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The distribution of silty soils in the Grayling Fingers region of Michigan: Evidence for loess deposition onto frozen ground

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A B S T R A C T

This paper presents textural, geochemical, mineralogical, soils, and geomorphic data on the sediments of the Grayling Fingers region of northern Lower Michigan. The Fingers are mainly comprised of glaciofluvial sediment, capped by sandy till. The focus of this research is a thin silty cap that overlies the till and outwash; data presented here suggest that it is local-source loess, derived from the Port Huron outwash plain and its down-river extension, the Mainstee River valley. The silt is geochemically and texturally unlike the glacial sediments that underlie it and is located only on the flattest parts of the Finger uplands and in the bottoms of upland, dry kettles. On sloping sites, the silty cap is absent. The silt was probably deposited on the Fingers during the Port Huron meltwater event; a loess deposit roughly 90 km down the Manistee River valley has a comparable origin. Data suggest that the loess was only able to persist on upland surfaces that were either closed depressions (currently, dry kettles) or flat because of erosion during and after loess deposition. Deep, low-order tributary gullies (almost ubiquitous on Finger sideslopes) could only have formed by runoff, and soil data from them confirm that the end of gully formation (and hence, the end of runoff) was contemporaneous with the stabilization of the outwash surfaces in the lowlands. Therefore, runoff from the Finger uplands during the loess depositional event is the likely reason for the absence of loess at sites in the Fingers. Because of the sandy nature and high permeability of the Fingers' sediments, runoff on this scale could only have occurred under frozen ground conditions. Frozen ground and windy conditions in the Fingers at the time of the Port Huron advance is likely because the area would have been surrounded by ice on roughly three sides. This research (1) shows that outwash plains and meltwater streams of only medium size can be significant loess sources and (2) is the first to present evidence for frozen ground conditions in this part of the upper Midwest.

1. Introduction

The Grayling Fingers is a large, upland landform assemblage in northern Lower Michigan, formed mostly by Late Pleistocene glacial and glaciofluvial processes. In the first geomorphic study of this region, Schaetzl and Weisenborn (2004) provided detailed data on the stratigraphy, geomorphology, and soils of the Fingers. The current paper adds to this earlier work by providing important characterization and comparative data on the uppermost sediment in the Fingers, a silty cap on the uplands of the Fingers. This cap is important because it is the last sediment deposited on this interlobate upland, and thus its depositional and geomorphic origins, which until now have been elusive, may be central to the understanding of the immediate post-glacial environments of northern Lower Michigan. I hypothesize that the silty sediment that comprises the cap is mineralogically and texturally unlike the sediments below and that it is a local-source loess deposit. Soil and geomorphic evidence are also used to explain the distribution of the silty cap within the Fingers; these data point to the presence of frozen ground for much of the loess depositional period. Because other glacial landforms in the upper Midwest also exhibit somewhat similar silty caps, the significance of this study extends beyond the Grayling Fingers proper and advances our understanding of landscape evolution and slope stability during the waning phases of glaciation in the Great Lakes region.

2. Study area, sediments and stratigraphy

The Grayling Fingers form the highest part of the dry, sandy uplands, also known as the High Plains, of northern Lower Michigan (Davis, 1935; Fig. 1). They are a triangular upland assemblage about 43 km in width and 40 km in N–S extent, cut into roughly five elongate, flat-topped interfluves by wide, dry, flat valleys. Part of a much larger, loosely termed “interlobate” region, the Fingers are centered primarily among the Lake Michigan and Saginaw lobes of the Laurentide Ice Sheet on the west and east, respectively (Leverett and Taylor, 1915; Schaetzl and Weisenborn, 2004), and the northwestern glacial sublobe (Burgis, 1981) to the northeast. To the east, north, and west of the Fingers lies the large Port Huron moraine (Fig. 2; Blewett and Winters, 1995).

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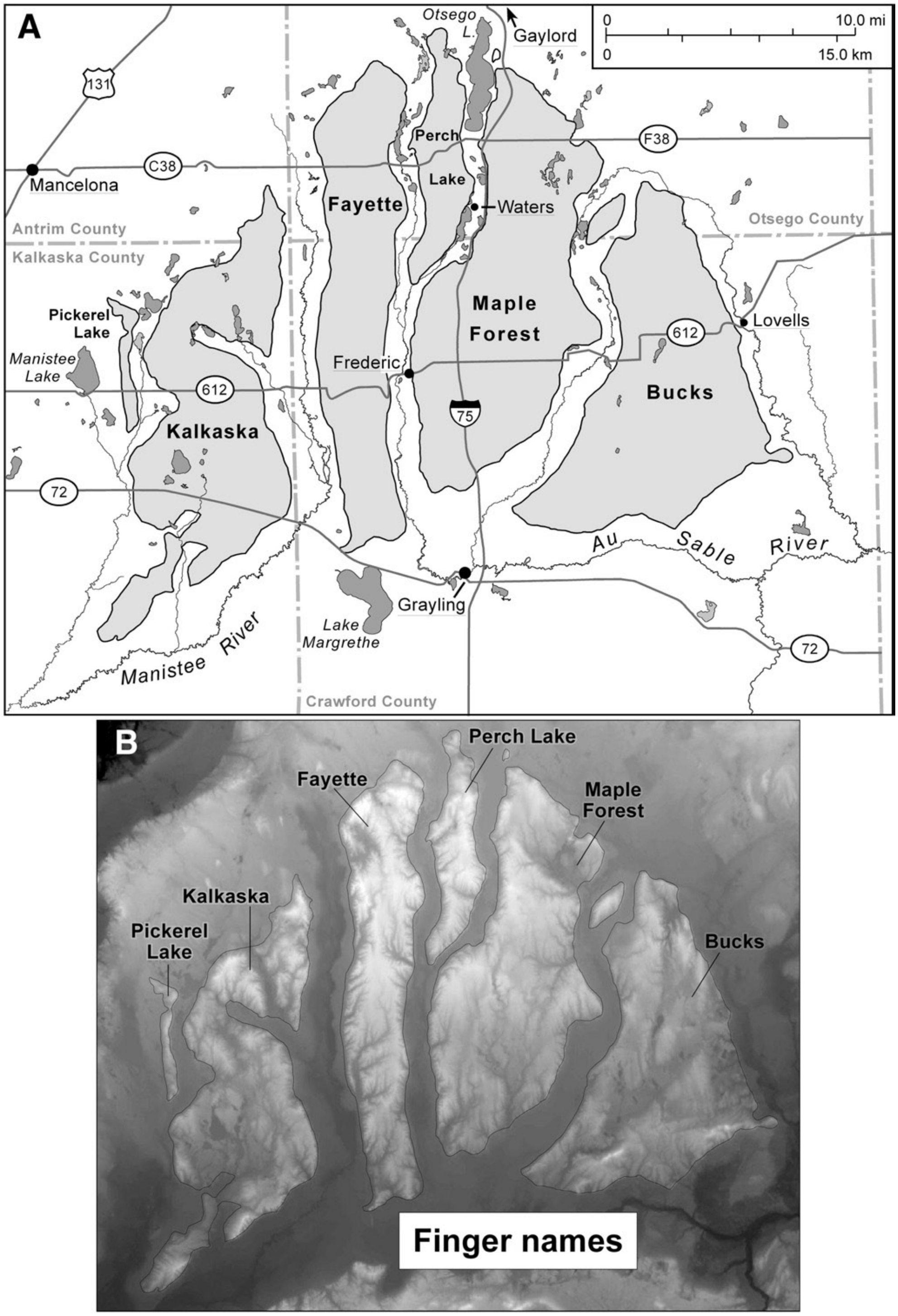

