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Glacial landsystems and dynamics of the Saginaw Lobe of the Laurentide Ice Sheet, Michigan, USA

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ABSTRACT

The surficial terrain of the Saginaw Lobe in southern Michigan is divided into 4 landsystems, numbered sequentially from southwest to northeast, containing related assemblages of sediments and landforms, two of which appear to have a genetic relationship with the bedrock units over which they lie. Landsystem 1 consists of the Sturgis Moraine, a terminal/recessional moraine, and an adjacent drumlin field. The moraine is a high-relief ridge with hummocky topography and ice-walled lake plains at its crest, and thick, coarse outwash fans on its distal margin. The drumlin field extends up-glacier from the Sturgis Moraine across the subcrop of the Mississippian Coldwater Shale to the subcrop of the overlying Marshall Sandstone. The low permeability of the shale may have increased basal pore pressures into a range in which deformation of basal sediment into drumlins occurred. Landsystem 2 overlies the subcrop of the Marshall Sandstone. Stagnation of the lobe behind a discontinuous moraine in this area is indicated by high relief, collapse topography, composed of kames, eskers, and ice-walled lake plains. A system of tunnel valleys terminates and merges in this landsystem with large outwash fans and plains sloping away from the margin. High basal drainage into the sandstone may have facilitated stagnation across a broad area to form this landsystem. Landsystem 3 may have also developed during stagnation of the lobe, but it differs from landsystem 2 by its more subdued relief. It contains a network of evenly spaced, southwest-trending open tunnel valleys that contain discontinuous esker segments. Landsystem 4 consists of till plains and low recessional moraines formed as the Saginaw Lobe retreated downslope into Saginaw Bay of the Lake Huron Basin. Tunnel valleys are absent in this area.

1. Introduction

Glacial landsystems are tracts of glaciated terrain with assemblages of sediment and landforms that can be related to the style or dynamics of the glacier that formed them (Evans, 2005). Although numerous approaches have been used to define glacial landsystems, this paper attempts to follow in general the classification of Colgan et al. (2005), who mapped the landsystems of the entire southern Laurentide Ice Sheet (LIS) margins. Because the Michigan portion of the Saginaw Lobe occupies only a small fraction of the total LIS margin, it does not include the entire range of landsystems recognized by Colgan et al. (2005). As they indicate, glacial landscapes are complicated by multiple advances and retreats of the ice and the subsequent overprinting of landsystems developed under vastly different conditions. For example, significantly different landsystems would be expected from the initial advances to the Late Glacial Maximum (LGM) positions when the climate was very cold, as compared to later readvances when readvances and retreats were accompanied by copious amounts of meltwater.

To date, only small portions of the Saginaw Lobe have been mapped at a detailed scale. This work is therefore based on the interpretation of digital elevation models (DEMs) and topographic maps, along with the areas where mapping has been completed. In recent years, mapping has been conducted under the auspices of the US Geological Survey STATEMAP, EDMAP, and FEDMAP programs, which are combined state geological survey/federal cooperative projects, as well as by the Great Lakes Geologic Mapping Coalition, which is also under the oversight of the US Geological Survey.

2. The Saginaw Lobe

The Saginaw Lobe (SL), first described in detail by Leverett and Taylor (1915), occupies the central part of what is now the Lower

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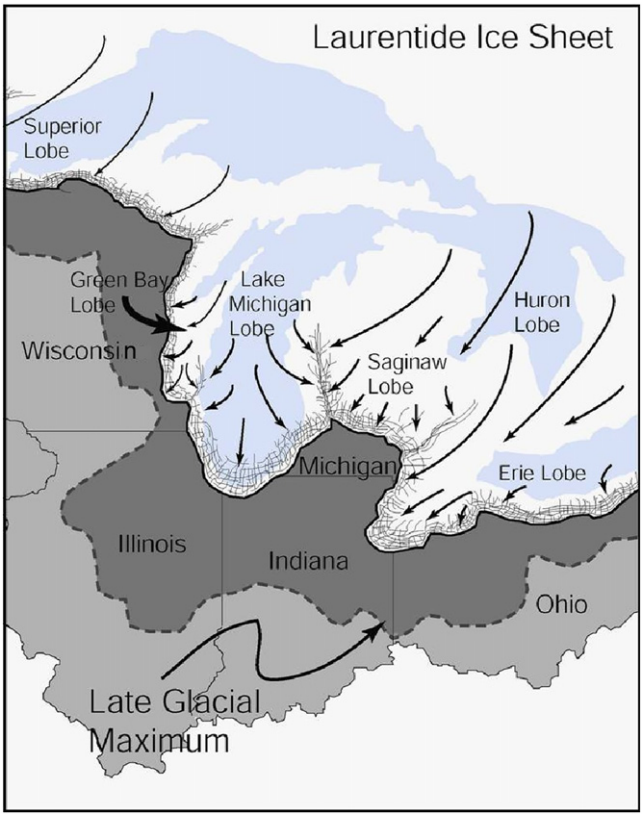

Fig. 1. Glacial lobes interacting in Michigan after the LGM.

Peninsula of Michigan (Fig. 1), bounded on the west by the Lake Michigan Lobe (LML), and on the east by the Huron-Erie Lobe (HEL). Kehew et al. (1999, 2005) summarized evidence from cross-cutting relationships that suggests the three lobes were asynchronous, at least after the LGM. This evidence includes linear valleys interpreted as SL tunnel valleys that were overridden by the LML at a time when they were partially buried by debris and stagnant ice. In the current landscape, LML tills and outwash extend across the SL tunnel valleys. These relationships suggest that the SL was retreating or stagnant during the time that the LML was advancing and expanding in size. As a result, the current area of surficial SL sediment is smaller than it would have been at the full extent of the lobe.

The depositional record of the surficial glacial materials of the SL in Michigan reflects the conditions present during the overall retreat of the lobe from the LGM, during which time the warming climate was producing abundant meltwater from the decaying lobe. Although there is a general correspondence of advances and retreats of LIS lobes to cooling and warming periods, respectively (Lowell et al., 1999), the advance of the LML and HEL over partially to completely deglaciated SL terrain suggests a non-climatic driver. The development of streaming behavior in the LML and HEL associated with high basal fluid pressures in the deep, lake-filled troughs occupied by these lobes (Patterson, 1997, 1998; Kehew et al., 2005; Jennings, 2006) could be a possible explanation. Evans et al. (2008) suggest that rapid advances of some terrestrial paleo ice streams were surges.

Both the bedrock topography and geology exerted an important influence on the dynamics and influence of the three lobes. A map of the bedrock topography (Fig. 2) shows a broad, linear bedrock ridge extending NE from southern Michigan. The black, dashed line shows the approximate boundary of the SL. In addition, Fig. 2 shows the positions of moraines and ice-contact outwash mapped by Farrand and Bell (1982). The SL moraines define a lobe that advanced into the peninsula from the NE through Saginaw Bay. Farther to the SW, the current extent of SL terrain narrows to a thin band. If the moraines of the southern SL are projected parallel to those farther to the NE, it implies a much larger extent of the SL prior to the encroachment of the LML and HEL (Kehew et al., 2005). The moraines of both the LML and HEL extend only to the base of this upland on the western and eastern sides, respectively. It is apparent that their advances into the SL terrain were blocked by this bedrock upland, which is overlain by some of the thinnest glacial drift in southern Michigan.

