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Final inversion of the Midcontinent Rift during the Rigolet Phase of the Grenvillian Orogeny

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ABSTRACT

Despite being a prominent continental-scale feature, the late Mesoproterozoic North American Midcontinent Rift did not result in the break-up of Laurentia, and subsequently underwent structural inversion. The timing of inversion is critical for constraining far-field effects of orogenesis and processes associated with the rift's failure. The Keweenaw fault in northern Michigan (USA) is a major thrust structure associated with rift inversion; it places ca. 1093 Ma rift volcanic rocks atop the post-rift Jacobsville Formation, which is folded in its footwall. Previous detrital zircon (DZ) U-Pb geochronology conducted by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) assigned a ca. 950 Ma maximum age to the Jacobsville Formation and led researchers to interpret its deposition and deformation as postdating the ca. 1090–980 Ma Grenvillian Orogeny. In this study, we reproduced similar DZ dates using LA-ICP-MS and then dated 19 of the youngest DZ grains using high-precision chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS). The youngest DZ dated by CA-ID-TIMS at 992.51 ± 0.64 Ma (2σ) redefines the maximum depositional age of the Jacobsville Formation and overlaps with a U-Pb LA-ICP-MS date of 985.5 ± 35.8 Ma (2σ) for late-kinematic calcite veins within the brecciated Keweenaw fault zone. Collectively, these data are interpreted to constrain deposition of the Jacobsville Formation and final rift inversion to have occurred during the 1010–980 Ma Rigolet Phase of the Grenvillian Orogeny, following an earlier phase of Ottawan inversion. Far-field deformation propagated >500 km into the continental interior during the Ottawan and Rigolet phases of the Grenvillian Orogeny.

INTRODUCTION

The late Mesoproterozoic Midcontinent Rift (MCR) is a prominent tectonomagmatic feature that extends >2000 km through the Laurentia craton (Fig. 1; Ojakangas et al., 2001; Woodruff et al., 2020). In the vicinity of Lake Superior, there is a well-exposed >10-km-thick succession of ca. 1110–1083 Ma rift-related volcanic rocks overlain by >4 km of post-rift sedimentary strata (Cannon, 1992; Swanson-Hysell et al., 2019). Given the significant lithospheric thinning associated with rifting (Behrend et al., 1988), an outstanding question is why the rift did not lead to the break-up of Laurentia. A leading hypothesis is that cessation of extension occurred due to far-field compressional stresses associated with the ca. 1090–980 Ma Grenvillian Orogeny (Cannon and Hinze, 1992; Cannon, 1994). Following rifting and an interval of post-rift thermal subsidence, the MCR underwent structural inversion with crustal-scale folding and reverse faulting (Fig. 1; Cannon et al., 1993). However, the timing of inversion is disputed. It has been proposed that this inversion occurred during the Ottawan Phase (ca. 1090–1030 Ma; Cannon, 1994) or during the Rigolet Phase (ca. 1010–980 Ma; Swanson-Hysell et al., 2019) of the Grenvillian Orogeny, or during post-Grenvillian Appalachian compression (Craddock et al., 2013; Malone et al., 2016).

The timing of rift inversion may provide geodynamic insight into the cessation of rift development and constrain links to episodes of orogenesis. However, existing geochronological constraints are too imprecise to resolve this history and have led to conflicting interpretations. Interpretations of regional inversion during the Ottawan Phase of the Grenvillian Orogeny have relied on low-precision Rb-Sr dates of uplifted basement lithologies (Cannon et al., 1993) and secondary minerals that precipitated from fluids whose migration may be associated with inversion (Ruiz et al., 1984; Bornhorst et al., 1988). Low-precision U-Pb detrital zircon (DZ) geochronology from the Jacobsville Formation has been interpreted to provide a maximum depositional age of ca. 950 Ma (Craddock et al., 2013; Malone et al., 2016), suggesting that the final rift inversion that folded Jacobsville strata in the footwall of the Keweenaw fault postdated the Grenvillian Orogeny. We provide new geochronological constraints to evaluate linkages between MCR inversion and Grenvillian orogenesis. Specifically, we constrain the timing of the latest significant motion on the Keweenaw fault with a high-precision maximum depositional age for the Jacobsville Formation combined with direct U-Pb ages for syn- to post-kinematic calcite that precipitated within the fault zone.