Fig. 1. General physiography and cultural features of the Grayling Fingers. (A) Base map with Finger names, major place names, major rivers, and valleys. (B) Digital elevation model of the region with Finger names. After Schaetzl and Weisenborn (2004).

Each Finger is a broad, elongated upland with a generally flat or slightly rolling summit (Fig. 3). Deep, flat-floored valleys (hereafter referred to as "Finger valleys") probably first cut by Port Huron meltwater and then, later, partially filled with Port Huron glaciofluvial sediment separate what must have once been a large massif into the individual Finger uplands. The Finger uplands stand 100 to175 m above the valley floors, with edges that break abruptly from flat summits to steep sideslopes (Fig. 3). Many sideslopes are deeply incised by gully or rill-like valleys that begin on the flat Finger uplands and quickly develop steep gradients (often >40%) and narrow channels, grading down to the dry Finger valleys (Figs. 3 and 4). Lag gravels at the bases of these side (rill) valleys attest to the fluvial processes that cut them. Only rarely does a depositional landform (e.g., a small fan) exist at the contact of the steep side valleys and Finger valleys, suggesting that the cutting of the low-order tributary gullies occurred contemporaneously with the flow of Port Huron meltwater through the Finger valleys. At that time, the Fingers would have been surrounded by Port Huron ice on three sides.

The stratigraphy of the Grayling Fingers guided Schaetzl and Weisenborn (2004) in their interpretation of the formation and

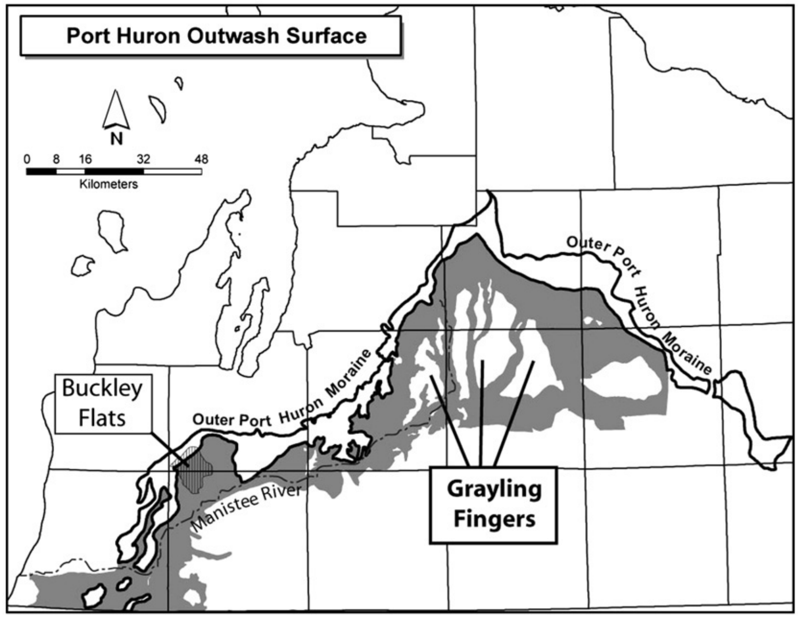

Fig. 2. Map showing the configuration of the Port Huron moraine and outwash surface (represented in gray, the part that could have contributed loess to the Grayling Fingers) in relation to the Grayling Fingers and the Manistee River. The location of the Buckley Flats, another known area of loess derived from the Manistee valley, is also shown.

geomorphic history of this landform assemblage; the majority of the discussion below has been distilled from that source. Soils, near-surface stratigraphic data, and well-log data point to three main sedimentary deposits in the Fingers, which are stacked in a sequence that does not vary in vertical arrangement even though they are variously intact across the region. These stratigraphic relationships point to a clear, orderly succession of depositional and erosional events that led to the formation of the Fingers.

The lowermost sedimentary unit, which constitutes the great majority of the volume of the Fingers, is well-sorted, sandy, stratified, glacial outwash (Fig. 3). Based on well-log data, Schaetzl and Weisenborn (2004) estimated that the outwash exceeds 150 m in thickness in the core of the Fingers. Water well logs, a few gravel pit exposures, and exposures in a sanitary landfill atop the Fingers all confirm that the lowermost material in the Fingers is stratified, well-sorted sand or gravelly sand (Schaetzl and Forman, in press). One particularly prominent gravel pit exposure, near Waters, MI, shows over 10 m of well-stratified and cross-bedded sand, interbedded with layers containing small, highly rounded gravel fragments (Fig. 5). The Fingers outwash has sand textures averaging only 0.6% silt and 1.1% clay and typically with <5% gravel, based on 39 samples from throughout the Fingers (Table 1; Fig. 6). Most of the outwash gravels are <8 cm in diameter, which is suggestive of clean meltwater transport from a fairly distant ice margin. Sedimentology at the Waters gravel pit (Fig. 5) indicates that the outwash was deposited in shallow, braided streams that flowed roughly north to south. The uppermost outwash surface of the Fingers has a gentle N–S slope, which corroborates the conclusion that the outwash accumulated under the influence of N–S flowing, proglacial streams.