The bedrock geology of southern Michigan (Fig. 3) consists of concentric bands of mostly Paleozoic formations subcropping beneath the glacial drift at the eroded surface of the Michigan Structural Basin. Two of these formations, the Coldwater Shale and Marshall Sandstone (Fig. 3) are related to specific SL landsystems to be discussed below. The Marshall Sandstone subcrop crosses the bedrock ridge in a NW-SE orientation near the southern border of Michigan and then turns NE and follows the trend of the ridge (Fig. 2). The subcrop of this formation generally forms a cuesta on the bedrock surface.

3. Saginaw Lobe landsystems

The SL terrain in Michigan was divided into 4 landsystems, (Fig. 4). These landsystems developed during the retreat of the SL from its LGM position at an undetermined location to the south. Because no high-quality dates are available for the retreat of the ice in Michigan, the retreat chronology of the SL is very poorly constrained, with respect to the adjacent LML and HEL.

3.1. Landsystem 1; the sturgis moraine and drumlinized till plain

Landsystem 1 (Fig. 5) consists of a well defined terminal/recessional moraine known as the Sturgis Moraine, which lies at the distal end of a drumlinized till plain. Its current E-W length is most likely much less than at the time of formation due to post-constructional overriding by the adjacent ice lobes. The Sturgis Moraine (Fig. 5), along with the drumlins to the northeast herein designated as landsystem 1, are most similar to the southern Laurentide landscapes classified by Colgan et al. (2005) as landsystem B. Moraines of this type develop at the terminus of a drumlin-producing advance. The moraines themselves are large, contain tunnel valleys and internally consist of stacked slabs of basal diamicton interbedded with glaciofluvial sediment. The crests of the moraines are hummocky and mantled with ice-walled lake plains. The Sturgis Moraine conforms to most of these characteristics. Total relief is about 25 m. Glaciofluvial sediment is the dominant sediment type exposed on the distal margins, where it occurs within thick alluvial fans that slope off the moraine. Stacked slabs of basal diamicton have not been directly observed, but could occur within the internal architecture of the moraine. Tunnel valleys cut through the moraine, and extend beyond it (Fig. 6), indicating that they were active prior to the advance that built the moraine. The partial, rather than complete burial of these valleys suggests that they were filled with stagnant ice and debris at the time of the Sturgis Moraine (Kehew and Kozlowski, 2007).

A drumlinized till plain, named the Union Streamlined Plain by Dodson (1985), lies directly up-ice from the Sturgis Moraine. Drumlins in the field vary considerably in length, elongation and other parameters. Although some forms are smoothly streamlined, others consist of irregular elongated shapes. The orientation of the drumlins, along with associated linear features (Dodson, 1985) is NE-SW, which is parallel to the assumed flow direction of the SL in this region. The sediment comprising the drumlins is mostly sandy

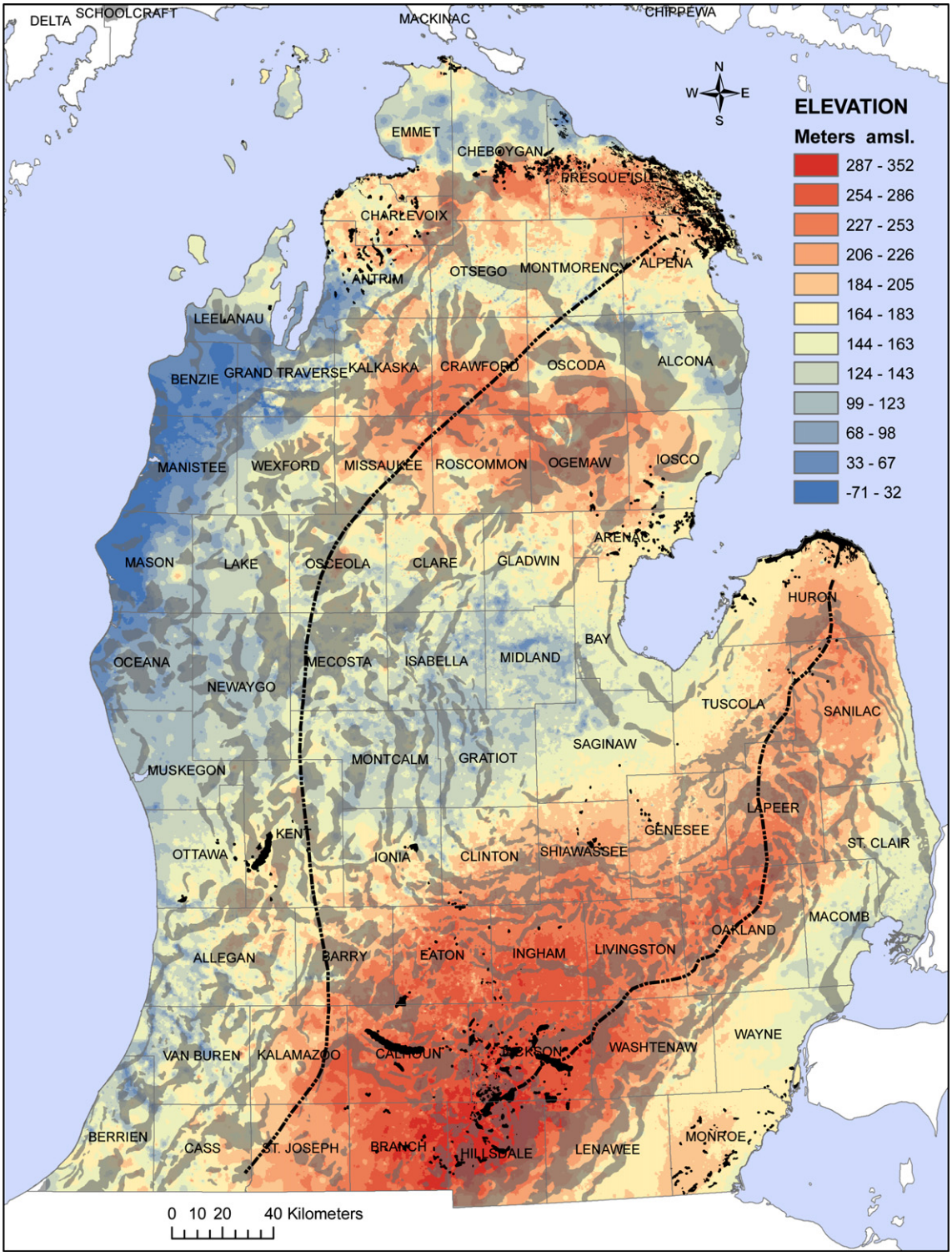

Fig. 2. Topography of the bedrock surface of southern Michigan. Black, dashed line is approximate boundary between Saginaw Lobe and Lake Michigan Lobe to the west and Huron-Erie Lobe to the east. Light gray polygons are moraines and ice-contact outwash mapped by Farrand and Bell (1982). Black polygons are bedrock outcrops; sources include Akers (1938), Martin and Straight (1956) and USDA SSURGO County Soil Survey data.

diamicton (Dodson, 1985; Kozlowski, 1999). In the eastern part of the drumlin field, diamicton-cored drumlins overlie gravels (Fisher et al., 2005). Within the drumlinized plain, drumlins lie on upland tracts, bounded by liner channel-like lowlands interpreted by Fisher et al. (2005) as tunnel channels.

