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RESEARCH ARTICLE

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# Neoproterozoic sedimentation and tectonics of the Laurentian midcontinent: Detrital zircon provenance of the Jacobsville Sandstone, Lake Superior Basin, USA and Canada

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## Abstract

The Neoproterozoic Jacobsville Sandstone outcrops along the south and east shores of Lake Superior, USA. It records intraplate deformation, some during its deposition and some afterwards, after the c. 1,100 Ma Midcontinent Rift (MCR) failed. Here we analyse 549 new detrital zircon ages from five sites, combined with prior data. Initially, local palaeo-topography controlled the source material, including the MCR-adjacent Penokean and Archaean rocks. With time the percentage of distal sources increased, including the c. 1,300–980 Ma Grenville orogeny and 1,480–1,360 Ma Granite-Rhyolite Province. Sites near the Keweenaw fault contain a significant number of MCR-age zircons, presumably uplifted to the surface, indicating fault motion during deposition. Only a relatively small percentage of 1,090–980 Ma Grenville-age zircons from collisions to the east are present, suggesting that they were not efficiently transported to the Lake Superior area. This work is innovative in that it is the first to use detrital zircon geochronology to understand the internal stratigraphy of the Jacobsville Sandstone, whose provenance provides new information about the Neoproterozoic tectonic and sedimentary history of Laurentia.

## 1 | INTRODUCTION

The provenance and deformation of the Neoproterozoic Jacobsville Sandstone, which outcrops near the north and east shores of Lake Superior in the United States (Figure 1), is important for understanding two major tectonic episodes. It post-dates the formation of the Midcontinent Rift (MCR), the c. 1,100 Ma major rifting event which failed to split Laurentia (the Precambrian core of North America). The Jacobsville also contains a detrital record of collisional events that affected North America starting with the Grenville orogeny, the sequence of events from c. 1.3–0.98 Ga culminating in the assembly of the supercontinent Rodinia (Craddock, Craddock, Konstantinou, Kylander-Clark, & Malone, 2017; Dalziel, 1991; Rivers, 2012).

The Jacobsville is a succession of feldspathic and quartzose sandstones, conglomerates, siltstones and shales deposited in terrestrial fluvial and lacustrine environments (Mitchell & Sheldon, 2016). Borehole measurements show that the Jacobsville might be up to 1 km thick (Ojakangas, Morey, & Green, 2001), and geophysical data suggest a maximum thickness ≥2 km (Kalliokoski, 1982).

Although the Jacobsville was traditionally considered part of the Keweenawan Supergroup, the maximum age from detrital zircons is ~140 million years after extension ended, so the Jacobsville is not temporally related to MCR tectonic and magmatic activity. The Jacobsville unconformably overlies the ~1,100 Ma MCR volcanic and older rocks at many sites in the western study area (Kalliokoski, 1982). However, in the eastern area, at three boreholes and some outcrops, the Jacobsville and the youngest Oronto Group (Freda sandstones in Michigan and corresponding Mica Bay in Ontario) are in contact, probably unconformably (Ojakangas & Dickas, 2002).

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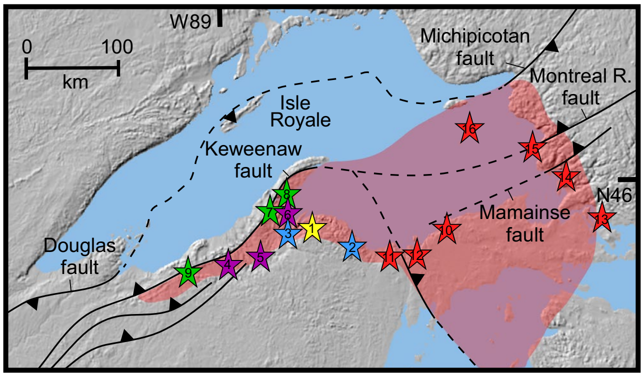