Above the outwash, Schaetzl and Weisenborn (2004) described a sandy diamict, which they informally named the Blue Lake till. The unsorted, unstratified, matrix-supported Blue Lake till has a strong

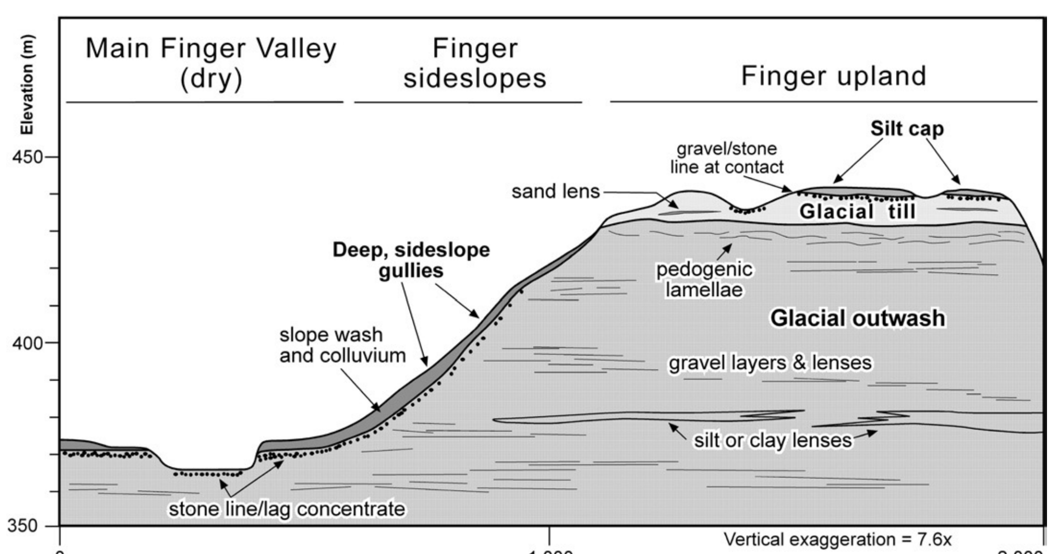

Fig. 3. Diagram of the internal stratigraphy and physiography of the Grayling Fingers, as exemplified by the three westernmost Fingers. Soil series names are shown above their representative landscape segments, in italics. After Schaetzl and Weisenborn (2004).

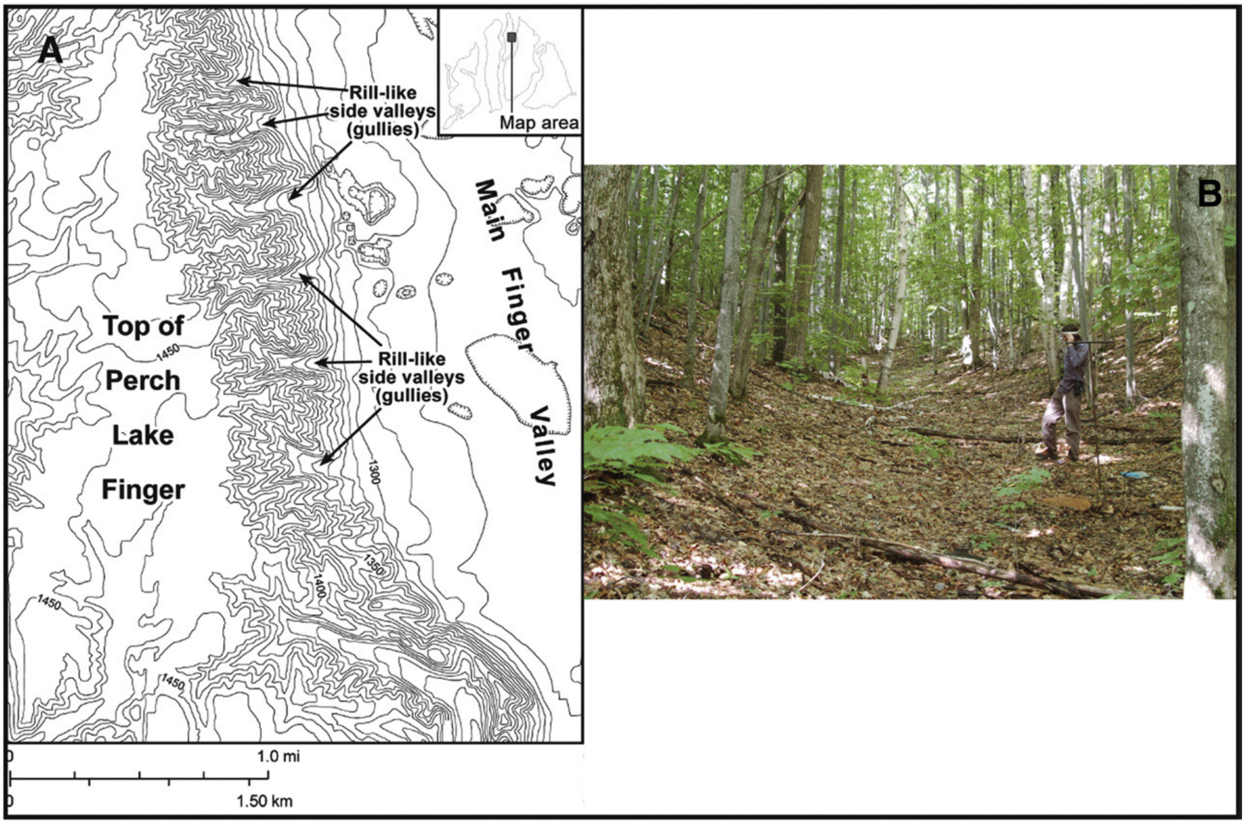

Fig. 4. Steep, sideslope gullies. (A) Retraced topographic map showing the summit, sideslope, and the main Finger valley of a section of the Perch Lake Finger. The steep, gullied sideslopes shown here are a focus of this study. (B) Image of a gully in the field, prior to sampling. Photo by the author.

and consistent N–S trending fabric across a wide area of the Fingers, suggesting that it was deposited by the Laurentide ice as it flowed generally north-to-south. The slightly pink Blue Lake till typically has from 2 to 10% coarse fragments and has many similarities to the outwash below. The till, however, is pinker, contains more and larger coarse fragments, and is unstratified. The fine earth fraction (<2 μm) of the Blue Lake till is also slightly finer textured than the outwash, containing on average 1.4% silt and 4.0% clay. A stone line or gravelly zone often coincides with the contact between the till and outwash, assisting in their differentiation in outcrop. Blue Lake till is exposed at the surface in the northern two-thirds of the Fingers, on stable upland surfaces (or those that have had only a slight amount of post-glacial erosion) and on the upper sideslopes of the Finger valleys. Beneath the geomorphically stable Finger uplands, Blue Lake till is usually <5 m in

Fig. 5. Exposure of sandy, stratified glacial outwash in a gravel pit ~1 km east of Waters, MI.