Bedrock lies at a very shallow depth on the eastern side of the field compared to the thicker drift on the western side. The drumlinized till plain overlies the subcrop of the Mississippian Coldwater Shale and ends at the contact with the overlying Marshall Sandstone.

Fig. 3. Map of the Marshall Sandstone and Coldwater Shale bedrock formations subcropping in the Michigan Structural Basin below the glacial drift. Formations dip gently toward the center of the basin. Other units not shown.

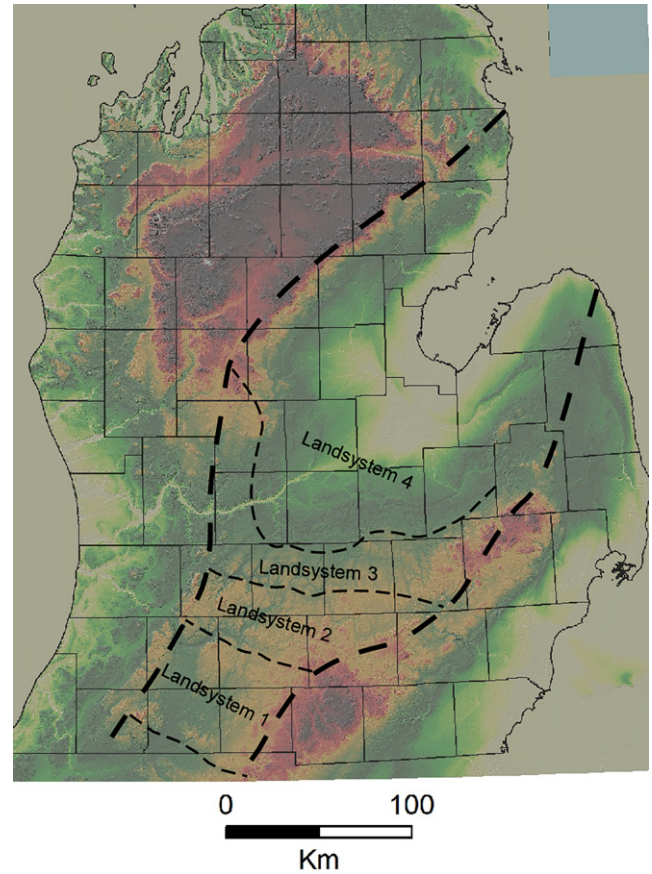

Fig. 4. Digital elevation model of southern Michigan showing the locations of landsystems described in this paper.

The western boundary of the drumlinized zone is a valley train that carried meltwater southward between the LML or its moraines to the west and the higher SL terrain to the east. Along the eastern margin of the valley train, which corresponds to the western edge of the bedrock escarpment (Fig. 5), the drumlins are truncated by this outwash system, without a moraine or any other landform that may have developed at an ice margin. The meltwater flow in this lowland adjacent to the drumlins is associated with the formation of landsystem 2, which is described below. A number of palimpsest tunnel valleys are present in this valley train lowland, although they are almost completely buried by post-erosional till and outwash. Several of these are visible only by shallow, linear depressions on the landscape. This provides evidence for the presence of multiple generations of tunnel valleys, the first extending beyond the Sturgis Moraine of landsystem 1 and the second adjacent to the drumlins of landsystem 1. These were partially buried by younger meltwater deposits of the SL and by outwash and till from the LML advancing from the west (Kehew and Kozlowski, 2007).

3.2. Landsystem 2: broad, stagnant glacial margin

Landsystem 2 (Fig. 6) is bounded by a major west-flowing river valley on the north, the Thornapple Valley, and a major westerly sloping valley on the south, the Kalamazoo Valley. Both of these valleys were cut to their current levels after the formation of landsystem 2 by the SL. The Thornapple Valley appears to have carried meltwater from the HEL to the east prior to its post-glacial history. The Kalamazoo Valley is an even larger, trench-like valley, which begins as a network of tunnel valleys within landsystem 2 (Kozlowski et al., 2005). The largest tributary is an incised south-trending valley that turns west to form the central Kalamazoo Valley. This south-trending reach is incised to limestone bedrock and its floor is mantled with numerous glacial boulders that may have been left as a lag during downcutting of the overlying glacial drift. As a whole, the Kalamazoo Valley was interpreted by Kozlowski et al. (2005)to record at least one major outburst event originating from beneath the SL. The smooth valley sides, as well as the size and dimensions of the central valley reach suggest continuation of the outburst as a subaerial megaflood. It is also possible that impounded meltwater near the boundary of the SL and the HEL drained westward into the Kalamazoo Valley and contributed to its downcutting.

Landsystem 2 corresponds in general to the Kalamazoo Moraine of the SL (Leverett and Taylor, 1915). It is a broad zone of high relief topography (Fig. 6) containing both subglacial and supraglacial landform elements. Landforms suggesting ice stagnation and collapse include hummocks, kames and ice-walled lake plains. The subglacial elements of this landscape, including tunnel valleys and eskers, are partially buried by supraglacial sediment that accumulated over a broad, stagnant margin of the SL. The term “moraine”, which in the traditional sense is considered to be a distinct depositional ridge at the edge of an ice sheet, is not an adequate description of this entire landsystem. There is a thin, discontinuous diamicton-capped ridge bordered by collapsed outwash fans at its distal margin. The southern boundary of landsystem 2 has been placed at the Kalamazoo Valley. South of the Kalamazoo, similar

