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Grooving in the midcontinent: A tectonic origin for the mysterious striations of L'Anse Bay, Michigan, USA

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ABSTRACT

A striated surface is present at an erosional unconformity between foliated Paleoproterozoic Michigamme Formation and fluvial conglomerate and sandstone of the Neoproterozoic Jacobsville Formation exposed at L'Anse Bay (Michigan, USA). These striations have been interpreted to be the result of ice flow in either the Proterozoic, the Pleistocene, or the modern. Recently, the glacial origin interpretation for this striated surface has been used to argue that it may be related to ca. 717–635 Ma Cryogenian snowball Earth glaciation. This interpretation would make the surface a rare example of a Neoproterozoic glacial pavement, with major chronostratigraphic implications that in turn impose constraints on the timing of intracratonic erosion related to the formation of the Great Unconformity. In this contribution, we present new observations showing that the surface is a tectonic slickenside caused by largely unconformity-parallel slip along the erosional unconformity. We document structural repetition of the Michigamme-Jacobsville contact with associated small-scale folding. The unconformity-parallel slip transitions into thrust faults that ramp up into the overlying Jacobsville Formation. We interpret that the surface records contractional deformation rather than ancient glaciation, recent ice movement, or recent mass wasting. The faulting likely occurred during the Rigolet phase of the Grenvillian orogeny, which also folded the Jacobsville Formation in the footwall of the Keweenaw fault.

■ INTRODUCTION

In a 1955 paper in *GSA Bulletin* (Murray, 1955), Raymond C. Murray reported a striated surface at the southern end of L'Anse Bay (Michigan, USA; Fig. 1) on slate of the Michigamme Formation where it is unconformably overlain by fluvial conglomerate and sandstone of the Jacobsville Formation. Striations, consisting of grooves on a rock surface, can have origins through multiple geologic processes including glaciation (glacial striation) and faulting (slickenside). In a time before Neoproterozoic glaciation was well established, Murray (1955) put forward the provocative hypothesis that the striations were the result of late Precambrian or early Cambrian glaciation. In a comment published the following year, William M. Gussow expressed concern that the study would be accepted as evidence of Precambrian glaciation and argued that the striations were likely the result of modern seasonal ice rafting along the Lake Superior shoreline (Gussow, 1956). Hamblin (1958) also invoked glaciation as being responsible for the striations but through a different mechanism, suggesting that they resulted from drag of rock units by Pleistocene ice sheets. Kalliokoski (1982) suggested that the striations were the result of geologically recent slip along the unconformity toward Lake Superior associated with mass wasting and highlighted that this explanation would remove the conundrum of low-latitude glaciation that would be implied by the interpretation of Murray (1955).

While subsequent research referring to the striations reported by Murray (1955) has largely favored his glacial interpretation for their origin, few have presented additional observations. Wilson (1991) even reported that the exposure of the striated surface was gone due to lakeshore erosion. While there is active erosion along the shoreline, this conclusion was erroneous given that the locality is included as a field-trip stop in a Bornhorst and Rose (1994) guidebook. Bornhorst and Rose (1994) highlighted the potential explanations of the striations as being the result of ancient glaciation (attributed to Murray, 1955) and recent mass wasting (attributed to Kalliokoski, 1982).

Now that Neoproterozoic glaciation is well established (e.g., Hoffman et al., 1998; Evans and Raub, 2011), these striations have been tentatively suggested to be caused by Cryogenian low-latitude glaciation (Malone et al., 2016). An alternative proposal was also put forward that the striated surface could be the result of an otherwise undocumented pre-Cryogenian (ca. 900 Ma during the Tonian Period) glaciation (Craddock et al., 2013).

Given the implications of a preserved Proterozoic glacial pavement, we sought to carry out a detailed study of the site and develop new observations and data to constrain the origin of the striations. The Lake Superior region contains no other discernable Neoproterozoic glacial record preserved as either glacigenic sediment or glaciated pavement. The presence of a glacially striated Cryogenian surface in the midcontinent of Laurentia would give insight into snowball Earth glacial erosion and processes that led to the development of the Great Unconformity—a topic of much current research interest (Keller et al., 2019; Flowers et al., 2020; Peak et al., 2021; Sturrock et al., 2021; McDannell et al., 2022). Additionally, if the striations originated from snowball Earth glaciation, it would imply that the Jacobsville Formation itself may be Cryogenian in age or younger and that all contractional deformation it experienced post-dated the Grenvillian orogeny (Malone et al., 2016). Relative