Table 1
Summary textural data for the three main types of sediments in the Grayling Fingers

Parameter	Outwash (n=39)	Till (n=67)	Silty cap (n=31)
		Mean percent by weight (min–max)	
Total sand (50–2000 μm)	98.3 (96.1–99.4)	94.7 (89.5–99.3)	57.8 (17.5–84.5)
Total silt (2–50 μm)	0.6 (0.0–1.7)	1.4 (0.0–5.6)	35.3 (11.9–75.6)
Total clay (<2 μm)	1.1 (0.0–2.6)	4.0 (1.1–7.6)	7.0 (1.7–15.6)
Total very coarse sand (1000–2000 μm)	1.2 (0.0–5.6)	1.3 (0.2–4.9)	1.0 (0.3–2.6)
Total coarse sand (500–1000 μm)	14.4 (0.2–40.3)	13.9 (8.1–23.3)	9.4 (4.2–27.7)
Total medium sand (250–500 μm)	63.1 (44.6–76.7)	58.8 (51.5–66.9)	32.9 (7.4–50.9)
Total fine sand (125–250 μm)	18.6 (3.8–49.4)	18.7 (9.8–26.8)	10.2 (2.0–17.6)
Total very fine sand (50–125 μm)	1.1 (0.1–3.8)	2.0 (0.3–4.6)	4.4 (1.6–11.1)
Clay-free sand	99.4 (98.3–100.0)	98.6 (94.1–100.0)	61.9 (18.8–87.4)
Clay-free silt	0.6 (0.0–1.7)	1.4 (0.0–5.9)	38.1 (12.6–81.2)

thickness, although on the far western edge of the Fingers it attains thicknesses>10 m.

The uppermost sedimentologic unit in the Fingers, the focus of this paper, was referred to by Schaetzl and Weisenborn (2004) as a silt cap. This cap is spatially variable and thin, seldom thicker than 90 cm and commonly thinner. At places, it is intimately mixed with the till below, mainly from tree uprooting and long-term frost action and faunal bioturbation. Texturally, the cap contains far more silt than do either of the two sediments below, which contain almost none (Table 1). For example, of 31 samples Schaetzl and Weisenborn (2004) analyzed from silty caps at 14 different sites within the Fingers, only eight had <25% silt and 12 had >40% silt. The silty cap is also relatively impoverished in clay; most samples have <9% clay (Table 1). Everywhere in the Fingers, the cap is within the soil profile and thus has undergone varying degrees of pedogenesis. At the lithologic discontinuity between the cap and the till below, a stone line commonly occurs, providing accessory evidence for the genetic uniqueness of each sediment. The distribution of the silty cap within the Fingers, based on two soil series that contain it (Feldhauser: coarse-loamy, mixed, active, frigid Oxyaquic Glossudalfs; and Klacking: loamy, mixed, semiactive, frigid Arenic Glossudalfs), indicates that it is found only on the highest, flattest Finger uplands; even in slight swales or incised channels on the uplands, the silty cap is absent or nearly so (Fig. 5).

3. Materials and methods

3.1. Field methods: sediments

Most of the methods associated with sampling sediments and compiling initial sedimentologic characterization data are discussed in Schaetzl and Weisenborn (2004) and are not repeated here. Their study focused on field observation and measurement, followed by laboratory analysis of soil and sediment samples. Most samples were obtained from backhoe pits (2 m deep) and by hand augering. Over 100 sampling locations were eventually used, with selection criteria based largely on geomorphology and soil data. Topographic maps and digital, 1:20,000 soil map data obtained from the Natural Resources Conservation Service were mainly used to guide sampling site decisions. Representative soils and the subjacent C horizons were sampled and described according to USDA procedures (Schoeneberger et al., 2002). Commonly, pits were dug for sampling purposes where their physical characteristics (e.g., stratification, texture, content of gravel, color) of the soils and sediments were noted, samples taken, and further quantification later performed in the laboratory. Research on the soils and stratigraphy helped refine “field calls” regarding type of parent material. Because multiple, stacked parent materials exist in this area, soil-based information was highly useful in identifying parent materials and contacts between them. Pedogenically “unaltered” parent materials in this area can be readily determined, as they are usually calcareous.

3.2. Laboratory methods: sediments

In the laboratory, soil samples were analyzed for particle size (PS) by pipette (Soil Survey Laboratory Staff, 1996). Color and clay-free particle-size data, generated from the PSA data, were used to substantiate or reject lithologic discontinuities observed in the field (Schaetzl, 1998; Tsai and Chen, 2000). These methods were used to verify or refute the validity of the genetic classifications given to each of the various stratigraphic units in the field. Detailed PS analyses were also performed on a few, highly characteristic samples of the silty cap, using chemically dispersed, 2.0-g samples (in a water-based solution with $(NaPO_3)13{\cdot}Na_2O$ as the dispersant, after shaking for 2 h), on a Malvern Mastersizer 2000E laser particle-size analyzer.

In order to further and more definitively determine the similarities and differences among the three main sediment types (outwash, till, and the silty cap), each was characterized using geochemical and mineralogical methods. Comparisons were made on comparable particle-size subsets only, rather than on bulk samples of the fine earth fraction. No one size fraction is present in all three sediment types, however, in sufficient abundance to allow for statistical comparisons among the three. Thus, outwash samples were compared with till samples (both of which are very sandy) and then the till samples were compared with those from the silty cap (both of which have ample amounts of coarse silt). The outwash and silty cap sediments could not be compared to each other, because neither has enough of any one particle-size fraction to allow for an adequate sample to be fractionated. For this analysis, a subset of 35 samples (9 outwash, 13 till, and 13 till cap samples) were selected from the 137 samples used to initially characterize the sediments (Table 1). All till and outwash data came from deep (C horizon) samples, so as to minimize the effects of weathering and soil formation. For this analysis, the fine earth fraction was first passed through a sample splitter and re-combined (four passes total) in order to achieve a high level of homogeneity, i.e., complete within-sample mixing. Approximately 10 ml of dispersing solution and about 50 ml of water were added to the ~10-g resultant samples. The samples were then shaken on an oscillating shaker for 4 h and washed through a 45-μm sieve; the finer silt and clay fractions were discarded. The 45–2000 μm fraction (remaining on the sieve) was dried and then dry-sieved for 10 min to isolate either the 45–63 μm fraction (till and silty cap samples) or the 63–125 μm fraction (outwash and till samples).

3.2.1. Outwash and till samples

After accumulating ~4 g of the 63–125 μm (very fine sand) fraction, the sediment was placed in a plastic vial and thoroughly mixed into an epoxy resin. Heating the sediment–resin mixture to 70 °C was then used to facilitate hardening. The hardened resin block, with the very fine sand grains embedded within, was then cut into thin sections, stained for K-spar with alizarin red, and examined under a petrographic microscope. At least 300 mineral grains were counted per sample. The following minerals were routinely identified: quartz, potassium and plagioclase feldspar, hornblende, biotite, garnet, microcrystalline quartz, and dolomite/limestone, as well as lithic and opaque fragments.