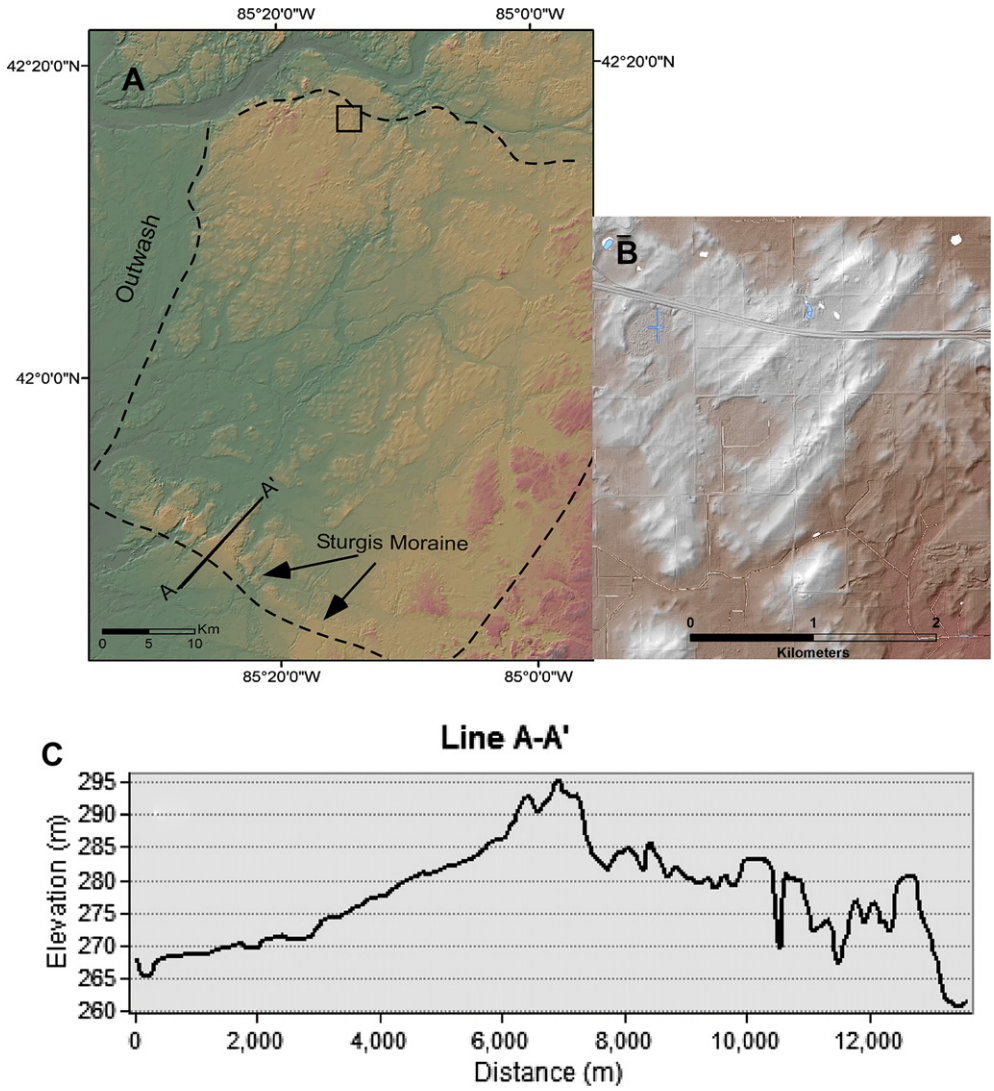

Fig. 5. (A) Digital elevation model of landsystem 1, consisting of the Sturgis Moraine and a drumlin field extending to the landsystem boundary to the N-NE (dashed line). (B) LiDAR DEM image of drumlins. Location shown as box in (A). (C)Profile across Sturgis Moraine showing high relief and smooth distal slopes on outwash fans.

marginal terrain covers an area known as the Tekonsha Moraine of the SL (Leverett and Taylor, 1915), perhaps genetically similar to landsystem 2. Although it occupies a small area, it could also be considered as an extension of landsystem 2, although it partially overlaps landsystem 1.

Major eskers cross landsystem 2 (Fig. 7) trending from north-northeast to south-southwest. A rotasonic boring (Fig. 8) drilled through the crest of a large esker located within a shallow tunnel valley showed a fining upward sequence from coarse gravel in the tunnel valley to horizontally laminated silt and clay near the top of the section (Woolever, 2008). This interval is capped by coarser sediment probably emplaced during final collapse of the ice roof of the tunnel. The stratigraphy of this esker suggests a subglacial hydraulic system consisting of high energy meltwater flows in tunnels transporting coarse gravel changing gradually to low energy flows approaching ponded water conditions at the end of the depositional period. A conceptual model for the formation of this esker is illustrated in Fig. 9. A high energy flow, perhaps catastrophic in nature, eroded the tunnel valley downward from the bed of the glacier. The widths of tunnel valleys in landsystem 2 range from less than half a kilometer to several kilometers, suggesting the large magnitude of such flows, if they happened as single events. Erosional depths are difficult to estimate, but probably ranged between 20 and 50 m. After the main erosional phase, filling of the tunnel valley began, initially with high energy flow transporting and depositing coarse gravel. Partial closure of the tunnel would have occurred by flowage of basal ice into it. Despite the tendency for ice to fill the tunnel, however, it remained an open subglacial conduit for meltwater as the margin of the lobe gradually stagnated and collapsed above it. The gradual fining of the tunnel fill indicates that it was persistently active over a relatively long period of time. The presence of eskers within tunnel valleys confirms both the diminishment in conduit size as ice deformed into the void, as well as the continuing utilization of the conduit.

3.3. Landsystem 3: straight, open tunnel valleys behind margin

The landscape north of the Thornapple Valley is significantly different than the stagnant margin to the south. This area (Fig. 10) consists of a gently rolling, subdued plain cut by mostly open tunnel valleys. The tunnel valleys are regularly spaced at about 7–10 km apart and contain occasional eskers. Several of the tunnel

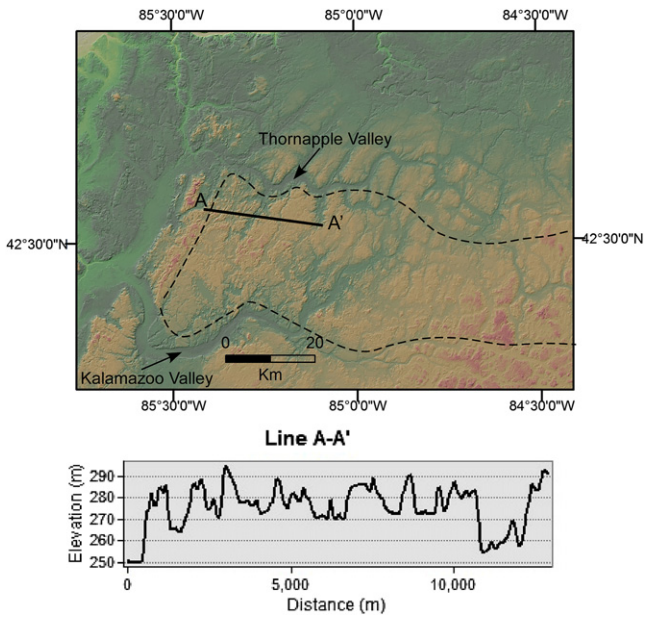

Fig. 6. DEM of landsystem 2 (dashed lines), an area of high relief, hunmmocly topography containing eskers, kames, and ice-walled lake plains. Topographic profile below shows relief across landsystem.

valleys appear to continue across the Thornapple Valley to the south, but the depth of burial of the tunnel valleys in landsystem 2, along with the incision of the Thornapple Valley, probably by meltwater from the HEL, makes it difficult to trace specific tunnel valleys from landsystem 3 to landsystem 2. The topographic profile (Fig. 10) illustrates the lack of high-relief collapse features that occur in landsystem 2. Ice-walled lake plains are present, but they tend to lack raised rims and appear to be shallower than those in landsystem 3. The interpretation of this landsystem is that it represents stagnation but with less supraglacial sediment available to be deposited in thick, high-relief landforms. The tunnel valleys of the central SL end up-glacier at a topographic divide that constitutes the boundary between landsystems 3 and 4.