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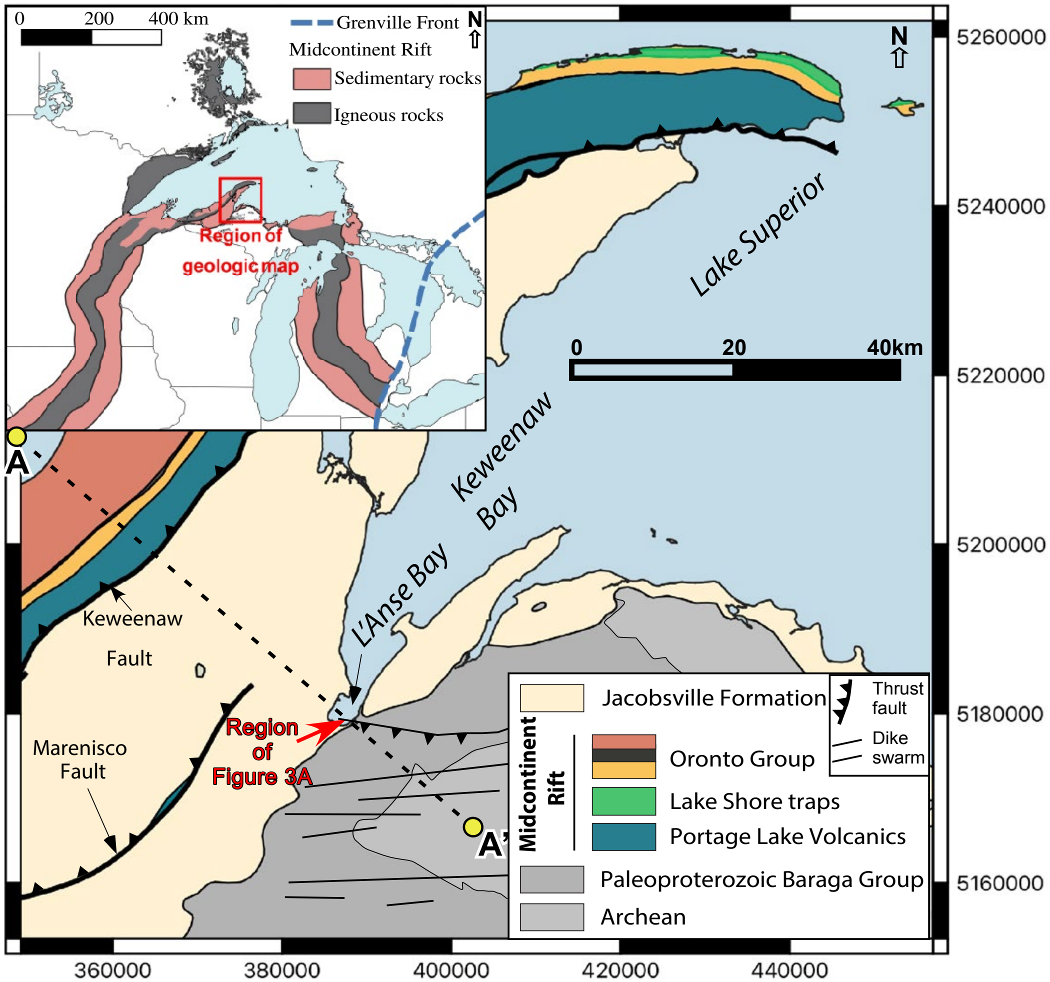

Figure 1. Simplified geologic map of the Keweenaw Peninsula region (Michigan, USA) with units modified from Nicholson et al. (2004). Inset map of the Great Lakes region highlights the position of the study region relative to the Midcontinent Rift and Grenville Front. Location of the study region shown in the aerial photo in Figure 3A is indicated. Coordinates are in meters in Universal Transverse Mercator zone 16N (WGS84 datum).

to their Paleozoic counterparts, Cryogenian striated surfaces are uncommon in the geological record, and it is rare for the surfaces to be readily exposed (Laajoki, 2002, and references therein). Other examples of putative Cryogenian glacial pavements have been reinterpreted as tectonic upon closer examination (Daily et al., 1973; Vandyk et al., 2021). Vandyk et al. (2021) argued that the Mill B North Fork pavement in Utah, USA, is more consistent with being a structurally controlled erosional feature than a Cryogenian glacial pavement. The interpreted glacial origin of striations at L'Anse Bay during the Cryogenian is also deserving of reevaluation given the major implications for the glacial history and chronostratigraphy of the region.

This contribution presents new observations from the southern shore of L'Anse Bay (46.75037°N, 88.473055°W) where, as of July 2021, there are excellent exposures of the unconformity and the striated surface. These new data enable us to reevaluate the origin of the striations.

GEOLOGIC SETTING

The Paleoproterozoic Michigamme Formation and the unconformably overlying Neoproterozoic Jacobsville Formation are the major bedrock lithologies in the study area (Fig. 1). The Michigamme Formation is part of the Paleoproterozoic Baraga Group, which in turn is part of the Marquette Range Supergroup (Morey and Van Schmus, 1988; Nicholson et al., 2004). The Michigamme Formation comprises metasedimentary grayish-green slate and greywacke (Fig. 2A), exhibiting a prominent regional NW-SE-striking foliation with a dip of ~25° toward the SW (Murray, 1955; Klasner, 1978). Elsewhere in the region, units of the Marquette Range Supergroup are overlain by Midcontinent Rift volcanic and sedimentary rocks. The Midcontinent Rift system is a ca. 1.1 Ga continental rift that developed within the interior of Laurentia in which a thick succession of volcanic and sedimentary rocks accumulated that are now well exposed in the Lake Superior region (Fig. 1; Ojakangas et al., 2001; Swanson-Hysell et al., 2019). Following active extension and an interval of post-rift subsidence that led to the deposition of sediments of the Oronto Group, the Midcontinent Rift underwent contractional inversion during the Grenvillian orogeny (Cannon, 1994; Hodgin et al., 2022). This structural inversion led to major reverse faults that have been mapped from integrated field and subsurface geophysical studies (e.g., Cannon and Nicholson, 2001). In particular, the NW-dipping Marenisco and Keweenaw reverse faults (10–30 km west of L'Anse Bay, respectively) accommodated significant contraction (Fig. 1; Cannon et al., 1993).

