Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Geomorphology 61 (2004) 251–274
GEOMORPHOLOGY
www.elsevier.com/locate/geomorph

The Grayling Fingers region of Michigan: soils, sedimentology, stratigraphy and geomorphic development

Randall J. Schaetzl[a,*], Beth N. Weisenborn[b]

[a] *Department of Geography, Michigan State University, 315 Natural Science Bldg., East Lansing, MI 48824-1115, USA*
[b] *Center for Remote Sensing and Geographic Information Science, Michigan State University, 315 Natural Science Building, East Lansing, MI 48824-1115, USA*

Received 6 August 2003; received in revised form 14 January 2004; accepted 14 January 2004
Available online 6 March 2004

Abstract

This paper provides data on the landforms, soils, and sediments within a unique northern Michigan landscape known as the Grayling Fingers, and evaluates these data to develop various scenarios for the geomorphic development of this region. Composed of several large, flat-topped ridges that trend N–S, the physiography of the "Fingers" resembles a hand. Previously interpreted as "remnant moraines", the Grayling Fingers are actually a Pleistocene constructional landscape that was later deeply incised by glacial meltwater. The sediments that comprise the Fingers form a generally planar assemblage, with thick (>100 m), sandy glacial outwash forming the lowest unit. Above the outwash are several meters of till that is remarkably similar in texture to the outwash below; thus, the region is best described as an incised ground moraine. Finally, a thin silty "cap" is preserved on the flattest, most stable uplands. This sediment package and the physiography of the Fingers are suggestive of geomorphic processes not previously envisioned for Michigan.

Although precise dates are lacking, we nonetheless present possible sequences of geomorphic/sedimentologic processes for the Fingers. This area was probably a topographic high prior to the advance of marine isotope stage 2 (Woodfordian) ice. Much of the glacial outwash in the Fingers is probably associated with a stagnant, early Woodfordian ice margin, implying that this interlobate area remained ice-free and ice-marginal for long periods during stage 2. Woodfordian ice eventually covered the region and deposited 5–10 m of sandy basal till over the proglacial outwash plain. Small stream valleys on the outwash surface were palimpsested onto the till surface as the ice retreated, as kettle chains and as dry, upland valleys. The larger of these valleys were so deeply incised by meltwater that they formed the large, through-flowing Finger valleys. The silt cap that occupies stable uplands was probably imported into the region, while still glaciated. The Fingers region, a col on the ice surface, could have acted as a collection basin for silts brought in as loess or in superglacial meltwater. This sediment was let down as the ice melted and preserved only on certain geomorphically stable and fluvially isolated locations. This study demonstrates that the impact of Woodfordian ice in this region was mostly erosional, and suggests that Mississippi Valley loess may have indirectly impacted this region.

Keywords: Glacial geomorphology; Glacial stratigraphy; Soils; Till; Palimpsest landforms; Loess; Kettle chains

* Corresponding author. Tel.: +1-517-353-7726; fax: +1-517-432-1671.
E-mail address: soils@msu.edu (R.J. Schaetzl).

0169-555X/$ - see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2004.01.002

1. Introduction

The Grayling Fingers is a large landform assemblage in northern lower Michigan, formed mostly by Late Pleistocene glacial and glaciofluvial processes. Informally given the name "Grayling Fingers" by regional researchers, it was only recently referred to as such in published literature (Schaetzl, 2002). The name originates from its physiography, which consists of several large N–S trending ridges, much like fingers on a hand (Fig. 1). Some of the nomenclature of the individual Fingers (Fig. 1) stems back to the work of Burgis (1977, 1981), whereas some originates here. Very little research on geomorphology and stratigraphy has been done in this region. Indeed, until recently, these features were viewed as "remnants" of moraines (Burgis, 1977); the origins of the Fingers are, however, much more complex and generally do not involve solely ice-marginal depositional systems. By the late 1990s, most of the soils of the four counties that span the Fingers had been mapped by the Natural Resources Conservation Service (NRCS) at large scales, fueling this research. This paper represents the first major work on the soils and landforms of this region, with a goal of integrating this information into a discussion of its geomorphic and environmental history. In this paper, we will (1) present and discuss physical (geomorphic, pedogenic and stratigraphic) data about the Grayling Fingers and (2) utilize these data to ascertain the evolution of this landscape during and since the Late Pleistocene. In several instances, when a definitive process scenario for a sediment or a landform cannot be isolated, more than one is provided, along with data to support or refute each. Thus, like many geomorphic studies of large regions, all the "answers" are not yet in place, but ample data exist to justify reporting on what is now known.

2. Physiography and nearby landforms

The Grayling Fingers are located in northern lower Michigan, USA and are named for the city of Grayling, at the southern end of the Fingers (Fig. 1). They form a triangular assemblage of uplands that are about 43 km in width and 40 km in N–S extent with broad, flat valleys (hereafter: Finger valleys) between them. The Finger valleys are commonly 1.5 to 3.5 km wide and incised between 100 and 175 m below the adjacent uplands. First called "Grayling Channels" by Burgis (1981), the Finger valleys are today generally devoid of running water. Most even lack the imprint of an incised channel, implying that the valleys may have been wall-to-wall water at the time when they were cut by meltwater.