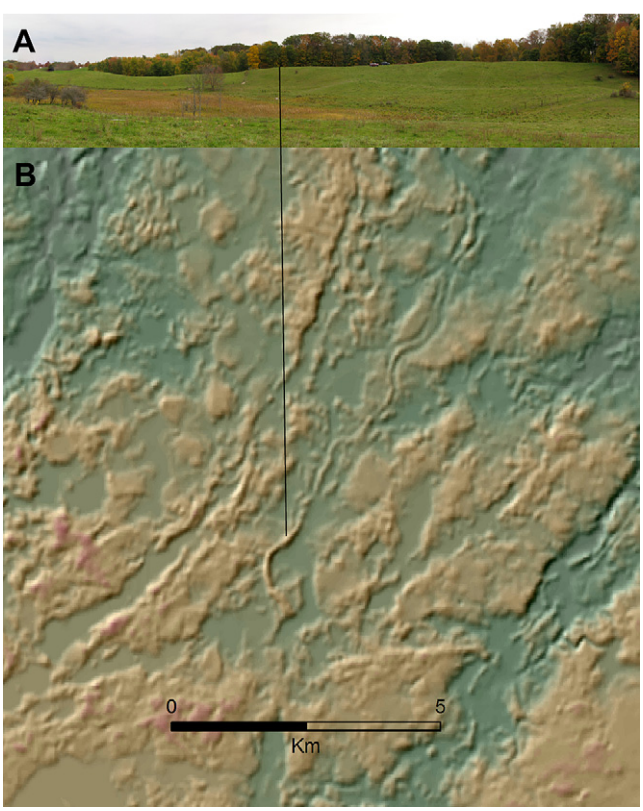

Fig. 7. (A) Ground view of large esker in landsystem 2. (B) location of esker on DEM.

3.4. Landsystem 4: recessional moraines

Up-glacier of the divide that separates landsystems 3 and 4, the land surface slopes downward toward Saginaw Bay to the north, the opposite direction from the ice surface slope (Fig. 11). The topography in this landsystem consists of gently sloping till and outwash plains, punctuated by occasional low-relief recessional moraines formed as the ice retreated downslope toward Saginaw Bay. Tunnel channels are absent in this landsystem. Thus, this landsystem probably represents active retreat with occasional pauses or readvances.

4. Meltwater drainage

The landsystems associated with the Saginaw Lobe in Michigan represent the overall retreat of the lobe from its LGM positions south of Michigan (Fig. 1). Superimposed on this retreat was a re-advance from an unknown distance to the Sturgis Moraine, followed by a readvance to the margin of landsystem 2 followed by broad stagnation of the lobe. Final reactivation and retreat to the north was interrupted by only a few short pauses or re-advances. During the time interval represented by these landsystems, meltwater production was abundant, as indicated by the amount of glaciofluvial sediment present throughout the area covered by the lobe. Tunnel valleys occur in landsystems 1, 2, and 3. The chronology of formation of these valleys is not yet worked out, but they range from totally buried to open valleys. It is almost certain that multiple generations are present, perhaps dating to LGM positions south of the study area as well as those active during the deglacial events represented by the current landsystems. The abundance of tunnel valleys indicates that basal meltwater could not be sufficiently drained by infiltration into the bedrock and drift materials below the ice and that alternate mechanisms were necessary to evacuate the meltwater.

The Sturgis Moraine of landsystem 1 is buried in glaciofluvial sediment and its distal margin consists of thick outwash fans sloping to the southwest. The huge volume of meltwater sediment transported to these fans requires rapid melting of the lobe at both its base and perhaps its surface. In landsystem 2, which was probably formed during the advance to the Sturgis Moraine, high basal pore pressures associated with low permeability bedrock may have played a role in the formation of the drumlin field that exits there. The drumlins occur on upland surfaces within this area and tunnel valleys dissect the uplands into a series of smaller polygons (Fisher et al., 2005).

The stagnant margin of landsystem 2 lies at the head of a huge outwash system that forms broad ice-marginal outwash fans as well as a valley train sloping southward, confined between the truncated drumlinized uplands of landsystem 1 on the east and the LM or moraines of the lobe on its west. The most likely source of the glaciofluvial sediment in this system was the erosion and transport of sediment through the tunnel valleys extending back beneath the SL. Later, meltwater deposits from both the LML and the HEL were emplaced on top of the SL deposits. Whether or not meltwater was stored in a subglacial lake or lakes beneath the SL and drained catastrophically through the system of tunnels or