The Jacobsville Formation unconformably overlies volcanic and sedimentary strata of the Midcontinent Rift as well as older units, such as the Paleoproterozoic Michigamme Formation. The Jacobsville Formation is widely exposed in the study area and is dominated by medium-grained cross-bedded fluvial sandstones (Fig. 2B). The contact with the underlying Michigamme Formation in the study area is marked by a sharp angular unconformity beneath the conglomeratic beds at the base of the Jacobsville Formation (Fig. 2C). The surface of this unconformity shows striations (Fig. 2D) at L'Anse Bay that are the focus of this study.

The Jacobsville Formation has shallowly dipping bedding throughout the study region, with the exception of where it is deformed in the footwall of the Keweenaw fault (Cannon and Nicholson, 2001). Some portions of the formation may have been deposited during faulting (Brojanigo, 1984; Hedgman, 1992; Cannon and Nicholson, 2001; DeGraff and Carter, 2022) associated with deformation that propagated toward the continental interior from the Grenville Front tectonic zone (Hynes and Rivers, 2010; Swanson-Hysell et al., 2019, 2023; Hodgin et al., 2022). That the Jacobsville Formation experienced contractional deformation during the late stages of the Grenvillian orogeny ca. 985 Ma is supported by U-Pb dates on calcite within the Keweenaw fault (Hodgin et al., 2022). Precise U-Pb dating of detrital zircon from the Jacobsville Formation provides an earliest Neoproterozoic maximum depositional age (<992.51 ± 0.64 Ma; Hodgin et al., 2022), which, given the constraints on the timing of deformation from the fault calcite date, is likely close to a true depositional age.

Note that while the Jacobsville Formation is commonly referred to as the Jacobsville Sandstone (e.g., Cannon and Nicholson, 2001), given the presence of minor conglomerate, sandstone, siltstone, and shale, we follow Hamblin (1958) in using "Formation" rather than "Sandstone."

METHODS AND RESULTS

We conducted fieldwork in the Lake Superior region in July 2021 at L'Anse Bay, Michigan (Fig. 1), to investigate the striations. Along the shore of Lake Superior at the southern edge of L'Anse Bay (which itself is the southern extension of Keweenaw Bay; Fig. 1), a 2–3-m-tall cliff exposes foliated slate of the Michigamme Formation overlain by a basal conglomeratic sandstone facies of the Jacobsville Formation along a relatively flat to gently undulating unconformity surface (Figs. 2 and 3). Subangular to rounded clasts in the conglomeratic facies of the Jacobsville Formation range in size from granules to cobbles, and their lithology based on our pebble counts (in order of decreasing abundance) consists of vein quartz, quartzite, iron-formation and/or chert, and angular clasts of slate. The angular slate clasts were locally sourced from the underlying Michigamme Formation. These results are consistent with previous pebble counts at L'Anse (Babcock, 1975) and indicate a provenance from local basement lithologies. Above the basal conglomeratic facies, the Jacobsville Formation is dominated by decimeter-scale cross-stratified medium-grained sandstone (Fig. 2B).

Exposure of the Michigamme-Jacobsville contact occurs just above the July 2021 Lake Superior water level (183.56 m, which is slightly higher than the average water level for the month; NOAA, 2022) and can be traced along the shoreline (Fig. 3B). Along the unconformable contact, a subhorizontal (dip <5°) striated surface is well developed on slate of the Michigamme Formation. The striated surface extends into the outcrop atop the slate and under the Jacobsville Formation, as can be confirmed by excavating the overlying conglomeratic sandstone (Fig. 3C). That the striated plane extends into the outcrop, as observed by Murray (1955), indicates that the striations are a bedrock rather than surficial feature. The striated surface is a slickenside with well-developed slickenlines and slickenfibers (Fig. 3C). Slickenfiber steps consistently indicate a top-to-the-east slip direction with a mean direction of 70° (Fig. 3C). A layer of light green clay ~1 cm thick is atop the slickenside. There are also subhorizontal slickensides within the underlying Michigamme Formation that cross-cut its foliation and are subparallel to the contact (Fig. 3D).