GEOLOGICAL BACKGROUND

Stratigraphy

Along the south shore of Lake Superior, MCR strata were deposited unconformably on Paleoproterozoic basement rocks. Lower MCR strata consist of >10 km of ca. 1108–1083 Ma rift-related volcanic rocks (Cannon, 1992, Swanson-Hysell et al., 2019). Rift volcanics are conformably overlain by >4 km of conglomerate, siltstone, and sandstone of the Oronto Group (Cannon et al., 1995, 1996), interpreted to have been deposited during post-rift thermal subsidence (Cannon, 1992). Overlying the Oronto Group are sandstone-dominated fluvial sediments of the Jacobsville Formation whose thickness can exceed 1 km (Kalliokoski, 1982).

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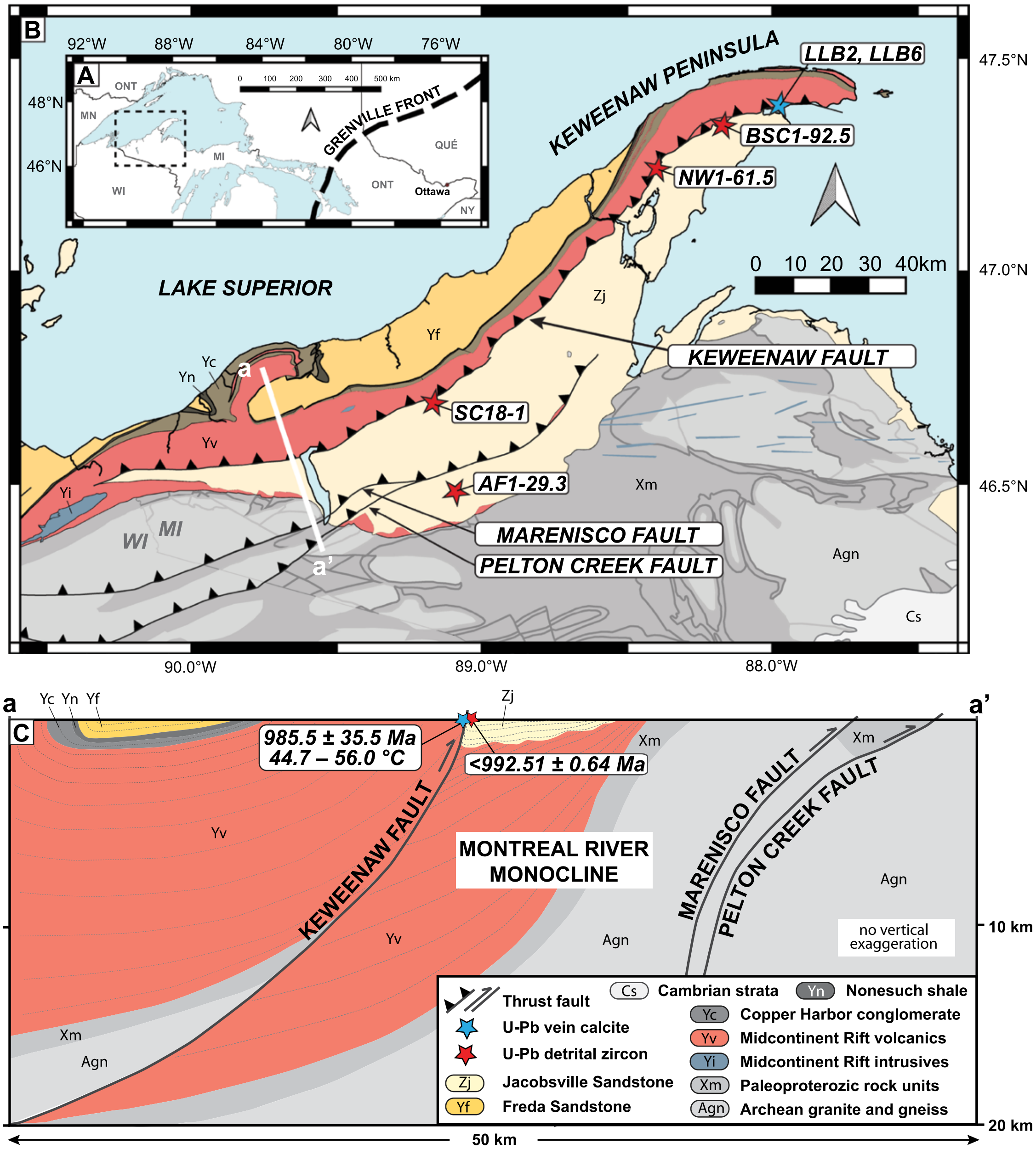