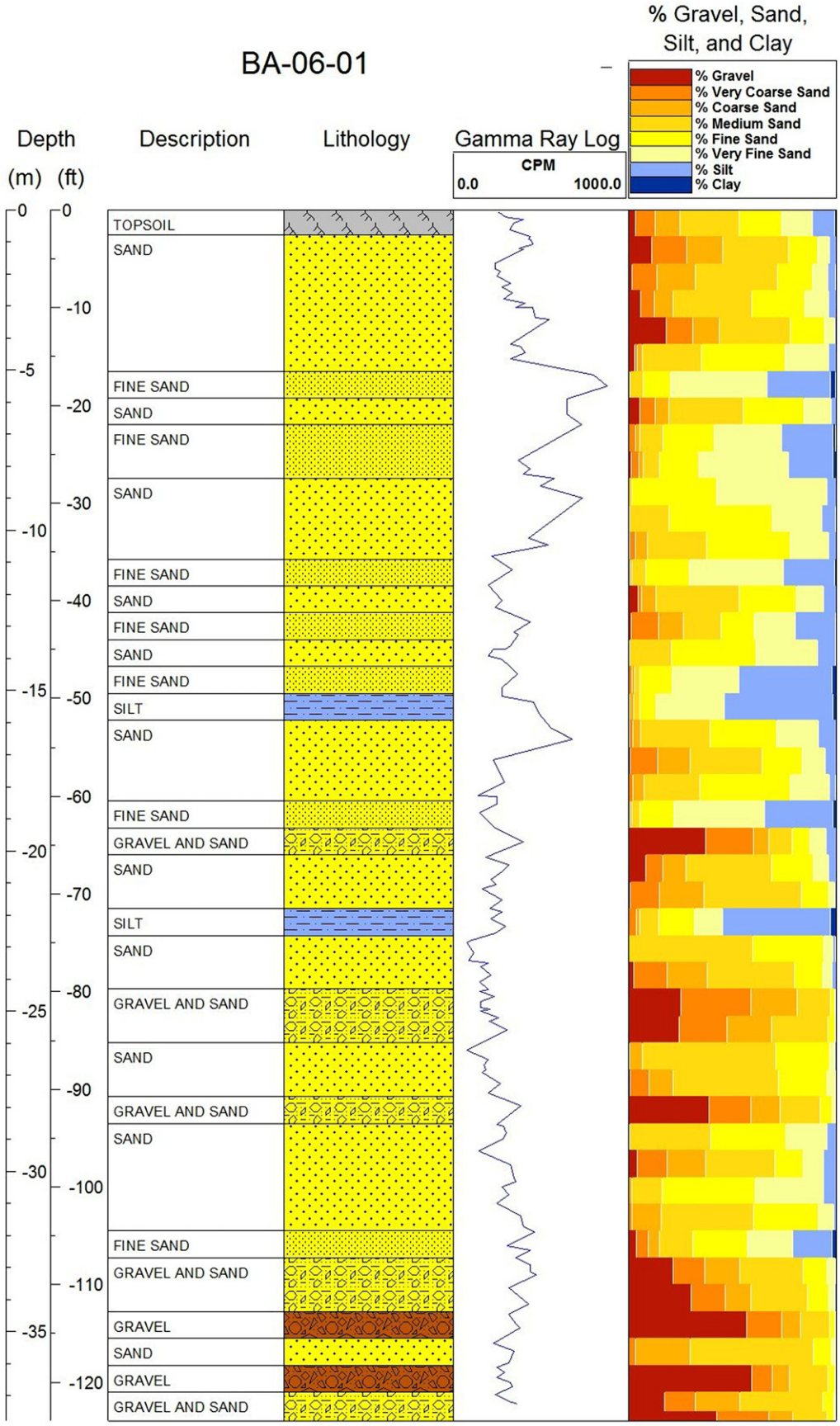

Fig. 8. Log of rotasonic boring drilled in the crest of the esker shown in Fig. 7. Grain size column on right shows cumulative percentages of grain sizes at top from 0 (left) to 100% (right). Within tunnel valley at base of boring, sediment is coarse sand and gravel. Section fines upward to laminated silt and sand to approximately 5 m depth. Upper 5 m consist of coarser sediment interpreted as roof collapse material. Modified from Woolever (2008).

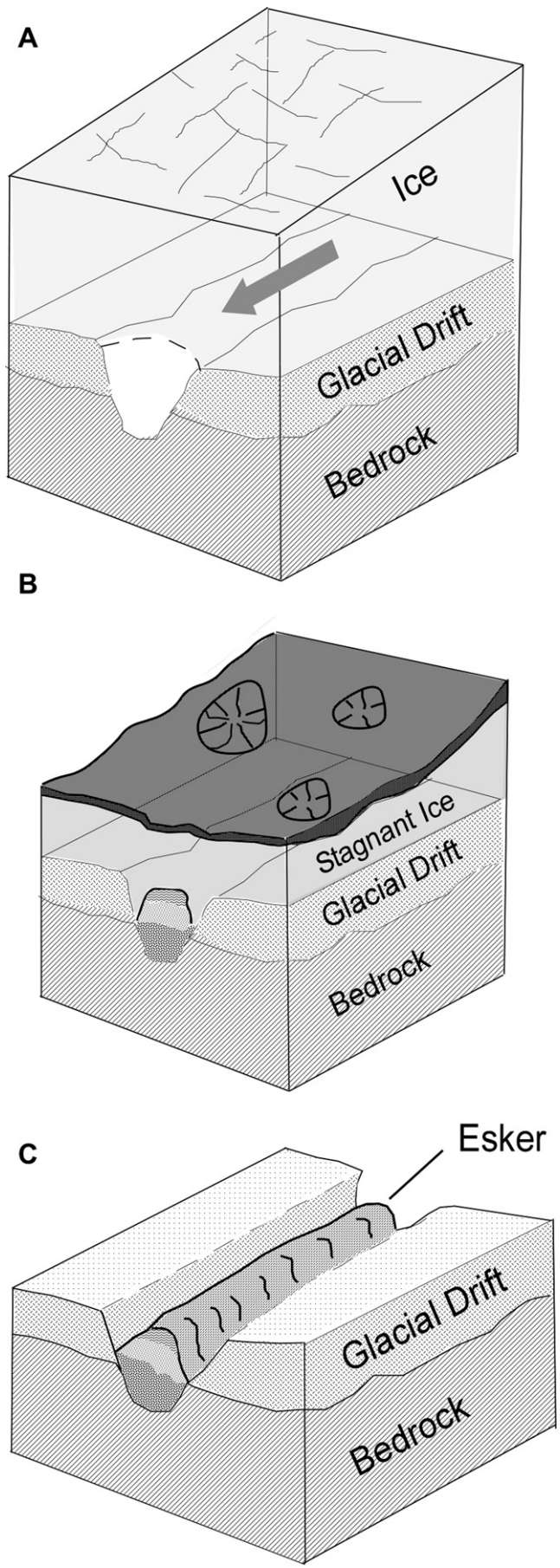

Fig. 9. Conceptual model for formation of esker represented by rotasonic boring log. (A) Tunnel valley eroded beneath active ice by subglacial meltwater. (B) Lobe stagnates and begins to downwaste. Basal ice flows into eroded valley, but smaller conduit remains open and carries declining flows of subglacial meltwater. (C) Final wastage of lobe leaves esker inset into larger tunnel valley.

whether more episodic activity was present is not yet known. The greater apparent depth and thickness of sediment within the tunnel valleys of landsystem 2, as compared to landsystem 3 as well as the larger size of eskers in landsystem 2, perhaps indicates that surface meltwater produced during stagnation of the margin of the lobe drained downward to the bed and then to the margin through tunnels. The fining upward texture of the esker described above supports this hypothesis.

A late stage valley, the Kalamazoo Valley, was described by Kozlowski et al. (2005). The erosion of this valley, which occurred after the LML had retreated from its easternmost position, cut a deep trench across the south-trending valley train originating at landsystem 2. The source of this meltwater appears to have been from either beneath the SL, because the valley bends north and joins a network of tunnel valleys most likely associated with the SL; or from drainage of a lake impounded against the western edge of the HEL. The erosional intensity of this event, as indicated by the width and depth of the valley, which is incised to bedrock, suggests a more catastrophic release of impounded meltwater than the buried to open tunnel valleys distributed throughout the study area.

5. Discussion

The objective for delineating landsystems across the SL terrain is to use the distribution and characteristics of landform assemblages to infer the dynamics and behavior of the lobe as it retreated across this area from the LGM. Two major readvances are identified – one that terminated at the Sturgis Moraine and forms landsystem 1 – and one that reached the Kalamazoo margin and stagnated over a broad area to form landsystems 2 and 3. The landsystems representing these two advances differ significantly.

5.1. Landsystem 1

Landsystem 1 consists of a narrow, high relief morainal ridge at the distal edge of a broad drumlin field, which is closely analogous to landsystem B of Colgan et al. (2005). The crest of the moraine has a high relief, hummocky surface with prominent ice-walled lake plains. Ice-walled lake plains imply the existence of depressions in debris-covered stagnant ice (Clayton et al., 2008). Alternative origins for these features, subglacial, for example, are ruled out by their elevated positions on the landscape, which require surrounding ice-cored walls that subsequently melted and subsided (Clayton et al., 2008). Colgan et al. (2005) suggest that the high relief of these moraines developed through stacking of basal till sheets facilitated by a frozen margin. Marginal permafrost in this region was likely during ice retreat (Johnson, 1990; Clayton et al., 2001; Lusch et al., 2009). In fact, relict permafrost features described by Lusch et al. (2009) in the Saginaw Bay lowlands indicates that permafrost conditions postdated the retreat of the Saginaw Lobe through the landsystems described in this paper. The limited extent of submarginal permafrost conditions is indicated by drumlins up-ice and by the abundance of coarse glaciofluvial fans on the distal margin of the moraine that must have been produced by discharge of large volumes of basal meltwater. Tunnel valleys extend through the moraine, suggesting that they were cut prior to the formation of the moraine and were perhaps still filled with