Other structures provide insight into the formation of the striated plane. The most prominent structure at the outcrop is a thrust fault that propagates up from the Michigamme-Jacobsville contact into the overlying fluvial sandstone of the Jacobsville Formation (Fig. 3E). This listric fault has a mean dip direction of 215° and ramps up from subhorizontal to a dip of 40°, leading to tilting of sandstone and conglomerate beds in the hanging wall in contrast to the relatively flat-lying beds in the footwall (Figs. 3E). Like at the Michigamme-Jacobsville contact, there is a centimeter-scale clay-rich layer along the faulted Jacobsville-Jacobsville contact that is consistent with being fault gouge (Fig. 3F). We also observed that the erosional unconformity between the Michigamme Formation and Jacobsville Formation is fault repeated along the contact (Figs. 3G). Associated with this structural repetition are NE-verging decimeter-scale folds and brecciation within the Michigamme Formation slate, which contrasts with the coherent foliation of the slate below

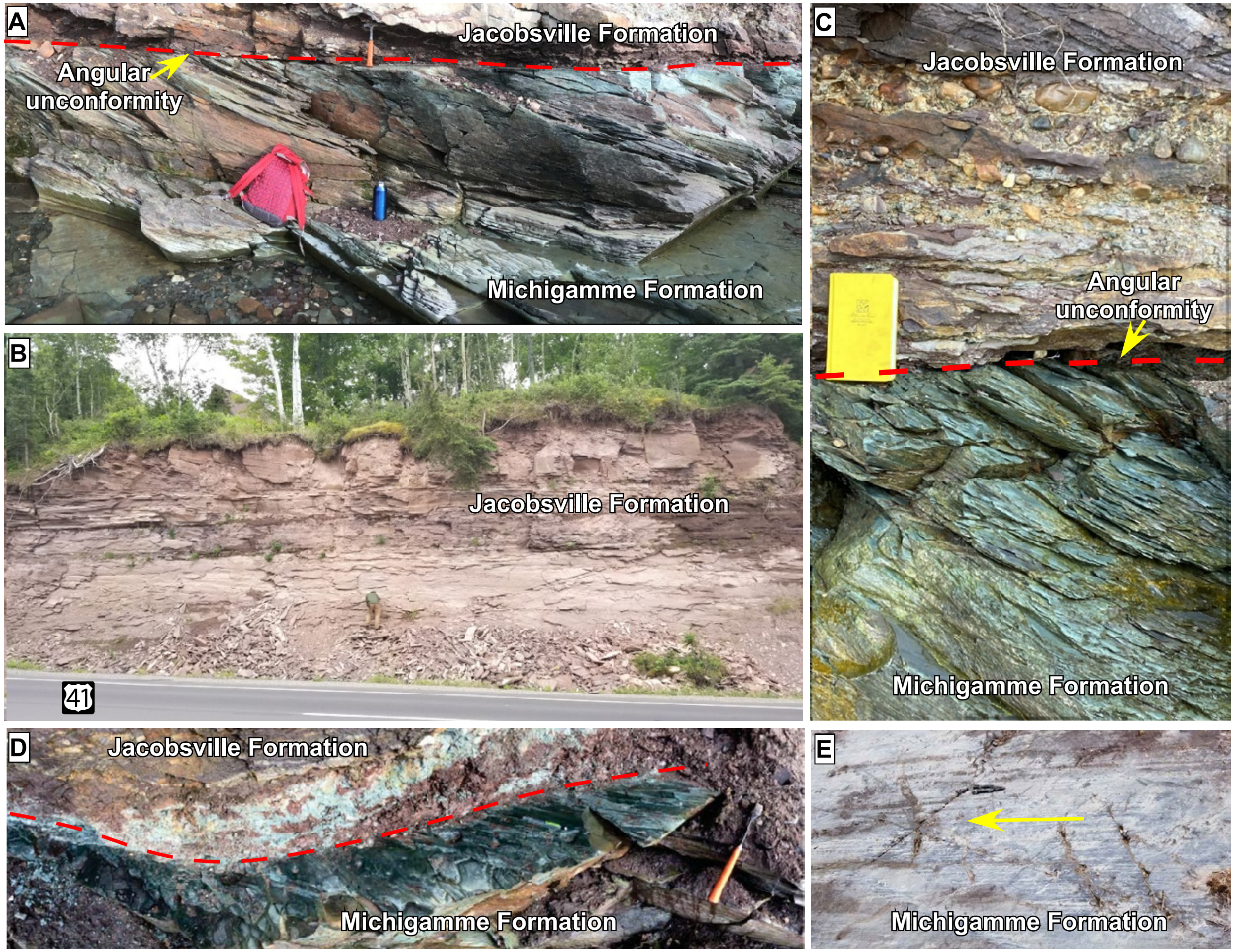

Figure 2. Field observations of stratigraphic and structural features relevant to the local geology. (A) Outcrop of the Michigamme Formation showing metamorphosed greenish slate with SW-dipping foliation. (B) Outcrop of the Jacobsville Formation showing decimeter-scale cross-stratified, reddish medium-grained sandstone well exposed in a prominent roadcut above the unconformity along U.S. Highway 41 (46.74975°N, 88.47404°W). (C) Angular unconformity between the Michigamme Formation (lower) and the Jacobsville Formation (upper) is shown with a red dashed line and labeled with a yellow arrow. Lowermost Jacobsville consists of sandstone and conglomerate whose clasts indicate local provenance. (D) Excavated and cleaned striated surface of the Michigamme Formation at its contact with the overlying Jacobsville Formation. These striations on the Michigamme Formation extend into the outcrop. (E) Striations and associated cuspate chatter marks on the Michigamme Formation slate along U.S. Highway 141, 36 km south of L'Anse Bay (46.4287593°N, 88.5021026°W). These striations were developed on relatively flat bedrock due to recent Pleistocene glaciation. There is no Jacobsville Formation in the vicinity of this exposure. Broadly similar appearance of the structurally striated surfaces in D with the glacial striations in E highlight the importance of additional contextual data. The photograph includes a 15 cm long pair of pliers for scale.