3.2.2. Till and silty cap samples

After accumulating about 2.0 g of the 45–63 μm fraction via dry sieving, the sediment was washed with a sodium citrate–dithionite solution to remove any Fe and Al coatings (Mehra and Jackson, 1960). To accomplish this, 200-g sodium citrate was first dissolved in 1000 ml water and added to the 45–63 μm sediment in a glass bottle. Approximately 1.5 g of sodium hydrosulfite powder was then stirred

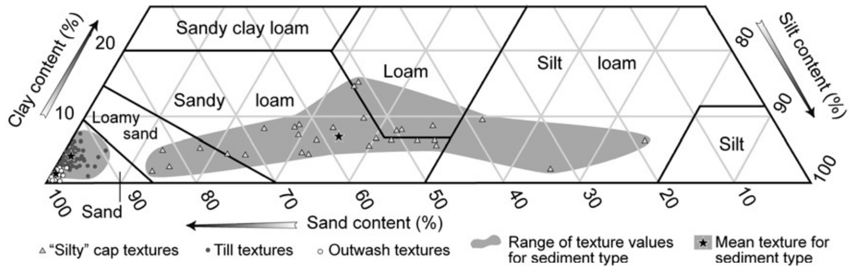

Fig. 6. Textural properties of the fine earth fraction (<2.0 mm diameter) of till, outwash, and cap samples plotted on a section of a standard USDA textural triangle. After Schaetzl and Weisenborn (2004).

into the solution. This mixture was allowed to stand for an hour, after which time the supernatant was poured off. The samples were then washed with distilled water three times and dried. Elemental composition of the 45–63 μm (dry) samples was then determined by X-ray fluorescence (XRF). To do this, the dry sample was diluted by adding 9.0 g of lithium tetraborate (Li_2B4O_7) and 0.5 g of ammonium nitrate (NH_4NO_3) as an oxidizer. This mixture was then melted in a platinum crucible at 1000 °C of oxidizing flame for >20 min while being stirred on an orbital mixing stage. The melt was poured into platinum molds to make glass disks, which were analyzed with an XRF spectrometer. XRF major element (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, P, and Zr) analyses were reduced by a fundamental parameter data reduction method, while trace element data were calculated using standard linear regression techniques. Although XRF is capable of analyzing for these elements, only the data for Si, Ti, K, and Zr were used in this study because of the mobility of the other elements in the udic, acidic soils of this area (Lichter, 1998; Muhs et al., 2004).

3.3. Statistical analyses

Using statistical software, data on particle-size fractions and mineralogy/geochemistry were compared in a standard *T*-test to determine of the sediment samples came from similar or unique populations.

3.4. Field methods: soils and slopes

In order to address slope stability and the likely age of the sideslope gullies in relation to the stable uplands and floors of the Finger valleys, the degree of soil development at 81 sites (including 40 gully sites, 15 sites on the adjoining, flat uplands, and 26 sites on the adjacent valley floors) was examined (Fig. 7). On gully sites, augering was performed within the center of the backslope portion of that gully. At all of the 81 sites, the soils were sampled with a standard bucket auger. Data on the horizon sequence, as well as the color value and chroma of the E and B horizons, were then used to estimate the subgroup taxonomic classification of the soil at the auger site. In order to minimize the influence of slope aspect on soil development within the steeply sloping gully sites (*cf.* Hunckler and Schaetzl, 1997), samples were acquired across a wide array of slope aspects: N (5), NE (8), E (3), SE (4), S (3), SW (4), W (9), and NW (4).

4. Results and discussion

4.1. Outwash vs. till

Detailed, continuous particle-size curves of characteristic silty cap, outwash, and till clearly show the similarity of the latter two sediments, suggesting that the till was derived largely from the outwash, which it overrode (Figs. 6, 8; Table 1). Both the outwash and till sediments peak in medium sand fraction, suggesting that the till was largely derived by the glacier overriding its own proglacial outwash (Schaetzl and Weisenborn, 2004). The similarities also make geomorphic sense; till and outwash from the same ice advance often have similar origins and sedimentological histories. Both sediments are dominated by sand and have almost no silt and clay. The similarities are even more apparent if the sand and silt data are compared on a clay-free basis, which eliminates any

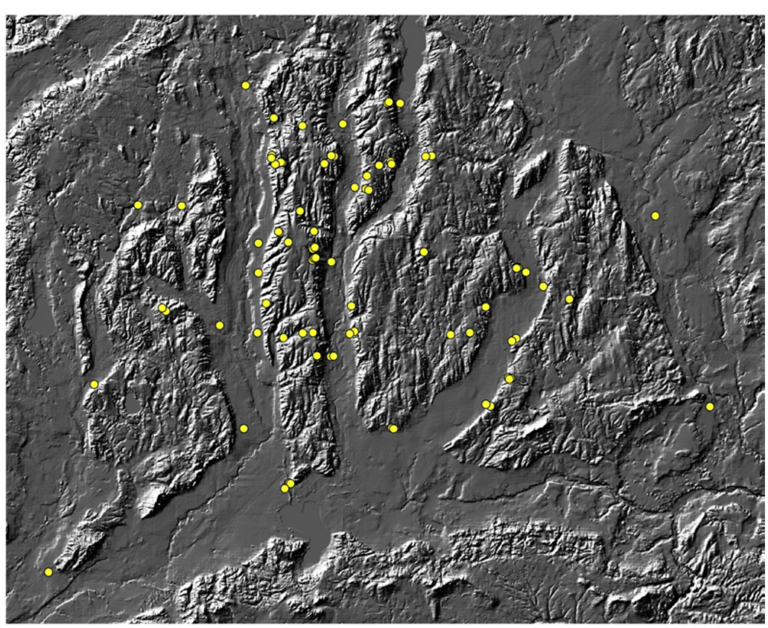

Fig. 7. Map of the sampled sites (dots) for the gully/soil development part of this research, set on a digital elevation model of the Grayling Fingers.