Figure 1. Geologic map and cross section of part of the North American Midcontinent Rift. (A) Regional map showing location of the Grenville Front relative to the study area. (B) Geologic map of northern Michigan and Wisconsin showing geochronology sample locations, major thrust faults, and location of cross section (a–a′) shown in C. (C) Montreal River Monocline cross section, modified after Cannon et al. (1993). Annotations provide a fault calcite date and clumped-isotope temperature estimates from the Keweenaw fault and a maximum age constraint for the Jacobsville Formation derived from the youngest detrital zircon dated by chemical abrasion–isotope dilution–thermal ionization mass spectrometry in the fault's footwall. Dates shown on the cross section are from sites off the section at similar positions relative to the fault.

An angular unconformity between the Oronto Group and the overlying Jacobsville Formation has been interpreted from seismic data beneath Lake Superior (Cannon et al., 1989). Onshore in northern Michigan (USA), the Jacobsville Formation directly overlies MCR volcanic rocks, as well as Archean and Paleoproterozoic basement, in angular unconformity (Fig. 1; Hamblin, 1958; Kalliokoski, 1982). The Jacobsville Formation is unconformably overlain by the Cambrian Munising Formation (Hamblin, 1958).

Structure

The Keweenaw fault is a north- to northwest-dipping thrust that juxtaposes MCR volcanics atop the Jacobsville Formation, and extends ~250 km from the tip of the Keweenaw Peninsula in Michigan southeastward to a termination in northeastern Wisconsin (Fig. 1; Cannon et al., 1996; Cannon and Nicholson, 2001; DeGraff and Carter, 2022). Thrust faults parallel to the Keweenaw fault include the Marenisco and Pelton Creek faults (Fig. 1). Similarly oriented thrust faults continue southwestward through northern Wisconsin (Ojakangas et al., 2001) and possibly eastward below Lake Superior toward Ontario, where there are also faults that thrust MCR volcanics atop post-rift sandstone (Manson and Halls, 1994). The typically shallowly dipping Jacobsville Formation has sub-vertical to overturned beds in the immediate footwall of the Keweenaw fault (Irving and Chamberlin, 1885; Cannon and Nicholson, 2001).

Deposition of the Jacobsville Formation predated final motion of the Keweenaw fault but postdated development of the crustal-scale Montreal River monocline that folded rift-related volcanic and sedimentary rocks in the hanging wall of the Marenisco thrust fault (Fig. 1; Cannon et al. 1993). The Jacobsville Formation overlies an erosional angular unconformity that developed on lithologies that were exhumed through this earlier reverse motion on the Marenisco fault (Fig. 1; Cannon et al., 1993). Biotite extracted from Archean granites and gneisses in the hanging wall of the Marenisco fault yield ca. 1060–1040 Ma Rb-Sr dates (Cannon et al., 1993) which were interpreted to represent cooling ages associated with ~25 km of crustal exhumation during the Ottawan Phase of the Grenvillian Orogeny. This contraction is interpreted to have uplifted and tilted MCR volcanics and the sedimentary rocks of the Oronto Group prior to deposition of the Jacobsville Formation and subsequent motion on the Keweenaw fault (Fig. 1).