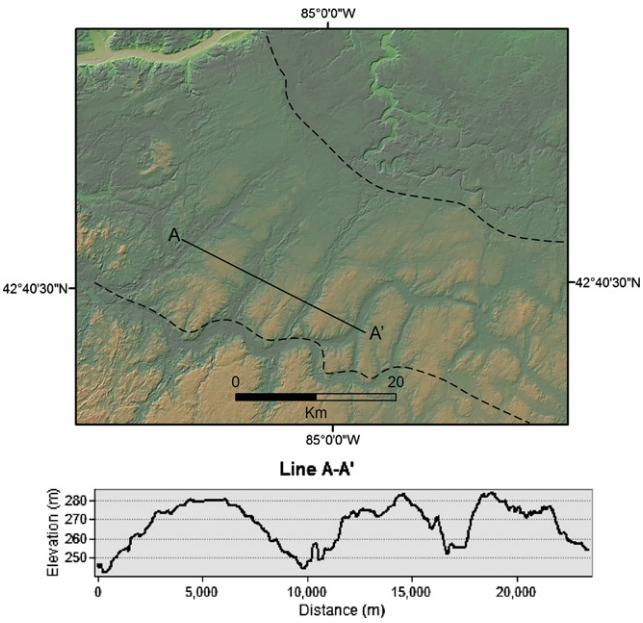

Fig. 10. DEM and topographic profile of landsystem 3 (dashed lines). Regularly spaced, open tunnel valleys are inset into a subdued, low-relief landscape relative to landsystem 2.

debris and stagnant ice at the time of moraine formation (Kehew and Kozlowski, 2007).

Bedrock lithology appears to have played a role in the formation of the drumlins of the Union Streamlined Plain, because they are limited to the area of subcrop of the Mississippian Coldwater Shale (Fisher et al., 2005; Kozlowski et al., 2005). Fig. 12 illustrates the subcrop relationships between the drumlin field and the adjacent up-ice land system. In a down-ice direction, the drumlins begin near the subcrop contact between the Marshall Sandstone and Coldwater Shale. Because drift is thin over the drumlin field, generally less than 20 m, the ice was probably in direct contact with the bedrock surface during drumlin formation, over much of the area. The major effect of the bedrock on glacial dynamics may have been the decrease in bed permeability encountered by ice as it moved from the subcrop of the Marshall Sandstone onto the Coldwater Shale. Decreasing bed permeability would have raised basal pore pressures, weakened basal sediment and facilitated the deformation of basal sediment into drumlins. Jørgensen and Piotrowski (2003) attribute bed dynamics of a soft-bedded glacier to the level of pore water pressure over a range of values from well below the ice flotation pressure to pore water pressures close to or at the ice flotation level. When the fluid pressure drops just below the flotation level, coupling of the ice to the bed and pervasive bed deformation occur, leading to the formation of drumlins. Under this hypothesis, the lower basal pore pressure over the Marshall Sandstone in landsystem 2 would result in basal sediment in which the shear strength was high enough to prevent deformation into streamlined basal forms. Alternative hypotheses for the drumlins of landsystem 1 include a catastrophic subglacial sheet flood (Fisher et al., 2005), which also produced tunnel channels that occur between the drumlinized uplands of landsystem 1. Evidence supporting a sheet flood includes coarse gravels beneath a surficial diamicton in the eastern part of landsystem 1. This hypothesis is rejected because of a lack of specificity regarding the source and magnitude of such an event and the lack of geomorphic evidence for the discharge of massive amounts of meltwater at and beyond

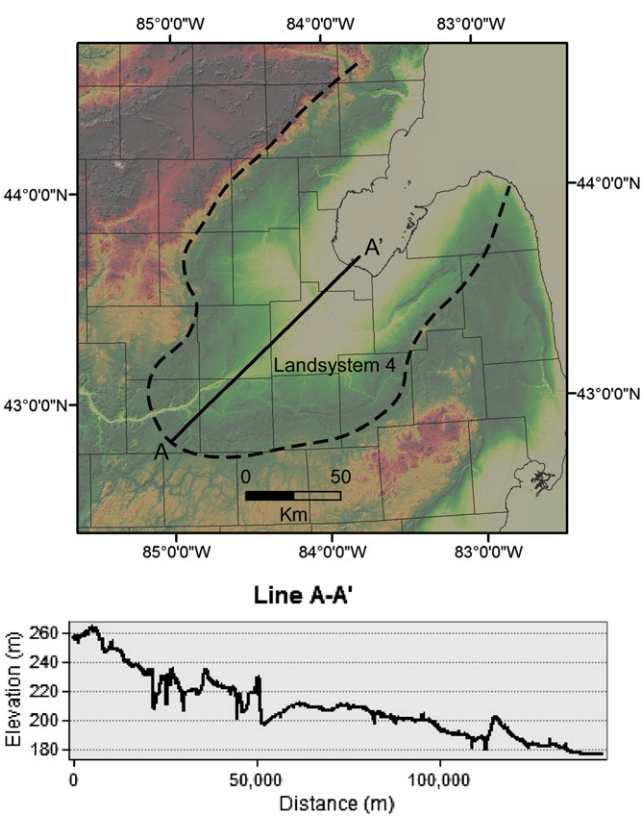

Fig. 11. DEM and topgraphic profile of landsystem 4. Profile shows adverse land surface slope downward to NE relative to ice surface profile. Landscape consists of low-relief till and outwash plains punctuated by low recessional moraines.

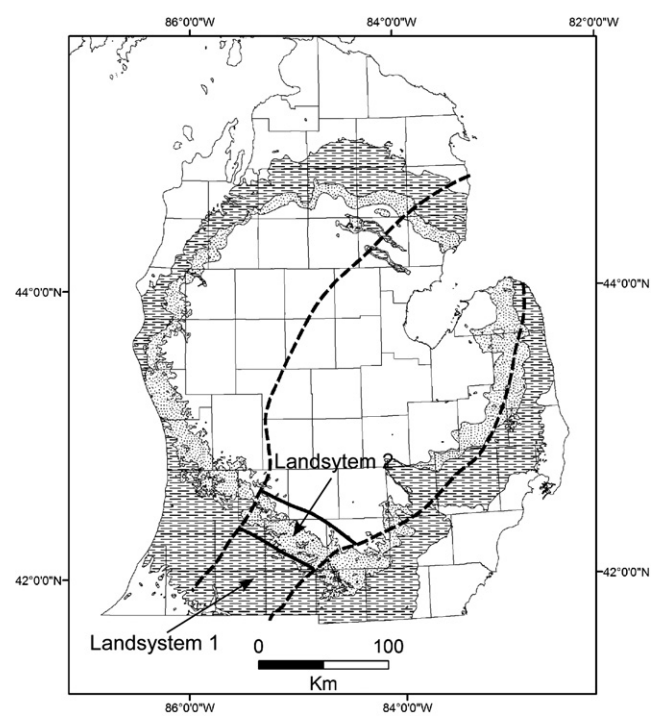

Fig. 12. Locations of landsystems 1 and 2 with respect to the subcrop areas of the Marshall Sandstone (stippled) and Coldwater Shale (hatchured). The low permeability of the shale may have facilitated higher basal pore pressures and sediment deformation to form drumlins, whereas the lower basal pore pressure over the permeable sandstone is considered to have played a role in stagnation of the lobe behind an ice margin located in landsystem 2.

the ice margin. If correct, it would negate the proposed relationship between the subglacial landforms, pore water pressures and bedrock lithology proposed here.