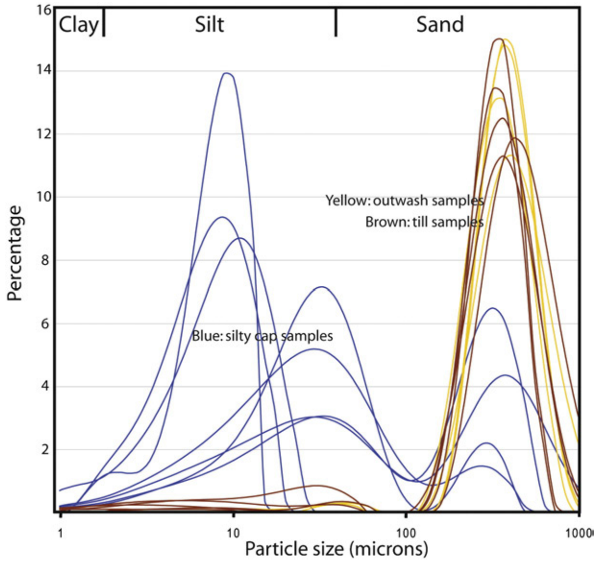

Fig. 8. Continuous particle-size distribution curves for some representative samples of (loess) silty cap, outwash, and till based on the laser particle-size analysis. Note the distinct bimodality of the samples of the silty cap, suggestive of in-mixing of sand into a more silty, initial matrix.

influence of clay illuviation on the particle-size data (Schaetzl, 1998). Clay-free sand and silt data for the outwash and till samples are both within 0.8% of each other (Table 1). In the field, the similarities between these two sediments are also very apparent.

Till and outwash sediments are also, mineralogically, very similar (Table 2). *T*-test output indicates that there is no significant difference between these two sediments with respect to the contents of nine different minerals. The one mineral category that shows the most difference, albeit not a significant one, is limestone and dolomite. The outwash has less limestone and dolomite than does the till, probably because of corrasion during transport. It is clear from these data that the till and outwash are similar sediments, genetically, with the outwash providing the source sediment for the till as the ice overrode it, as suggested earlier by Schaetzl and Weisenborn (2004). Alternatively, the outwash is so similar to the till because it (the outwash) was derived from till that was being released from a stable ice margin and carried into the proglacial environment by meltwater (Schaetzl and Forman, in press).

4.2. Till vs. silty cap

Texturally, the silty cap is quite different than the sandy sediments that underlie it (Table 1; Figs. 6, 8). It has far more silt and clay-free silt than do the till or the outwash. As expected given its eolian origin, it is slightly enriched in very fine sand relative to the till below (Table 1). In all other sand fractions, however, the silty cap sediment is relatively impoverished when compared to the underlying till.

Laser particle-size analysis data show that some of the silty cap samples have a distinct bimodal particle-size distribution, with peaks in the medium silt and medium sand categories (Fig. 8). These data suggest that sand has been mixed into a sediment that was probably, initially, better sorted and much more silt-dominated, i.e., more typical of pure loess (Pye, 1987). Schaetzl and Hook (in review) found a similar particle-size distribution for the (even thinner) loess deposit on the Buckley Flats, ~90 km SW of the Fingers (Fig. 2). Clay contents, although minimal, are slightly higher (3.0%) in the silty cap than in the till, which may reflect near-surface weathering more than initial sedimentology.

Geochemically, all four of the elements analyzed in the 45–63 μm fraction for the 13 silty cap samples were shown to be present in significantly different amounts than they were in the suite of the nine till samples (Table 3). (The samples were not analyzed in pairs, i.e., the till samples did not come from immediately below each silty cap sample.) The data in Table 3 strengthen the argument that the silty cap samples are from a different population than the till samples and that the silty cap has a different sedimentologic history than do its underlying sediments. In sum, the silty cap should not be associated with the glacier that deposited the till (and associated outwash) beneath it.

4.3. Origin of the silty cap

The data in Tables 1–3 and Fig. 8 show that the silty cap in the Grayling Fingers is texturally, mineralogically, and elementally different from the till below and, because of its thinness, lies wholly within the soil profile. It has had some sand intermixed into it from below, via pedoturbation. The silty cap could not have been derived from the till below by weathering or pedogenesis. Neither could it have been a glaciogenic sediment derived from the wasting ice sheet because it is so dissimilar (in terms of texture, mineralogy, and geochemistry) to the till that the glacier *was* carrying and eventually deposited in this region. Thus, I conclude that the silty cap sediment is not a superglacial till and neither was it transported englacially. As Schaetzl and Weisenborn (2004) concluded earlier and which these additional data support, I also conclude that the silty cap sediment was not associated with the ice advance that covered the Grayling Fingers.

The silty cap samples are from the various sites on the flat uplands of the Grayling Fingers. In the bottoms of many dry kettles on the same Finger uplands, however, up to a meter of silty sediment is also found (Schaetzl and Weisenborn, 2004). Here, in the kettle bottoms, the silty sediment usually overlies outwash sand but does not extend up the sides of the kettles. This silt exists even where the surrounding

Table 2
Mineralogy data for the 63–125 μm fraction of outwash and till sediments from the Grayling Fingers

Parameter of comparison	Outwash samples	Till samples	Significantly different at P=0.01?	Level of significance (P)
Number of samples analyzed	9	13		
Mean values (%)				
Quartz content	80.7	81.6	N	0.46
K-spar content	3.3	2.8	N	0.37
Plagioclase content	9.3	9.4	N	0.93
Hornblende content	0.5	0.5	N	0.81
Biotite content	0.1	0.1	N	0.72
Garnet content	0.2	0.2	N	0.70
Lithics content	0.9	0.9	N	0.90
Microcrystalline quartz content	2.1	1.8	N	0.47
Dolomite and Limestone content	1.0	2.2	N	0.19

Table 3
Geochemical data for the 45–63 μm fraction of till and silty cap sediments from the Grayling Fingers

Parameter of comparison	Till samples	Cap samples	Significantly different at P=0.01?	Level of significance (P)
Number of samples analyzed	9	13		
Mean values (%)				
SiO_2 content	69.05	85.09	Y	0.004
TiO_2 content	0.36	0.23	Y	0.000
K_2O content	2.17	2.72	Y	0.006
Mean values (ppm)				
Zr content	697.4	276.7	Y	0.000

uplands lack a silty cap, i.e., it could not have been transported in by slopewash. Although only three samples of this kettle-bottom silt were analyzed, based on PS data alone they appear to be vastly different material than the till or outwash below and very similar to the silty cap. The three samples of kettle-bottom silt average 70% silt and <13% sand, whereas the 31 cap samples average 35% silt. The lack of appreciable sand in the kettle silts points to an origin not directly associated with the sand-rich glacier that last covered the Fingers, similar to the conclusion made for the silty cap material. The silty cap material probably has more sand simply because it is usually thin and thus is more prone to bioturbation and in-mixing of sand from below (Fig. 7), as was observed for a thin loess cap on the nearby Buckley Flats outwash surface (Figs. 2, 8; Schaetzl and Hook, in review). For this reason, the silty cap is sandier than most traditional loesses cited in the literature (Pye, 1987).