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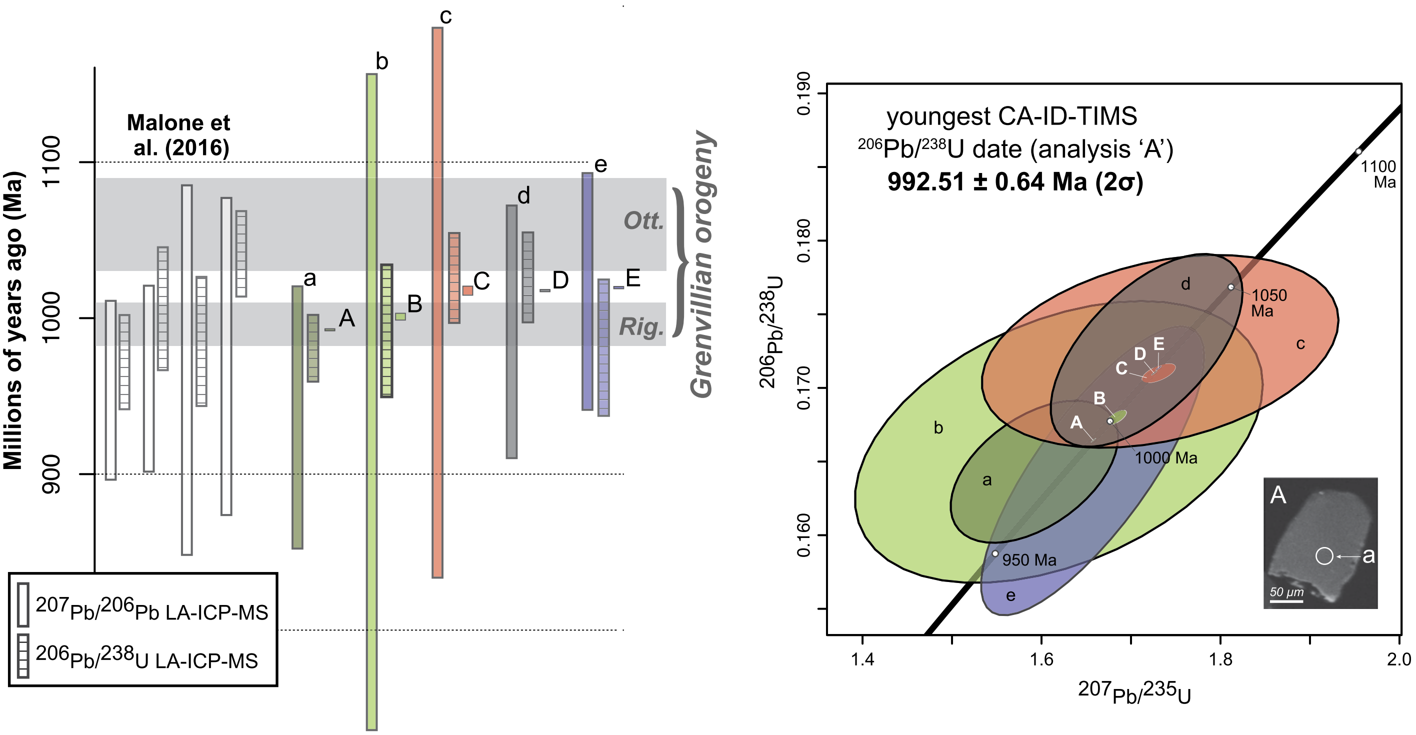

Figure 2. Results of paired dates determined by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) and chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS) for the five youngest detrital zircon (DZ) grains from the Jacobsville Formation (Great Lakes region of North America) analyzed in this study and compared to the four youngest LA-ICP-MS dates from Malone et al. (2016). The five DZ grains (A–E) shown in the age rank plot (left) and in the Concordia plot (right) are (A) sample SC18–1–z1 (cathodoluminescence image is displayed at bottom right); (B) AF1–29.3–z2; (C) AF1–29.3–z6; (D) SC18–1–z4; and (E) SC18–1–z11. Paired analyses are shown for each grain with the low-precision LA-ICP-MS dates labeled in lowercase and the paired high-precision ^{206}Pb/^{238}U CA-ID-TIMS dates in uppercase. Ott.—Ottawan Phase, Rig.—Rigolet Phase.