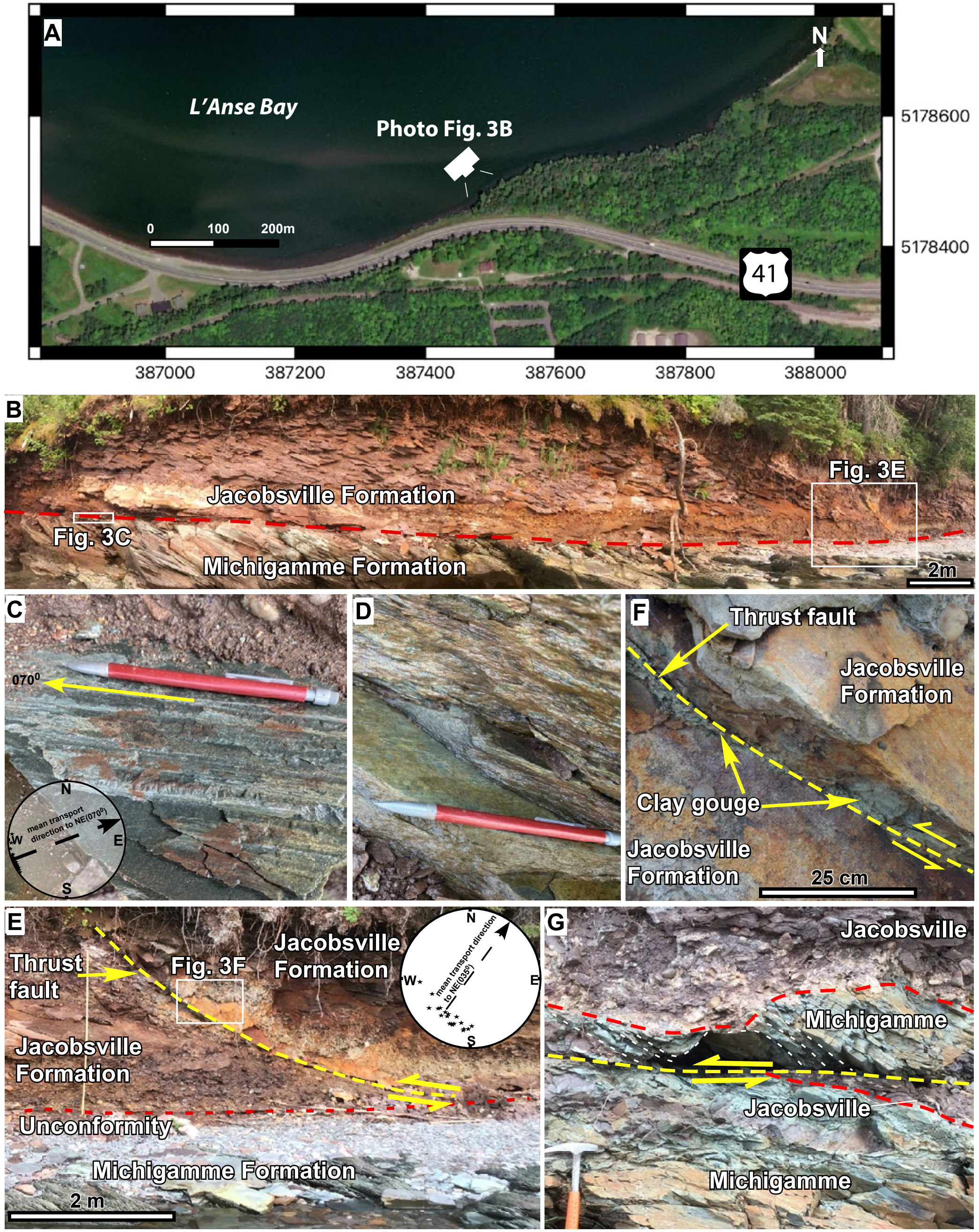

Figure 3. Field observations of the striated surface and associated structural features along the shore of L'Anse Bay. (A) Aerial photo of the southern end of L'Anse Bay where the Jacobsville Formation overlies an erosional unconformity with the Michigamme Formation, which is part of the Baraga Group. See Figure 1 for location. Coordinates are in meters in Universal Transverse Mercator zone 16N (WGS84 datum). (B) Panoramic photograph (looking to southeast) of the contact between the green foliated slate of the Michigamme Formation and the red overlying Jacobsville Formation. (C) Striated surface with slickenlines and slickenfibers developed on Michigamme Formation slate. Slickensteps on the slickenside indicate that motion was top to the left (east). Inset: Lower-hemisphere equal-area stereoplot showing slickenline orientations. (D) Slickenside within slate of the Michigamme Formation parallel to the unconformity-parallel slickenside. (E) Thrust fault resulting from slip along the Michigamme-Jacobsville contact that propagated up into the overlying Jacobsville Formation. Fault steepens to the left (northeast), leading to tilting of sandstone and conglomerate beds in the hanging wall in contrast to the relatively flat-lying beds in the footwall. Inset: Lower-hemisphere equal-area stereoplot showing thrust fault orientations. (F) Light-colored clay-rich fault gouge along the thrust fault. Clay-rich fault gouge is also observed along the striated Jacobsville-Michigamme contact. (G) Structural repetition of the Michigamme-Jacobsville contact observed to the east of the image in B (to the left) with small-scale folding and brecciation of the Michigamme Formation slate.

the contact (Fig. 3G). The structural measurements are available in Tables S1 and S2 in the Supplemental Material.[1]

DISCUSSION

The first-order observation of Murray (1955) that there is a striated surface on the slate at the unconformity between the Michigamme and Jacobsville Formations is confirmed through our observations. The challenge comes in interpreting the origin of these striations. That the surface extends into the bedrock rules out hypotheses that call on the effects of surficial scouring by Pleistocene or Holocene ice (e.g., Gussow, 1956). The interpretation of Murray (1955) that the striated surface could be the result of glacial abrasion prior to deposition of the Jacobsville Formation is intriguing. A Neoproterozoic maximum depositional age for the Jacobsville Formation (Malone et al., 2016; Hodgin et al., 2022) and the now well-documented evidence for low-latitude glaciation in the Cryogenian Period (Evans and Raub, 2011) make such a sequence of events more plausible than when Murray proposed it in the 1950s, as was highlighted by Malone et al. (2016). However, the new field data provide fresh insight for reevaluating this interpretation and instead show that the striations must be tectonic, rather than glacial, in origin.