**FIGURE 1** Tectonic map of the Lake Superior region, USA and Canada. The area of Jacobsville sandstone occurrence is indicated in red, and the sampling localities are indicated by coloured stars. Yellow = Type 1 detrital zircon provenance, Blue = Type 2, Purple = Type 3, Green = Type 4, Red = Type 5. 1 = Big Erick's Bridge, 2 = Little Presque Isle (Craddock, Konstantinou, et al., 2013), 3 = L'Anse, 4 = Bruce Crossing, 5 = Sturgeon Falls, 6 = Traverse Bay, 7 = Jacobsville Quarry, 8 = Hubble, 9 = Gogebic, 10 = Au Sable Point, 11 = Deer Lake, 12 = Munising, 13 = Echo Bay, 14 = Batchawana Bay, 15 = Alona Bay, 16 = Caribou Island. The Jacobsville is only present in the subsurface south of our sampling localities. The faults indicated are tectonically inverted, rift-bounding structures that may have been active through the late Palaeozoic (Craddock, Malone, et al., 2017)

Early provenance studies of the Jacobsville (Kalliokoski, 1982) suggested that the principal source was local Palaeoproterozoic basement rocks and a secondary source was the Archaean rocks to the north. However, reconnaissance detrital zircon work at one site suggested a more complex Jacobsville provenance (Craddock, Konstantinou, et al., 2013). Malone et al. (2016, 2018) sampled 10 sites for the Jacobsville (with a total of 2,048 ages) and determined that the oldest possible depositional age is 959 ± 19 Ma, and that the 19 Geon zircons may have been derived from Baltica. They did not, however, examine the details of the spatial and temporal evolution of the detrital zircon provenance for the individual sample sites. No common internal stratigraphy is designated for the Jacobsville, because it contains a wide range of lithologies, is poorly exposed and it has a variable thickness. Here we report new data for the basal Jacobsville that rests unconformably above the Archaean basement in Michigan and four localities in Ontario, adding 549 zircon ages to our dataset, and analyse the Jacobsville's provenance in space and time.

## 2 | POTENTIAL JACOBSVILLE SEDIMENT SOURCE AREAS

The Archaean Superior province, which occurs mainly in Ontario, Canada, consists of about 15 NE–SW trending terranes that were sutured at ~2.75 Ga (Card, 1990; King, Valley, Davis, & Edwards, 1998; Percival et al., 2006). Superior province zircons also are abundant in the early Palaeozoic arenites in the Laurentian midcontinent (Konstantinou et al., 2014), as well as the Baraboo interval quartzites (Medaris et al., 2003; Stewart, Stewart, Walker, & Zambito, 2018; Van Wyck & Norman, 2004) and Palaeo-Mesoproterozoic clastic rocks in the Lake Superior area (Craddock, Konstantinou, et al., 2013; Craddock, Rainbird, et al., 2013). Older Archaean rocks (2.9–3.6 Ga) are present in the Minnesota River valley terrane (Schmitz, Bowring, Southwick, Boerboom, & Wirth, 2006), the Marshfield terrane (Craddock, Malone, Schmitz, & Gifford, 2018) and the Watersmeet, Michigan area (Peterman, Zartman, & Sims, 1980).

The Proterozoic tectonic evolution of Laurentia is complicated, representing more than 800 million years of southward accretionary growth, crustal formation, deformation and metamorphism