METHODS AND RESULTS

Detrital Zircon U-Pb Geochronology

We collected four sandstone samples of the Jacobsville Formation for DZ geochronology. Three samples were taken from outcrops within the footwall of the Keweenaw fault (Fig. 1). We used paired U-Pb DZ dating to develop accurate and precise dates on the youngest DZ grains by combining two techniques: laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) to rapidly screen many DZ grains, followed by chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS) on the youngest grains (Fig. 2; see the Supplemental Material[1] and Table S1 therein for detailed methods). A total of 1011 DZ LA-ICP-MS analyses resulted in 881 concordant dates. We selected 19 DZ grains with the youngest concordant LA-ICP-MS dates (ca. 1050–950 Ma) for more accurate and precise CA-ID-TIMS dating (Fig. 2; Table S2). Five DZ grains were broken into multiple fragments yielding a total of 25 CA-ID-TIMS analyses. The results are as follows: sample AF1–29.3 (46.48046°N, 89.09026°W) yielded six CA-ID-TIMS ^{206}Pb/^{238}U dates ranging from 1073 Ma to 1003 Ma; sample SC18–1 (46.69132°N, 89.16658°W) yielded 16 CA-ID-TIMS ^{206}Pb/^{238}U dates ranging from 1096 Ma to 992 Ma; and sample NW1–61.5 (47.24115°N, 88.39647°W) yielded three CA-ID-TIMS ^{206}Pb/^{238}U dates ranging from 1090 Ma to 1082 Ma. Reported with 2σ analytical uncertainty, the five youngest DZ grains dated by CA-ID-TIMS are 1019.58 ± 0.73 Ma, 1017.71 ± 0.69 Ma, 1017.67 ± 2.95 Ma, 1003.21 ± 2.23 Ma, and 992.51 ± 0.64 Ma. CA-ID-TIMS and LA-ICP-MS dates from the same zircon crystals are compared in Figure 2 and Table S3.

Calcite U-Pb Geochronology and Clumped-Isotope Thermometry

Abundant sparry calcite veins are present in brecciated subophitic basalt of the Portage Lake Volcanics within the Keweenaw fault zone near the town of Lac La Belle (Fig. 3). These veins cross-cut a dense anastomosing network of slickensides and zeolite veins within the fault breccia (Figs. 3A–3D) and themselves experienced some deformation within the fault zone. We interpret these relationships to indicate that calcite formed after dilation and emplacement of zeolite veins but before the cessation of fault movement, making the calcite veins late syn-kinematic. We collected nine samples of vein calcite crystals for U-Pb LA-ICP-MS geochronology. After initial screening, three samples were selected for follow-up LA-ICP-MS analysis using an ~110 μm spot size (Kylander-Clark, 2020), and two samples yielded sufficiently variable concentrations of U to calculate isochron-based U-Pb dates (Fig. 3E; Fig. S3, Table S4; Vermeesch, 2018). The results are 985.5 ± 35.8 Ma (2σ; mean standard weighted deviation [MSWD] 0.76, n = 96/96) for sample LLB2 (47.38929°N, 87.97621°W), and 1020.2 ± 98.8 Ma (2σ; MSWD = 1.2, n = 93/97) for sample LLB6 (47.38891°N, 87.97903°W). Calcite from these two samples was also analyzed for carbonate clumped isotopes (Δ_{47}) to gain insight into formation temperatures. Three replicate (Δ_{47}) analyses for each sample yielded Δ_{47}-based temperatures of 56.0 ± 4.6°C and 44.7 ± 1.9°C (1 standard error [s.e.]) for LLB2 and LLB6, respectively (Fig. 1; Table S5).

DISCUSSION

Previous U-Pb DZ geochronology based on low-precision LA-ICP-MS analyses was interpreted to indicate that the Jacobsville Formation has a maximum depositional age of ca. 950 Ma, implying that it postdated the 1090–980 Ma

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[1] Supplemental Material. Detailed methods, Tables S1–S5 and Figures S1–S3. Please visit https://doi.org/10.1130/GEOL.S.18737453 to access the supplemental material, and contact editing@geosociety.org with any questions.