The striated surface itself has both slickenfibers with slickensteps and clay gouge that are consistent with being a fault plane. These findings are suggestive of a tectonic origin but are not completely definitive because there can be subglacial mineral precipitation along striated surfaces (e.g., Siman-Tov et al., 2021). Another interpretative challenge arises from the reality that in addition to producing glacial striations on rock substrates, subglacial shearing can result in faulting and folding within subglacial tills and poorly consolidated units (Evans et al., 2006). Murray (1955) interpreted the erosional unconformity as preserving glacial striations prior to deposition of the Jacobsville Formation. We can rule out that the faulted surface predates Jacobsville deposition given the presence of a thrust fault ramp that propagates up from the Michigamme-Jacobsville contact into the Jacobsville Formation where it emplaces Jacobsville atop Jacobsville (Fig. 3E). The thrust fault has a NE vergence (Fig. 3E) and contains a thin layer of clay-rich gouge that is similar in appearance to the one found overlying the striated surface (Fig. 3F), suggesting shallow brittle deformation (Sibson, 1977). Additionally, the contact between the Michigamme and Jacobsville Formations is structurally repeated due to the Michigamme being thrust atop the basal Jacobsville Formation (Fig. 3G). Associated with this fault-repeated contact, there is small-scale folding and brecciation within the slate that has been thrust atop sandstone of the Jacobsville Formation. This fault repetition results from slip deviating from being solely along the erosional unconformity such that there are complex relationships, with the contact being variably a depositional contact, a fault contact, and a fault-modified slickensided depositional contact (as illustrated in Fig. 4).

An alternate glacial scenario could posit that glaciation and deformation is associated with Jacobsville Formation deposition itself. However, the consistent fluvial lithofacies of the Jacobsville Formation are inconsistent with the sediments being associated with an ancient basal till that experienced lodgement or deformation. Deformation is concentrated at the unconformity rather than within the sedimentary rocks of the Jacobsville Formation, in contrast to persistent shearing that is seen in subglacial units (Evans et al., 2006). Instead, unconformity-parallel slip along the subhorizontal contact between

[1]Supplemental Material. Tables S1 and S2: Structural measurements. Please visit https://doi.org/10.1130/GEOS.S.22805165 to access the supplemental material, and contact editing@geosociety.org with any questions.