5.2. Landsystem 2

The significance of landsystem 2 is that behind the terminal moraine of a younger re-advance there is a broad zone of stagnation rather than a drumlinized plain indicating active retreat from the moraine as in landsystem 1. Meltwater, especially of subglacial origin, was routed to the ice margin in landsystem 2 through tunnel valleys for a long period of time during which the stagnant margin was downwasting. Although the tunnel valleys terminate in this stagnant marginal zone, they do not display the characteristics of those described by Clayton et al. (1999) and Cutler et al. (2002) in Wisconsin, in which a well defined valley leads to a distinct terminal moraine and ends at a coarse-grained outwash fan on the distal margin of the moraine. In landsystem 2, the tunnel valleys merge gradationally with huge, mostly collapsed outwash fans and plains. The tunnel valleys tend to be filled with large eskers and are flanked by hummocky, collapsed topography typical of the meltout of stagnant ice beneath thick supraglacial debris. The continuation of one of these large outwash systems forms a valley train that extends southward, along the eastern boundary of the LM Lobe, beyond the Michigan border.

The reasons for stagnation of the SL margin to form landsystem 2 may involve bedrock interactions. As mentioned above, the drumlins of landsystem 1 begin at the subcrop contact between the Marshall Sandstone and the Coldwater Shale. By contrast to the high basal pore pressure that would have characterized landsystem 1, the high permeability of the Marshall Sandstone would have facilitated infiltration of basal meltwater into the substrate below the glacier and a lowered basal pore pressure over the subcrop of the Marshall. As shown on Fig. 12, the zone of collapse terrain of landsystem 2 conforms closely to the subcrop of the Marshall Sandstone. Drainage of subglacial meltwater into the Marshall Sandstone bedrock would result in lowered basal pore water pressures. The combination of these basal conditions along with the decreased driving stresses due to thinning and weakening of the lobe relative to earlier, more extensive readvances may have caused the marginal stagnation within the area of landsystem 2.

Tunnel valleys constitute one of the most poorly understood glacial landform types. Hypotheses for their origin include erosion in basal conduits coupled to subglacial groundwater discharge areas near an ice margin under steady-state, low-pressure conditions (Boulton et al., 2009), erosion by outburst floods from subglacial meltwater impoundments, perhaps breaking through marginal permafrost wedges (Hooke and Jennings, 2006), and simultaneous scouring of anastomosing networks of channels during broad subglacial sheet floods (Brennand and Shaw, 1994). The fining upward stratigraphy of the esker described above fits best with a model of sustained flow in a conduit during ice stagnation. The coarseness of the valley fill below the esker suggests erosion and deposition by high energy flow during the early stages of valley formation. Esker formation followed during continued utilization of the subglacial conduit by meltwater flow, as ice from the walls and roof deformed in to decrease its size. In landsystem 2, close to the stagnant margin, it is likely that conduit flow was augmented by meltwater from the ice surface during the summer season, as suggested by Mooers (1989) and Boulton et al. (2009).

5.3. Landsystem 3

Landsystem 3 is similar to landsystem 2 except that it is farther from the margin and the topography is less hummocky. Tunnel valleys cross the landsystem from a topographic divide between landsystems 3 and 4. In contrast to landsystem 2, these tunnel valleys are open and eskers, where present, are smaller. Preliminary results from drilling (Kehew, unpublished) show that landsystem 3 tunnel valleys do not contain the thick, coarse-grained fills present in landsystem 2. This may indicate that the tunnel valleys closer to the margin were affected by much greater surface melting, infiltration to the bed and basal runoff through the tunnels.

5.4. Landsystem 4

At some time after the stagnation that produced landsystems 2 and 3, an active margin began to retreat downslope into Saginaw Bay. Narrow moraines were built by pauses or readvances as the lobe decayed. At this time, the HEL, perhaps streaming in the Lake Huron basin, became the dominant lobe along this segment of the LIS.

6. Conclusions

Delineation of glacial landsystems, areas of genetically related sediment/landform assemblages, in the Saginaw Lobe terrain of southern Michigan facilitates the interpretation of glacial dynamics and interactions between the ice and its substrate. The portion of the Saginaw Lobe terrain studied in this investigation begins at a large moraine formed at the end of a major readvance of the lobe subsequent to the LGM (landsystem 1). Warmer conditions are indicated by the deposition of large outwash fans on the distal margin of the moraine. By analogy with similar moraines in the Midwest (Colgan et al., 2005), the glacier may have been frozen to its bed in a thin zone near the margin, perhaps leading to stacking of slabs of drift to build the high relief moraine. The moraine is capped by hummocky topography and ice-walled lake plains, suggesting burial by supraglacial debris during the last stage of moraine building.

A large drumlin field lies behind the Sturgis Moraine to the northeast. The extent of this drumlin field only as far northeast as the subcrop of the Coldwater Shale suggests a genetic interaction between the glacier and its substrate. According to this hypothesis, higher basal pore pressures caused by the low permeability of the bedrock, weakened the basal sediment to the point at which it could be easily molded into drumlins. The drumlin field ends at the southwestern boundary of landsystem 2, which corresponds to the subcrop contact between the Coldwater Shale and the Marshall Sandstone. Landforms in landsystem 2, including high relief hummocky topography, kames, eskers, and ice-walled lake plains suggest a broad zone of stagnation behind the ice margin. A system of northeast-southwest trending, deeply incised tunnel valleys appears to terminate within this stagnation complex. Large eskers occupy some of these tunnel valleys and sediment fills are thick and coarse-grained. A finning upward sequence from gravel to silt and clay in one esker suggests persistence of the tunnel and declining energy of flow as the ice surface collapsed. The association of this landsystem with the Marshall Sandstone supports a hypothesis that rapid basal drainage into the permeable sandstone may have lowered basal pore pressure to the point where ice movement was impeded and stagnation ensued.

The landforms of landsystem 3 resemble those of landsystem 2, although the topography is much more subdued. Regularly spaced, open tunnel valleys cross landsystem 3 at a similar orientation with landsystem 2. However, the tunnel valleys in landsystem 3 are more distinct due to a lesser degree of burial. In addition, they appear to be incised to shallow depths and contain only thin sediment fills, relative to the landsystem 2 tunnel valleys. This difference between the two landsystems may be the result of greater surface melting in the marginal area of landsystem 2, linked to drainage to the base of the ice and then to the margin.

Landsystem 3 extends northeast to a topographic divide, where landsystem 4 begins. The terrain here slopes downward to the northeast, which would have been adverse to the ice surface slope. The landforms in landsystem 4 consist of small recessional moraines with intervening till/outwash plains. No tunnel valleys occur in this area.

Further work in this region is necessary to determine the mechanisms of tunnel valley formation in terms of the source of meltwater responsible for erosion of the valleys and the rates and processes of erosion.

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