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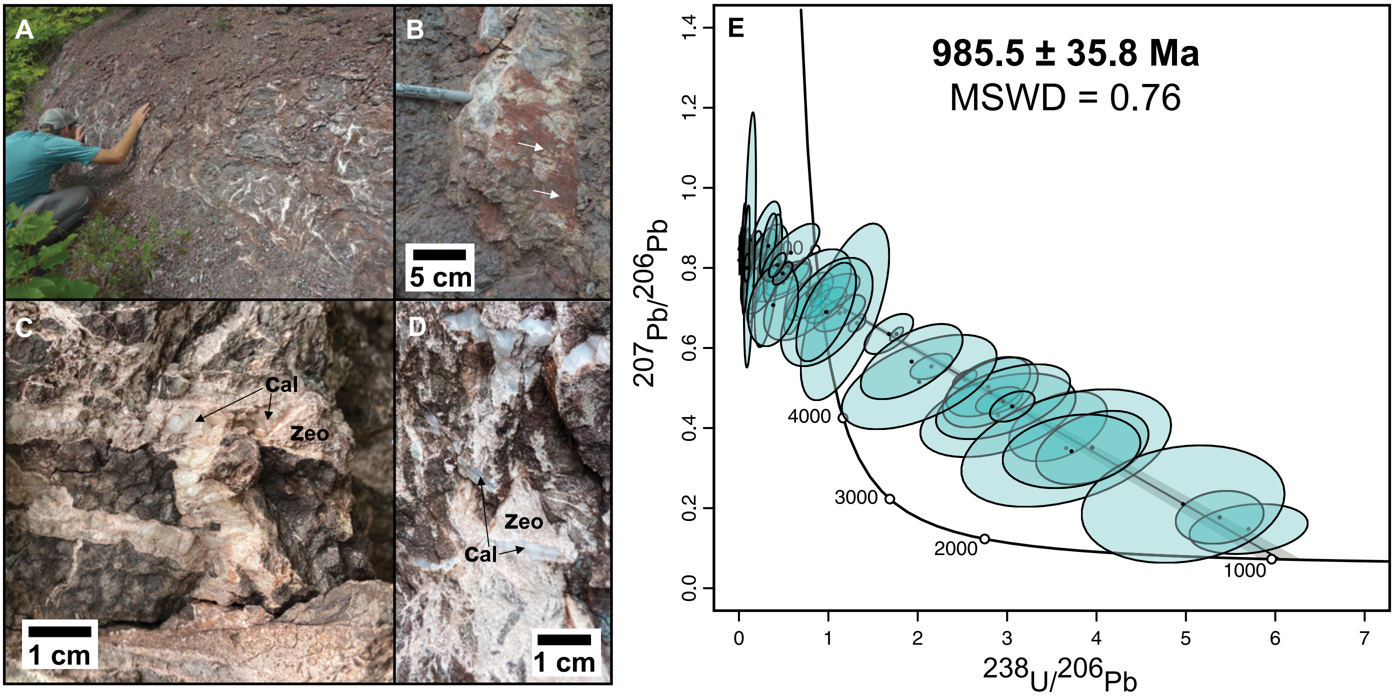

Figure 3. Field relationships of Keweenaw fault vein calcite and U-Pb geochronology. (A) Outcrop of vein calcite within brecciated Portage Lake volcanic host rock in the Keweenaw fault zone. (B) Vein calcite sampled as LLB6 with slickensides indicated by white arrows. (C) Sample LLB2 vein calcite cross-cutting older zeolite veins within brecciated ophitic basalt. (D) Slightly deformed vein calcite cross-cutting zeolite veins indicating late kinematic timing of calcite precipitation with respect to Keweenaw fault motion. Calcite (Cal) and zeolite (Zeo) are identified with black arrows. (E) Tera-Wasserburg plot of laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) U-Pb data from calcite sample LLB2. Lower intercept date of 985.5 ± 35.8 Ma (2σ) was determined from 96 LA-ICP-MS analyses with an unanchored upper intercept that gives an initial ^{207}Pb/^{206}Pb composition of 0.8495 ± 0.0040 (2σ). MSWD—mean square of weighted deviates.