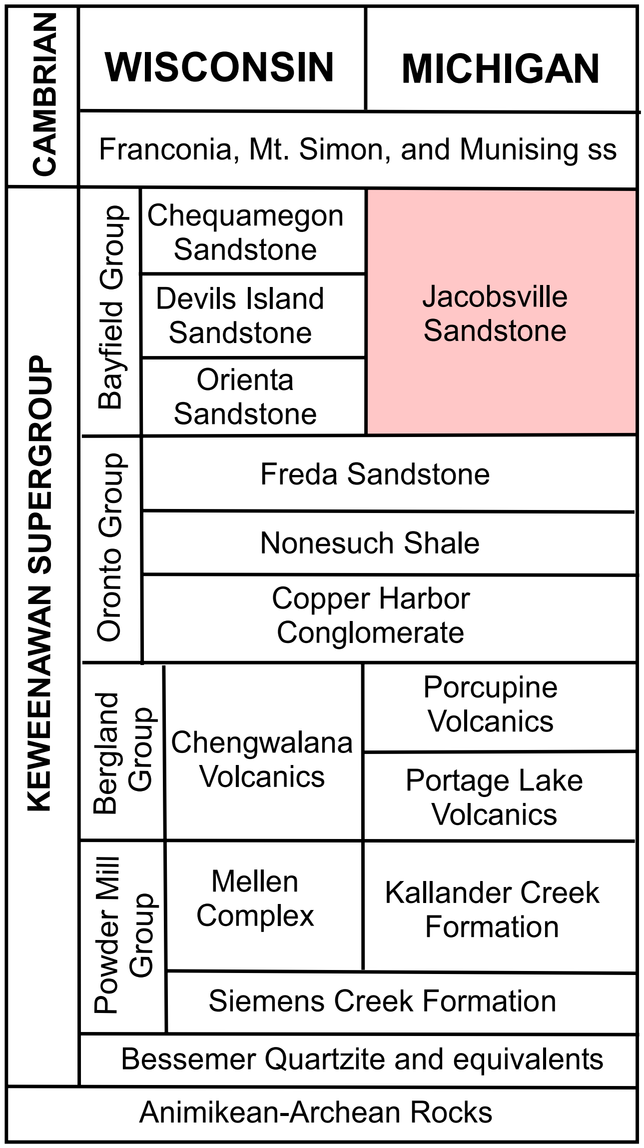


**FIGURE 2** Stratigraphic nomenclature of the rocks associated with the Midcontinent Rift. ss, sandstone. Bessemer equivalents include the Nopeming and Puckwungee quartzites

(Whitmeyer & Karlstrom, 2007). Laurentia formed as the result of accretion and suturing of Archaean cratons during the ~ 1.8–1.9 Ga Trans-Hudson and Penokean orogenies (Craddock et al., 2018; Holm et al., 2020; Whitmeyer & Karlstrom, 2007). In the southern Lake Superior region, the Penokean orogeny formed by the accretion of the Pembine-Wausau terrane, a juvenile island arc, and the Archaean Marshfield terrane (Medaris et al., 2007).

The Penokean orogeny was followed the Yavapai orogeny from 1,700 to 1,800 Ma and in turn by the Mazatzal orogeny from 1,600 to 1,700 Ma (Karlstrom & Bowring, 1988). These two belts as much as 1000 km wide and are comprised of juvenile crust. Yavapai-age granites are present in the Lake Superior area (Craddock et al., 2018; Holm et al., 2005), especially in southern Wisconsin. Rocks with a Mazatzal crystallization age have not been identified in the Lake Superior area but associated metamorphism and deformation is widely reported (Craddock & McKiernan, 2007; Czeck & Ormand, 2007; Holm, Schneider, & Coath, 1998).

The Yavapai and Mazatzal events were followed by additional crustal accretion from 1,480 to 1,360 Ma, which are collectively included in the Midcontinent Granite-Rhyolite province (GRP; Bickford, Van Schmus, Karlstrom, Mueller, & Kamenov, 2015; Bickford, Van Schmus, & Zietz, 1986; Freiburg, McBride, Malone, & Leetaru, 2020). The GRP includes undeformed and mostly unmetamorphosed rhyolite and granite formed in an intraplate tectonic setting (Bickford et al., 1986). A-type granites were intruded into Penokean crust in the southern Lake Superior area, most extensively in the Wolf River Batholith (Dewane & Van Schmus, 2007). GRP rocks also occur in southeastern Canada (Gower, Schärer, & Heaman, 1992).