Silty sediment from the upland cap and kettle bottoms may have related origins because they both overlie glacigenic sediment, yet are not directly associated with the glacial system, and they were the last sediments to be deposited on the respective geomorphic settings (Schaetzl and Weisenborn, 2004). Because these two sediments overlie but do not occur within the local glacial deposits, the data suggest that this silt is not a direct glacial sediment, but rather that it was imported into the Fingers via another geomorphic system, after the ice had retreated from the Fingers. Gravity can be ruled out; i.e., the sediments are not colluvium because the silty cap is only found on the highest, geomorphically stable landscape positions, and the silt in most kettle locations has no upslope source. Fluvial transport can be eliminated, as the silty caps on Finger uplands are not within fluvial channels and the kettle sideslopes do not normally show evidence of channelized flow.

Schaetzl and Weisenborn (2004) suggested that the silt was an eolian sediment but that it had been deposited onto the top of the ice sheet as a superglacial carapace. Another, less likely, possible explanation involves deposition associated with a superglacial lake (s). Invoking *local-source* loess as the origin of the silt in the Grayling Fingers was rejected by Schaetzl and Weisenborn (2004) because the feasibility of a local source for loess was minimal, even just a few years ago. The explanation given for this lack of post-glacial loess in Michigan has always been that most meltwater streams here were too short to have supplied adequate amounts of silt and/or that they quickly terminated into a proglacial lake, forcing any silt they may have been carrying to settle out within the lakes proper (Karrow and Calkin, 1985; Larson and Schaetzl, 2001). However, this scenario can be refuted for northern Lower Michigan, where Port Huron meltwater flowed subaerially as braided streams across vast outwash surfaces, around and between the Fingers, for perhaps a century or more (Blewett et al., 1993; Blewett and Winters, 1995; Fig. 2). Some of the flow paths for this meltwater, from the moraine, went through the Finger valleys and down the Manistee River valley, easily exceeding 80 km in total length and several kilometers in width.

New information about a nearby, similar silty deposit has just emerged that supports a loessial origin for the cap in the Fingers. A 35–45 cm thick silty deposit, interpreted by Schaetzl and Hook (in review) as loess, was recently described for a high, flat section of the Port Huron outwash plain, roughly 90 km SW of the Fingers, known as the Buckley Flats (Fig. 2). The deposit is 4–15 km from and 35–60 m above the Manistee River valley, which drained the Port Huron outwash plain through and around the Fingers. The "Buckley Silt" (as informally named) covers nearly 125 km^2 and, like most loess deposits, shows excellent spatial trends with distance from the nearby Manistee River, getting progressively finer and thinner away from the Manistee valley, making the river floodplain the logical loess source for the silty deposit. In this area, while flowing full with meltwater and sediment, the Manistee valley was probably 1.5–3.5 km wide. (It has since become incised and exhibits an excellent suite of terraces.) The combined width of the Port Huron outwash plain (including the Finger valleys and the low, broad outwash fans between the Fingers and the moraine) ranges from 35–45 km, making it one of the largest and most homogeneous, sandy outwash surfaces in the upper Midwest (Schaetzl et al., 2006).

I suggest that the silty cap on the Grayling Fingers is loess, with significant amounts of sand mixed into it from below (Fig. 8). Although the silty (loess) cap in the Fingers is sandier than typical for loess (Pye, 1987), it is not a cover sand, sandloess or loam deposit, as found in Europe and Alaska (Dowgiallo, 1965; Kocurek and Nielson, 1986; Koster, 1988; Lea, 1990; Gullentops et al., 1993), because the sandy component is clearly post-depositional. The loess was derived from the Port Huron outwash surface that surrounds the Fingers and grades through them as Finger valleys and, to a lesser extent, the Manistee River valley. The Finger uplands stand high above the Port Huron outwash plain and would have been directly within any silt cloud coming off this surface, regardless of wind direction.

Because wind is such an effective sorting agent, most loess deposits change regularly and predictably across space (Smith, 1942; Fehrenbacher et al., 1965; Frazee et al., 1970; Olson and Ruhe, 1979; Ruhe, 1984; Fehrenbacher et al., 1986; Pye, 1987; Muhs and Bettis, 2000); these spatial trends are a hallmark of loess and are often used to confirm the eolian origin of silty, surficial deposits. A spatial assessment of the texture and thickness of the loess sheet, as Schaetzl and Hook (in review) were able to do for the nearly continuous loess of the Buckley Flats, may not be meaningful or even possible in the Fingers for several reasons: (i) the loess here is highly discontinuous, making local geomorphology and slope conditions more important in determining thickness than distance from a source; (ii), multiple loess sources, i.e., each Finger valley, were probably operating during the loess generation period; and (iii) the likelihood of winds approaching the Fingers from many directions (given the crenulate nature of the nearby Port Huron ice margin) rather than from one dominant direction is high. Nonetheless, the localized *distribution* of the silty cap on the tops of the Grayling Fingers does provide insight into not only its eolian origin but also the evolution of the entire Fingers landscape.

4.4. Evidence for frozen ground

Fieldwork has consistently shown that the silty cap is present only on the very flattest Finger uplands (Schaetzl and Weisenborn, 2004). Detailed transect work on these uplands has confirmed that, even in areas of subtle channel incision or where slopes exceed 2–4%, the silty cap is absent. Tracking the thickness of the cap from the flat uplands (where it is thickest and most continuous) onto a shoulder slope, or into a slight gully, almost always results in its progressive thinning until the cap is absent on the shoulder or in the core of the gully. This distribution would support a loessial origin, with deposition across the entire Finger uplands, followed by (or simultaneous with) erosion and transport of the silt from all but the most stable, flat upland (or depressional) sites. However, envisioning runoff and erosion (which is necessary to remove the silt from the sideslopes and channels) from this landscape, which is so sandy and permeable, is difficult. Indeed, the till averages almost 95% sand (primarily medium sand) and the outwash averages over 98% sand. Recall that to explain the distribution of loess on the Fingers in this way a mechanism must be involved wherein even sites with extremely low slopes can generate runoff. One possible way to produce such runoff is to invoke frozen ground.

At the time of the Port Huron advance, conditions were probably cold enough to generate frozen ground in the Fingers, given the paleogeographic setting. At this time, glacial ice would have been surrounding the Fingers on nearly three sides at the Port Huron moraine exposing the Finger uplands to cold, strong winds, some regional, some katabatic (Fig. 2). Thus, a silt source (the Port Huron outwash plain) and the winds necessary to transport it can be readily envisioned. Still necessary, however, is a means to facilitate runoff, and the most reasonable means is frozen ground. In this landscape where exposures are few, however, none of the traditional geomorphic features associated with perennial frozen ground (such as ice wedge casts, polygonal patterns, sorted circles, or cryoturbation involutions) (Washburn, 1956; Price, 1972; Black, 1976; Clayton et al., 2001), have been observed. Permafrost features have, however, been identified in eastern Lower Michigan, an area 175 km to the SE (Lusch, 1982; Lusch et al., in press).

