events in Laurentia.

Second, the very different zircon age distributions between the JBE and the underlying Freda Sandstone (Craddock et al., 2013) may indicate that a large gap in time was needed to change river systems to bring the eastern source of Grenville zircons to the Lake Superior area. It also suggests that time was needed to erode the highlands and rift shoulders surrounding the MCR so that different material could be deposited.

Third, paleomagnetic data suggest a much younger, possibly Cryogenian to Ediacaran, age. We estimated the age using the Bayfield Group's Chequamegon Sandstone (McCabe and van der Voo, 1983), where the primary magnetic carrier is detrital magnetite. Figure 6 compares the JBE's paleolatitude to Neoproterozoic paleolatitudes of Laurentia found from sites outside of the MCR area. Given the uncertainties in reconstructions, we simplify the comparison by assuming that all paleomagnetic latitudes are in the same hemisphere. The paleolatitudes match at ca. 780 to ca. 755, ca. 700 to ca. 610, or ca. 570 to ca. 555 Ma.

A final, more speculative possibility is that a younger JBE age could be consistent with the JBE having formed after a Snowball Earth glacial event (Hoffman et al., 1998). The ratio of the partial pressure of atmospheric carbon dioxide (pCO_2) to present levels has been estimated for both an MCR- and a JBE-related paleosol. The paleosol within MCR volcanics has a value comparable to today's level (Sheldon, 2013). However, one paleosol beneath the Jacobsville near site #3 (Fig. 3) has a value about four times today's level (Mitchell and Sheldon, 2010). Immediately following a Neoproterozoic Snowball Earth event, pCO_2 is thought to have been very high (Le Hir et al., 2009), perhaps 3–270 times present atmospheric levels (Vieira et al., 2015). Hence the

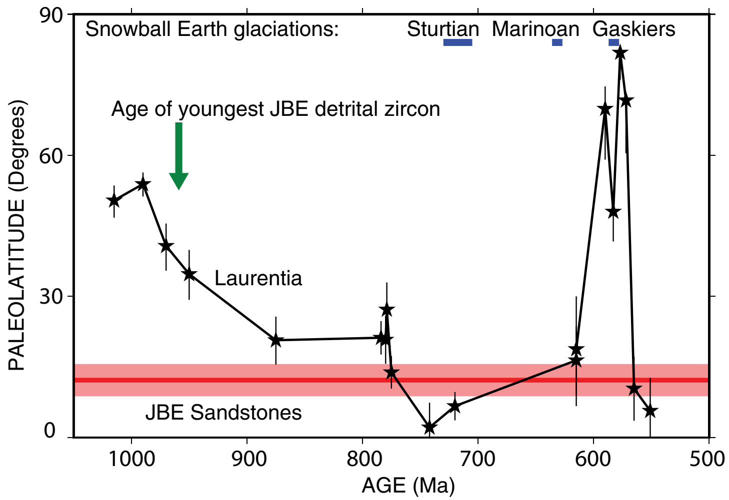

Figure 6. Comparison of predicted latitudes for Lake Superior area from paleopoles of Neoproterozoic Laurentia to those of JBE sandstones. Possible JBE ages are ca. 780–755, ca. 700–610, or ca. 570–555 Ma. The mean JBE paleolatitude (red line) and uncertainty (pink band) are shown. For comparison, all paleolatitudes are shown as positive. Laurentia data from Warnock et al. (2000), Harlan et al. (2003), Weil et al. (2003, 2006), and Brown and McEnroe (2012). Data compiled in Li et al. (2013) from Murthy (1971), Tanczyk et al. (1987), Park et al. (1989), Symons and Chiasson (1991), Meert et al. (1994), Harlan et al. (1997), McCausland and Hodych (1998), Hodych et al. (2004), Weil et al. (2004), Denyszyn et al. (2009), and McCausland et al. (2009, 2011).

JBE may have been deposited just after the Sturtian (ca. 717–660 Ma) or the Marinoan (ca. 640–632 Ma) Snowball Earth events (Rooney et al., 2015). The JBE paleolatitude data for 700–610 Ma are consistent with this time window (Fig. 6). This timing is also consistent with possible glacial features (striations, gouges, grooves, and polishing) (Murray, 1955) found near the younger paleosol, at the base of the Jacobsville Sandstone on the upper surface of the ca. 1.9 Ga Michigamme slate (Ding et al., 2012). Kalliokoski (1982) favored these features being produced by faulting because he assumed a near-equatorial position for the area during Jacobsville deposition. However, this paper was published before the concept of a Snowball Earth (Kirschvink, 1992; Hoffman et al., 1998). No major glacial periods occurred between ca. 2 Ga and 850 Ma (Young, 2013); so if these features are glacial, they likely result from Snowball Earth events. Hence, they may be the first recognized record of such events in this part of Laurentia.

CONCLUSIONS

An important constraint on the evolution of the Midcontinent Rift (MCR) comes from the Jacobsville Sandstone, Bayfield Group, and other equivalent sedimentary rocks (JBE) that overlie the volcanics and sediments deposited in the MCR basin near Lake Superior. It has been proposed that the JBE were deposited shortly prior to or during the time when the MCR failed—ceased extending—due to regional compression occurring as part of the Grenville orogeny. New detrital-zircon ages show that the JBE are Neoproterozoic. The compression recorded in the JBE, which inverted the basin, thus postdates the Grenville orogeny and is unrelated to the failure of the rift.

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