Grenville-age basement occurs throughout northeastern Laurentia; these rocks also occur as inliers in the Appalachian orogenic belt and in central Texas (Whitmeyer & Karlstrom, 2007). In northeastern Laurentia, the Grenville Orogeny occurred in several phases, including the (a) Elzevirian from ~1,300 to 1,220 Ma, (b) Shawinigan from 1,200 to 1,140 Ma, (c) Ottawan from ~1,090 to 1,030 Ma, and (d) Rigolet from ~1,010 to 980 Ma (Hynes & Rivers, 2010; Rivers, 2012). MCR volcanism occurred between the Shawninigan and Ottawan phases so the distinction between MCR and Grenville zircons is difficult.

The Midcontinent Rift (MCR) is a 3,000-km-long rift filled with dominantly mafic volcanic and sedimentary rocks outcropping near Lake Superior (Figure 1; Allen, Hinze, & Dickas, 1997; Cannon et al., 1989; Hinze et al., 1992; Stein, Kley, Stein, Hindle, & Keller, 2015; Stein et al., 2014, 2018; Swanson-Hysell, Ramezani, Fairchild, & Rose, 2019). The Keweenawan Supergroup (Figure 2), defined as rocks associated with the MCR, are exposed around Lake Superior and dip and thicken toward the rift's centre (Green et al., 1989). Regional magmatic activity started at c. 1,150 Ma (Heaman et al., 2007). Extension forming the MCR occurred c. 1,120–1,096 Ma (Stein et al., 2015), with most volcanism between c. 1,107 and 1,083 Ma (Fairchild, Swanson-Hysell, Ramezani, Sprain, & Bowring, 2017; Paces & Miller, 1993; Vervoort, Wirth, Kennedy, Sandland, & Harpp, 2007).

## 3 | METHODOLOGY

Jacobsville samples were collected from 15 localities in Michigan, USA and Ontario, Canada (Table 1; Figure 1). The details of the analytical methodologies at the Arizona Laserchron Center are provided in Data S1 and data tables.

**TABLE 1** Summary of sample locations, type signatures and zircon ages

| Sample | Location | Type | *n* | Oldest | Youngest | Age peaks |
|---|---|---|---|---|---|---|
| Caribou Island | 47.351963°, −85.823202° | Type 5 | 78 | 2,894 | 1,013 | 1,459 |
| Alona Bay | 47.177901°, −84.699796° | Type 5 | 114 | 2,312 | 1,059 | 1,165, 1,326, 1,471, 1,658 |
| Batchawana Bay | 46.907673°, −84.596561° | Type 5 | 148 | 2,767 | 1,109 | 1,456, 1,214, 1,678 |
| Echo Bay | 46.421508°, −84.191315° | Type 5 | 102 | 2,516 | 1,060 | 1,181, 1,456 |
| Munising | 46.438354°, −86.815226° | Type 5 | 302 | 2,940 | 1,026 | 1,461 |
| Deer Lake | 46.480834°, −86.957008° | Type 5 | 213 | 2,746 | 1,064 | 1,440, 1,262 |
| Au Sable Point | 46.665616°, −86.167460° | Type 5 | 308 | 1,707 | 954 | 1,456 |
| Gogebic | 46.587633°, −89.598991° | Type 4 | 183 | 3,283 | 998 | 1,108 |
| Hubble | 47.202926°, −88.429873° | Type 4 | 210 | 2,747 | 961 | 1,104, 1,332, 1,448 |
| Jacobsville Quarry | 46.979887°, −88.412679° | Type 4 | 107 | 2,516 | 1,021 | 1,392, 1,100, |
| Traverse Bay | 47.149965°, −88.232764° | Type 3 | 302 | 3,397 | 1,038 | 1,101, 1,883, 2,682, 1,355 |
| Sturgeon Falls | 46.642669°, −88.694305° | Type 3 | 107 | 2,974 | 1,076 | 1,886, 2,660 |
| Bruce Crossing | 46.535077°, −89.178380° | Type 3 | 212 | 3,005 | 967 | 1,882 |
| L'Anse | 46.749131°, −88.476523° | Type 2 | 104 | 2,656 | 976 | 1,194 |
| Little Presque Isle | 46.584420°, −87.385236° | Type 2 | 105 | 2,701 | 933 | 1,086, 1,176 |
| Big Erick's Bridge | 46.864944°, −88.082820° | Type 1 | 107 | 3,339 | 1,183 | 2,692 |