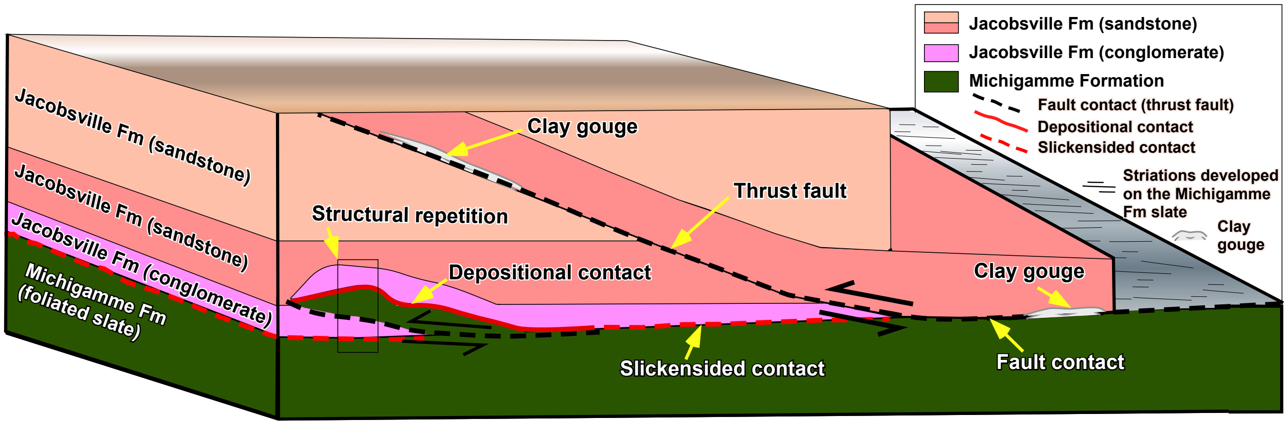

Figure 4. Simplified synoptic cartoon summarizing the contact relationships between the Michigamme and Jacobsville Formations at L'Anse Bay as well as evidence of contractional deformation as documented in Figure 3. Fm—formation.

the Michigamme and Jacobsville Formations that ramps up into a thrust fault is consistent with the kinematics of contractional tectonic regimes, in which frictional sliding can initiate along bedding planes (a basal plane corresponding with the plane of unconformity in this case) that then propagate into thrust ramps (e.g., Cooke and Pollard, 1997).

Taken together, the structural features at L'Anse Bay indicate that the area was subjected to contractional deformation that post-dated basal Jacobsville deposition, with striations developing due to horizontal slip along the unconformity. Such slip is also observed within the underlying Michigamme Formation and the overlying Jacobsville Formation. Such a hypothesis was rejected by Murray (1955), who argued that horizontal slip associated with contractional deformation was unlikely. However, horizontal slip is now a widely accepted phenomenon (e.g., Cooke and Pollard, 1997). It has also been shown that mechanical decoupling between layers of contrasting rheology, such as between slate and sandstone as at this unconformity, can lead to increased bed-parallel slip and associated thrust-fault propagation (e.g., Niño et al., 1998). Our observations of deformational features related to horizontal slip along the erosional unconformity are consistent with their development during such a contractional tectonic regime. Age constraints on vein calcite from the Keweenaw fault that deformed Jacobsville Formation strata constrain an episode of regional contractional deformation at ca. 985 Ma during the Rigolet phase of the Grenvillian orogeny (Hodgin et al., 2022). While faults such as the Keweenaw fault indicate that there was substantial regional deformation during the Grenvillian orogeny, the other possibility of the age of contractional deformation at L'Anse could be during subsequent Paleozoic orogenesis along Laurentia's margin (Craddock et al., 2017). Deformation of an outlier of Ordovician to Devonian carbonate 19 km to the east of L'Anse at Limestone Mountain (Milstein, 1987) has been attributed to post-Devonian contractional deformation (Craddock et al., 2017). However, other hypotheses, such as the deformation being the result of an impact crater, have also been put forward (Milstein, 1987).

The top-to-the-ENE slip recorded by the slickenlines on the unconformity-parallel fault plane (Fig. 3C) is broadly consistent with, albeit distinct from, the ESE vergence of the Marenisco and Keweenaw faults to the west of L'Anse Bay (Figs. 1 and 5). The orientation of the thrust fault within the Jacobsville Formation at L'Anse Bay indicates top-to-the-NE tectonic transport (Fig. 3E), similar to but more northerly than the slickenline slip direction. This tectonic transport direction is at an angle to what is expected to have resulted from contraction during the Grenvillian orogeny or during subsequent orogenesis on Laurentia's margin, such as the Alleghanian orogeny. However, the Keweenaw fault itself has varying orientations including becoming progressively E-W, and even ESE-WNW, in orientation toward the tip of the Keweenaw Peninsula (Fig. 1). Additionally, evidence for slip oblique to the Keweenaw fault associated