To this end, I hypothesized that, if large amounts of runoff at the time of the Port Huron advance could be invoked, this type of geomorphic evidence could be used to infer frozen ground. The deep, sideslope gullies were examined as geomorphic indicators of abundant runoff and, in turn, frozen ground. Priesnitz and Schunke (1983) described a permafrost landscape in NW Canada that was developed in sandy and gravelly sediment, much like that of the Fingers. On this landscape, very steep, V-shaped and flat-floored valleys descend from the uplands to a pedimentation surface below, with sharp knickpoints at the contact, a scenario similar to the Finger valleys. They describe intense fluvial erosion in these valleys and ascribe their genesis to large amounts of surface runoff, mainly concentrated in the warm season, from the frozen uplands. Indeed, Clayton et al. (2001, p. 173) identified “gullies that are today inactive” as one type of indicator for the presence of permafrost in modern Midwestern landscapes (see also Clayton, 1984; Johnson, 2000).

Soil development within the low-order tributary gullies (as well as on flatter landscapes nearby) was examined, assuming that if the gullies are old features, having formed as water flowed off the frozen Finger uplands, but stabilized shortly thereafter, the soils within them would be well-developed and perhaps even as strongly developed as nearby soils on stable, flat surfaces. Conversely, if the soils in the gullies are more weakly developed or showed evidence of recent erosion and/or overland flow, runoff from the Finger uplands could then be assumed to be an ongoing process and that the gullies post-date the Port Huron meltwater event. Therefore, invoking frozen ground as a means to reduce the permeability of the uplands and create runoff would not be necessary.

The data in Table 4 suggest that the soils in the gullies are as strongly developed (or even slightly stronger) than the soils on the flat Finger uplands or in the Finger valleys. Soils in the gullies have, for example, better developed E horizons and more often classify as Typic Spodosols than do soils elsewhere in the Fingers. This observation is supported by the Crawford County soil survey, which commonly maps Typic Haplorthods on the steep, gullied sideslopes and Entic Haplorthods on the bottoms of the Finger valleys (Werlein, 1998). These soil geomorphic data can be interpreted to mean that the gullies (and indeed, probably all of the sideslopes) were cut and stabilized at the same time as the Finger valleys were filled with outwash and stabilized. That is, the ages of all the geomorphic surfaces across the Fingers are generally the same. The slightly greater soil development in the gullies is probably due only to the enhanced microclimate there; cooler conditions favor podzolization, the dominant soil-forming process in this area (Mokma and Vance, 1989; Hunckler and Schaetzl, 1997; Schaetzl, 2002; Schaetzl et al., 2006).

Table 4
Soil development and slope data for gullied and flat sites within the Grayling Fingers

Parameter of comparison	Gully sites/soils	Finger upland sites/soils	Valley bottoms sites/soils	Best soil development on which sites?
No. of sites	40	15	26	n.a.
Slope gradient (%) (mean±SD)	13.5±8.0	0	0	n.a.
E horizon (mean color value)	5.0	4.8	4.5	Gullies
B horizon (mean color value)	3.7	3.9	4.0	Gullies
B horizon hues “browner” than 7.5YR (% of all soils)	20.0	20.0	11.5	Valley bottoms
Soils with distinct E horizon (% of all soils)	85.0	86.7	42.3	Uplands
Estimated soil classification (% of all soils)	Typic Haplorthods: 12.5% Entic Haplorthods: 72.5% Udipsamments: 7.5%	Typic Haplorthods: 6.7% Entic Haplorthods: 46.7% Udipsamments: 6.7%	Typic Haplorthods: 7.7% Entic Haplorthods: 50.0% Udipsamments: 42.3%	Gullies
Overall rank in soil development	1	2	3	Gullies

The soil geomorphic data presented here suggest that runoff from the Finger uplands, which could have eroded and transported away any infalling loess, dates to the time when Port Huron outwash was flowing through the Fingers. I suggest that any loess that was deposited onto the Fingers at this time was eroded on all but the flattest upland sites, which could not generate sufficient amounts of runoff. Silty sediment that is currently in dry, upland kettles was probably associated with stagnant blocks of ice and remained in the closed-basin kettle bottoms as the ice blocks melted. Alternatively, it could have been transported into the kettles by wind and gotten trapped in water that was present there.

Runoff from uplands was generated; and the deep, sideslope gullies cut at the time of the Port Huron advance because of the presence of frozen ground. Runoff has been minimal since that time because of the sandy, permeable nature of the sediments in the Fingers. Thus, most of the geomorphic surfaces in the Grayling Fingers have probably been stable since, and date to, the time of the Port Huron advance.

5. Conclusions

The geomorphology, soils, sediments, and stratigraphy of the Grayling Fingers have proven to be highly insightful in interpreting not only the landform assemblage's overall evolution, but also the immediate post-glacial evolution of the region. Stratigraphic data for the Fingers, reported by Schaetzl and Weisenborn (2004), reveal several meters of sandy till above a thick core of glacial outwash. The till and outwash are remarkably similar along many textural and mineralogical axes, suggesting that the till was derived mainly from its own proglacial outwash, or at the very least the outwash and till were derived from the same ice sheet in close temporal correspondence. The silty cap that lies atop the till on the flat uplands of the Fingers and in some dry kettle bottoms is a unique sediment to the Fingers, as textural and geochemical data show. Furthermore, the silty cap is *unlike* the till below it along many geochemical and textural axes.

All indications are that the silty cap is loess, derived from the Port Huron outwash plain and the Manistee River valley. The Buckley Flats, a small upland only 90 km to the SW of the Fingers, has a similar silty cap that has been shown to be loess, pointing to the efficacy of the Port Huron meltwater and sediments as loess sources. Given the proximity of the Port Huron ice margin to the Fingers, cold and windy conditions can easily be assumed for this time period. Lastly, in order to explain the distribution of loess on the Finger uplands, I suggest that the Fingers were largely frozen at the time of loess deposition, enhancing runoff on all but the flattest upland sites. This scenario explains why, today, loess is absent from sites that have even a slight amount of slope. Soil data also support this hypothesis, showing that the steep, gullied sideslopes of the Fingers have been stable and open to soil development for as long as other surfaces in the region. Runoff is almost nonexistent today, but had to have been occurring during the loess depositional event.

With respect to explaining the distribution of loess on Midwestern landscapes, this work points to the importance of surface stability in retaining any infalling loess in rapidly deglaciating, or recently deglaciated, landscapes. Slope stability is paramount to the preservation of loess on such landscapes; sites in the Fingers that were unstable during the loess depositional event do not, today, have a loess cover. This research also provides credible evidence of the likelihood of frozen ground in the interlobate region of the Grayling Fingers.

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