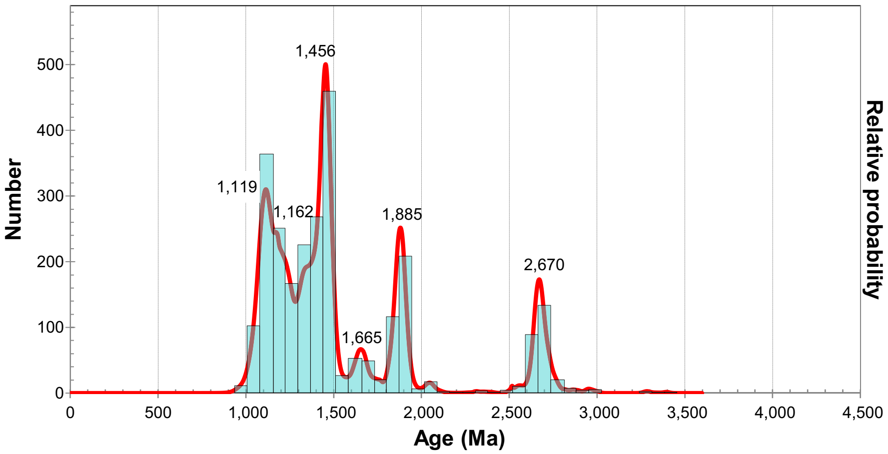


**FIGURE 3** Combined Jacobsville frequency plot for all sites and all analysis ($s$ = 16, $n$ = 2,702) indicating modal age peaks