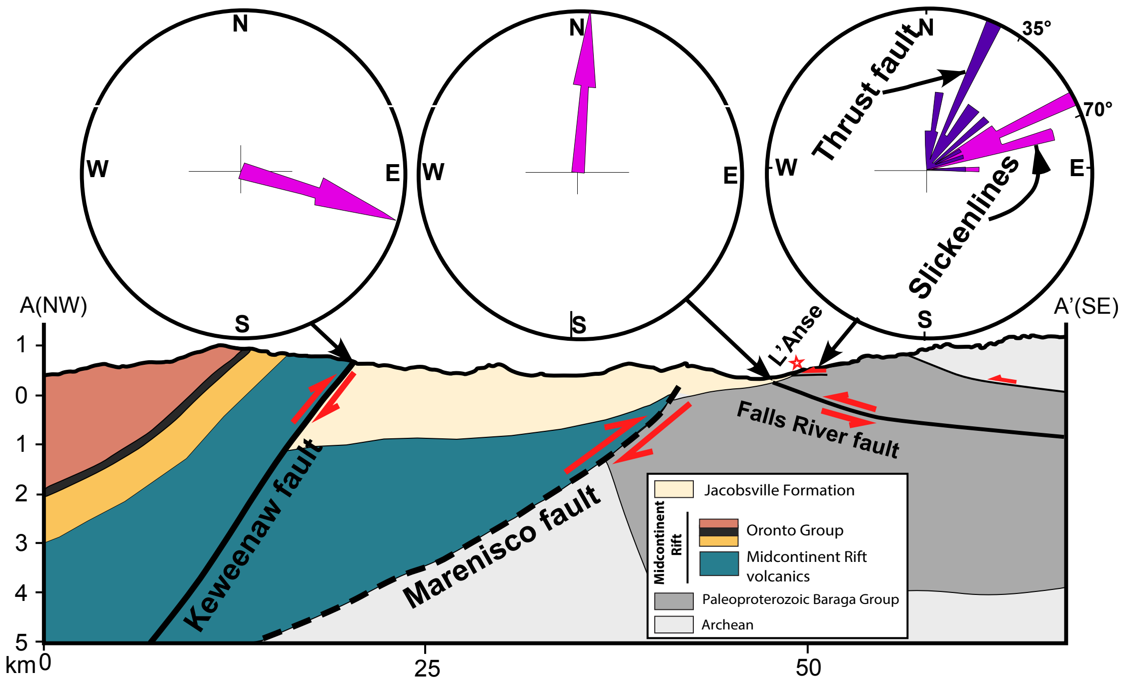

Figure 5. Geologic cross section along A-A′ of Figure 1. This cross section is modified from the A-A′ regional geologic cross-section of Cannon and Nicholson (2001) with adjustments given that our cross-section is to the northeast of their cross-section line. Directions perpendicular to the strike of the Keweenaw and Falls River thrust faults are shown in the left two circular diagrams. Structural orientation data from L'Anse Bay are shown on a directional rose diagram that summarizes the orientation data for both the thrust fault (purple) and striation plane slickenline (magenta) orientations. The y-axis represents depth in km, while the x-axis denotes the distance along the cross section, also in km.

with transpressional deformation indicates that slip was not always normal to the fault orientation (DeGraff et al., 2019). For example, approximately N-S-oriented transpressional deformation along the Keweenaw fault system increases toward the eastern tip of the Keweenaw Peninsula and farther eastward (Tyrrell, 2019; DeGraff et al., 2022). Still, there may be other mechanisms to explain regional deviation of the slip direction at L'Anse. One possibility is that there could have been small-scale reactivation of the E-W-oriented Falls River thrust fault—a fault associated with the Paleoproterozoic Penokean orogeny that is located 1.5 km northeast of the study site (Fig. 5; Gregg, 1993; Cannon and Nicholson, 2001). In addition to its proximity, the Falls River thrust fault has similar orientations to the L'Anse structures, dipping shallowly to the south (Fig. 5). Heterogeneous surface geometry along the Michigamme-Jacobsville contact, which was suggested by Kalliokoski (1982), could also explain the generation of heterogeneous slip distributions that deviate from the far-field stress regime (e.g., Chester and Chester, 2000).

While the substantial regional contractional deformation associated with the Grenvillian orogeny in the region makes it a likely driver of the features at L'Anse, there are no current constraints that rule out slip being the result of younger far-field deformation during Paleozoic orogenesis. Regardless of the age of the striated fault plane, it is clear that the striations at L'Anse developed due to tectonic movement. These new observations indicate that a genetic association of the striations with glaciation is erroneous. Rather, the surface is a non-glacial erosional unconformity that developed in the latest Mesoproterozoic to earliest Neoproterozoic and was subsequently modified through contractional, likely early Neoproterozoic, deformation. Because a glacial origin of the surface could have implications on the debated nature and timing of crustal erosion in the midcontinent (Keller et al., 2019; Flowers et al., 2020; Sturrock et al., 2021; McDannell et al., 2022), the tectonic origin of the striations at L'Anse Bay informs this debate. Our interpretation of the striations as tectonic provides a cautionary tale for interpreting all striations on subhorizontal surfaces as glacial in origin.

CONCLUSION

Contractional deformation within the interior of Laurentia resulted in slip along the unconformity between the Neoproterozoic Jacobsville Formation conglomeratic sandstone and underlying Paleoproterozoic Michigamme Formation slate, creating a slickenside. The presence of a thrust fault propagating from bedding-parallel slip into the Jacobsville Formation as well as structural repetition of the contact with small-scale folding and brecciation strongly support this structural interpretation. The difficulty in interpreting this striated plane arises from the colocation of an erosional unconformity with a fault plane. Where the contact is fault repeated, the erosional contact can be locally preserved without relative slip, resulting in a complex mix of a depositional and faulted contact. Given data that constrain large-scale contractional deformation to have occurred in the region during the Rigolet phase of Grenvillian orogeny, slip on the fault likely occurred at that time.

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