Grenvillian Orogeny (Fig. 2; Craddock et al., 2013; Malone et al., 2016). We also obtained LA-ICP-MS ages of ca. 950 Ma, but then determined a more accurate and precise maximum depositional age with CA-ID-TIMS analyses of the same crystals. We interpret the youngest concordant CA-ID-TIMS DZ age of 992.51 ± 0.64 Ma to constrain deposition of the upper Jacobsville Formation and final motion of the Keweenaw fault to have occurred after ca. 993 Ma. These tandem DZ dates illustrate that the younger LA-ICP-MS dates are attributable to greater analytical uncertainty and persistent Pb loss relative to the CA-ID-TIMS dates (Fig. 2; Table S3), which likely affected previous LA-ICP-MS data. Our results indicate that the Jacobsville Formation could have been deposited during the Rigolet Phase of the Grenvillian Orogeny, which occurred from ca. 1010–980 Ma (Krogh, 1994; Rivers et al., 2012). A timing of deposition near the maximum depositional age is consistent with interpretations that the Jacobsville Formation is syn-tectonic and was deposited during active shortening (Kalliokoski, 1982; Brojanigo, 1984; Hedgman, 1992; Cannon et al., 1993).

The timing of movement on the Keweenaw fault is constrained by calcite veins within brecciated basalt in the hanging wall for which the most robust U-Pb calcite isochron yields an LA-ICP-MS date of 985.5 ± 35.8 Ma (Figs. 1 and 3; sample LLB2), which is supported by a less precise isochron date of 1020.2 ± 98.8 Ma (sample LLB6; Fig. S3). While these dates have relatively low precision, they support fault motion during the Grenvillian Orogeny. The clumped-isotope temperature estimates of ~50°C indicate that the calcite formed at shallow depth. We consider this to be a maximum formational temperature as post-depositional reordering due to heating would only raise the temperature (Passey and Henkes, 2012; Stolper and Eiler, 2015). Assuming a geothermal gradient of 25–30°C/km would imply that this late kinematic calcite formed within 1 km of the surface. The inferred shallow setting is consistent with calcite precipitation during late kinematic motion as the hanging wall of basalt was thrust onto recently deposited sediments of the Jacobsville Formation.

Taken together, the updated maximum depositional age for the Jacobsville Formation (992.51 ± 0.64 Ma) and the new date for late kinematic calcite within the Keweenaw fault zone (985.5 ± 35.8 Ma) are interpreted to constrain deposition of the upper Jacobsville Formation and its subsequent deformation by motion of the Keweenaw fault to a narrow time window. Our results suggest that Jacobsville deposition was ongoing during a compressional regime that overlapped with the Rigolet Phase of the Grenvillian Orogeny (1010–980 Ma; Krogh, 1994). We interpret the temporal coincidence of Keweenaw fault motion with the Rigolet Phase to indicate a tectonic relationship between formation of the Grenville Front (Fig. 1; Rivers et al., 2012) and deformation >500 km to the west within the orogenic foreland.

Given that the distance of the Jacobsville Formation depocenter from the Grenville Front is consistent with backbulge subsidence (DeCelles, 2012), we speculate that the Jacobsville Formation may have been deposited in a Grenvillian foreland basin system that resulted from lithospheric flexure induced by orogenic loading (Rivers et al., 2012). This deposition could be part of the same foreland basin system that is interpreted to have accommodated strata deposited closer to the Grenville Front, such as the Middle Run Formation that occurs beneath Paleozoic cover in Ohio and Kentucky, USA (Santos et al., 2002; Moecher et al., 2018; Peterman et al., 2020; Clay et al., 2021).

CONCLUSION

By pairing LA-ICP-MS and CA-ID-TIMS DZ U-Pb geochronology with calcite LA-ICP-MS U-Pb geochronology, we have constrained late-stage inversion of the MCR during the Rigolet Phase of the Grenvillian Orogeny. Compressional deformation also occurred prior to deposition of the Jacobsville Formation as it unconformably overlies exhumed, tilted, eroded, and weathered units of the MCR and

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older basement rocks (Fig. 1; Hamblin, 1958; Cannon et al., 1993). We conclude that cessation of rift-related extension in the MCR was likely caused by far-field effects during the earlier Ottawan Phase (Cannon et al., 1993; Cannon, 1994). The inversion of the MCR was likely a two-stage process involving far-field crustal shortening during both the Ottawan and Rigolet Phases of the Grenvillian Orogeny.

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