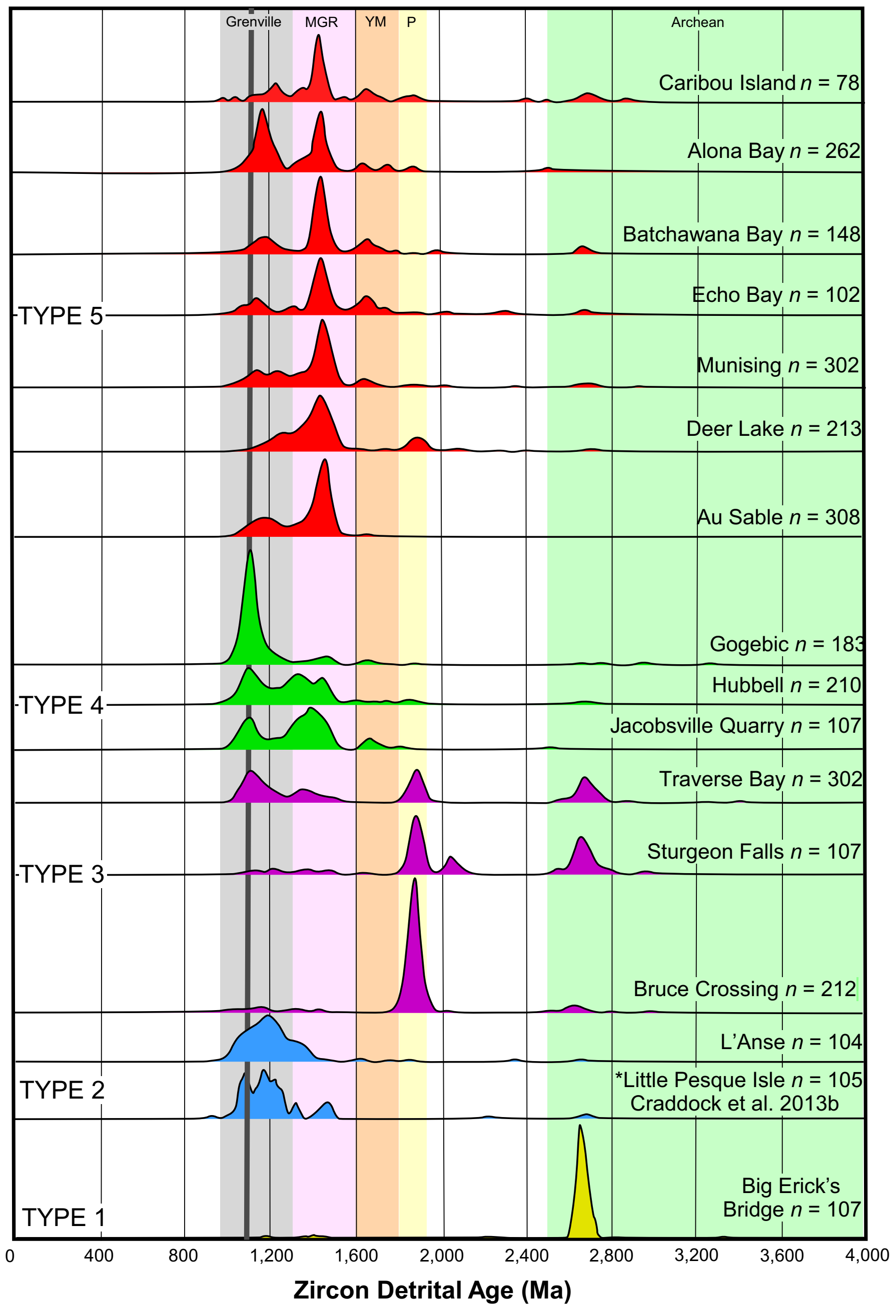


**FIGURE 4** Stacked probability plots (area beneath each curve is the same) of Jacobsville detrital zircon age spectra for the various sampling localities. Dark vertical line within the Grenville interval indicates age of MCR volcanism, GRP, Granite-Rhyolite province; P = Penokean Terrane; YP, Yavapai-Mazatzal terranes

## 4 | RESULTS

The cumulative histogram and frequency plot of all Jacobsville Sandstone detrital zircon ages are shown in Figure 3. Figure 4 shows the detrital zircon age frequency plots for each sample. The Type 1 signature, which is present only at Big Erick, MI is characterized by the nearly exclusive abundance of Superior province zircons (~2.7 Ga). The Type 2 signature consists of dominantly Grenville-age zircons, with all other age groups comprising less than 20% of the population and occur in Basal Jacobsville samples from L'Anse and Little Presque Isle (Craddock, Rainbird, et al., 2013). The Type 3 signature shows the highest proportion of Penokean-age grains, and is evident at Bruce Crossing, Sturgeon Falls, and Traverse Bay. Both Traverse Bay and Sturgon Falls have a smaller Superior Province age peak, and Traverse Bay also includes MGR and Grenville-age peaks, which are more evident in the Type 5 signature. The Type 4 signature is present in the Hubble, Jacobsville Quarry and Gogebic samples. These are the westernmost Jacobsville samples and occur near the top of the section in footwall of the Keweenaw thrust. This signature includes a dominant ~1,100 Ma (Keweenaw) age peak. Hubble and Quarry also include Grenville and MGR age peaks, and Quarry includes a small Mazatzal peak. The Type 5 signature is defined by a prominent early MGR (~1.45 Ma) age peak, and a paucity of Archaean zircons and moderate proportions of Grenville and Mazatzal zircons. This signature is evident at Au Sable, Deer Lake (which also has a small Penokean Peak), Munising, Echo Bay, Batchawana Bay, Alona Bay and Caribou Island samples. These are the easternmost and uppermost of the sample localities.

## 5 | DISCUSSION

The five type signatures indicate an evolution of provenance during Jacobsville deposition succession in space and time (Figures 5 and 6). Here we examine the distribution of zircon ages with sources and how the Jacobsville's provenance compares to that of other sedimentary rocks in the region. Then we consider whether the zircons came directly from their crystalline rocks or were recycled. Lastly, we consider why renewed sedimentation occurred.

Early Jacobsville sedimentation (Type 1) was derived from local basement rocks. Type 1 is confined to the lowest metre of the Jacobsville, where the Jacobsville occurs as joint infillings above the unconformity with local Animikie and Archaean basement rocks.

Type 2 rocks represent sources as much as 1,000 km away, with most zircons older than the MCR but younger than 1,300 Ma coming from Grenville-age rocks, with a lesser amount from the GRP. Some zircons between about 1,109 and 1,083 Ma probably come from MCR igneous rocks (as suggested by the peak for site #2), and others for these ages and younger probably come from the Grenville event.

Type 3, defined by a prominent Penokean peak, generally occur in the southernmost samples, which are among the stratigraphically lowest samples in this suite. This peak indicates sediment transport from ~100 to 200 km to the south if these zircons were derived directly from Penokean plutonic rocks.

Type 4 reflects a provenance dominated by ~1,100 Ma zircons eroded from MCR volcanic rocks, perhaps deposited in alluvial fans at the mouths of high energy streams that dissected the Keweenaw reverse fault's hangingwall (Craddock, Malone, et al., 2017). The proportion of these zircons increases with proximity to the fault and higher in the stratigraphic succession (Figures 5 and 6) indicating active faulting contemporary with deposition. Faulting also occurred after deposition because the Jacobsville is deformed (Craddock, Malone, et al., 2017). Further from the fault, the proportion of easterly derived Grenville and GRP zircons increases.

Type 5, defined by the prominent ~1,450 Ma peak from GRP and more Yavapai-Mazatzal age zircons, occurs in the eastern sites of the upper Jacobsville. It may represent a second influx of distally derived sand from the Grenville orogen, but in lower volumes.

### 5.1 | Directly from the primary location or recycled?

Archaean zircons are abundant in early Palaeozoic arenites in the Laurentian midcontinent (Konstantinou et al., 2014), Mesoproterozoic Baraboo interval quartzites in Wisconsin (Medaris et al., 2003; Stewart et al., 2018; Van Wyck & Norman, 2004) and Palaeo-Mesoproterozoic clastic rocks in the Lake Superior area such as the Huron (c. 2,400–2,200 Ma) and Animikie (slates and metagraywackes; c. 2,200–1,800 Ma) sedimentary basins, and the Oronto Group (Craddock, Konstantinou, et al., 2013; Craddock, Rainbird, et al., 2013). Thus, Archaean zircons, especially for Types 3 and 5, may come from erosion of sedimentary rocks, rather than directly from the older crystalline rocks.

We find that the Jacobsville's zircon age distribution differs from that observed elsewhere for sedimentary rocks in North America's

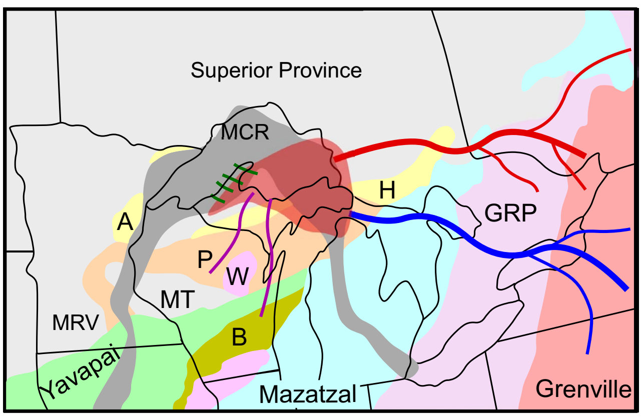


**FIGURE 5** Source areas for the Jacobsville sandstone and reconstruction of interpreted palaeodrainage patterns for the Lake Superior region. The locations of the source terranes are indicated. A, Animikie basin; B, Baraboo interval quartzites; H, Huron basin; MT, Marshfield Terrane; P, Penokean Belt; W, Wolf River Batholith. Type 2 river systems are in blue, Type 3 river systems are in purple, Type 4 river systems are in green and Type 5 river systems are in red

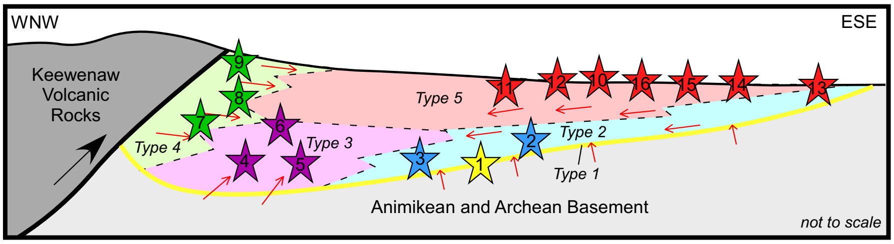


**FIGURE 6** Schematic cross-section (not to scale) of the distribution of the five provenance types of the 16 sites. Stars represent the sample locations

interior derived from the Grenville orogeny, such as Middle Run and equivalent sandstones in Ohio and Kentucky (Baranoski, Dean, Wicks, & Brown, 2009; Santos et al., 2002), in the Amundsen and Mackenzie basins of northwest Canada (Rainbird et al., 2017), and in the Hazel Formation of Texas (Spencer, Prave, Cawood, & Roberts, 2014). The Jacobsville has a relatively small percentage of zircons from the Ottawa (1,090–1,030 Ma) phase, but a larger percentage of Shawinigan (1,200–1,140 Ma), like rocks from southwestern Laurentia (Mulder et al., 2017) and Kentucky (Moecher, Bowersox, & Hickman, 2018), and perhaps the Middle Run. In contrast, there is a large Ottawa peak and a smaller Shawinigan peak for rocks in the Amundsen and Mackenzie basins of northwest Canada.

Presently we cannot determine if the Grenville-age zircons in the Jacobsville came directly from the orogen, were recycled from Grenville foreland basin strata and then transported to the Lake Superior area, or from older Keweenawan Oronto Group sedimentary rocks. Similarly, it is unclear why the last ~ 100 million years of the Grenville orogeny is not as well represented in the zircon record compared to earlier phases of the orogeny. Explanations include timing of erosion, river transport largely bypassing the mid-U.S. (Moecher et al., 2018) or the Ottawa phase for southern part of the orogeny had a significantly lower zircon fertility and was different from Grenville source areas to the north.

### 5.2 | Renewed sedimentation?

Why were Jacobsville sediments deposited? Although it is tempting to consider the Jacobsville as filling the last space of the thermally subsiding MCR basin, the Jacobsville is at least 140 million years younger than the end of the rift's extension and likely post-dates thermal subsidence. Thus, it is more likely that events outside the MCR region facilitated Neoproterozoic deposition. For example, dynamic topography can change elevations and river drainage patterns (Wang, Gurnis, & Skogseid, 2019). Locally, faulting could have provided topographic lows for deposition.

## 6 | CONCLUSIONS

The detrital zircon provenance of the Neoproterozoic Jacobsville sandstone initially reflected internal drainage into the failed Midcontinental Rift (MCR) basin from regional sources, with the earliest deposition largely eroded from local basement rocks. The next influx of Jacobsville sediment was mainly derived from distal Grenville orogeny sources. The Grenville influx was followed by sediment from nearby areas to the south including Penokean volcanic and plutonic rocks and overlying Palaeo- and Mesoproterozoic quartzites. Reverse motion on the Keweenaw fault exposed MCR basalts that shed sediment into alluvial fans in the fault's footwall. The final Jacobsville sediment flux is dominated by zircons from distal Granite and Rhyolite Provence to the east. Only a relatively small percentage of c. 1,090–980 Ma Grenville-age zircons from collisions to the east is present, suggesting that they were not efficiently transported towards the Lake Superior area.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

**Data S1.** Methodology.

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