The highest elevations in the Fingers and the Finger valleys are in the north; the highest point on the Fingers is near the extreme northern tip of the Fayette Finger, at 463 m above sea level. Most uplands in the northern third of the Fingers range in elevation from about 400 to 450 m, while in the south, the summits are about 365 to 400 m above sea level. The gradient of the Finger uplands ranges from about 5.7 to 7.8 m km^{-1}; gradients of the Finger valleys range from $\approx$ 3.4 to 4.2 m km^{-1}.

The Fingers have broad, elongated uplands with broad, generally flat summits (a combined 721 km^2) (Fig. 2). The edges of these flat summits break abruptly to the much steeper slopes on the sides of the Fingers (Fig. 2). Many sideslopes are deeply incised by dry, almost rill-like valleys that grade steeply down to the 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 feature, such as a fan, exist at the contact of the steep side valleys and Finger valleys. Side slopes on the Fingers, within rill valleys and on undissected backslopes, often exceed 50% (Fig. 4).

The Grayling Fingers are part of a much larger interlobate region, centered primarily between the Lake Michigan and Saginaw lobes of the Laurentide Ice Sheet (Fig. 5; Leverett and Taylor, 1915). Rieck and Winters (1993), who called this region the North-Central Interlobate area (Fig. 5B), reported on the great thickness of the drift in northern lower Michigan—commonly >150 m across the interlobate area in general, and approaching 300 m in the Fingers. Much of this sandy and stratified drift is not directly glacigenic, but is more commonly associated with glaciofluvial processes. This broad sandy upland, dominated by glaciofluvial sediment and coarse-textured glacial drift, is known locally as Michigan's "High Plains" (Davis, 1935). It was deglaciated about 14–13 ka.

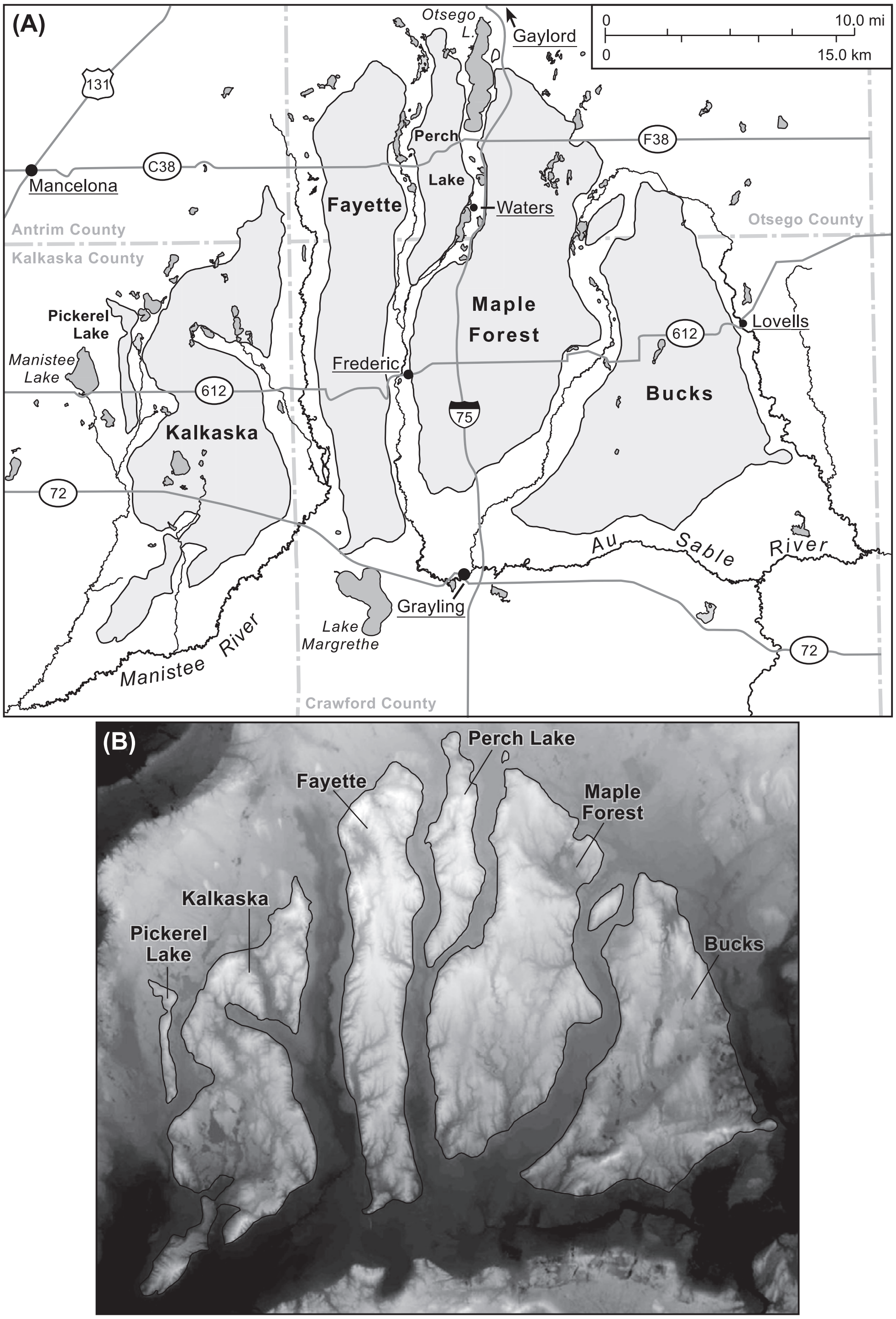

Fig. 1. General physiography and cultural features of the Grayling Fingers. (A) Base map with major place names, major rivers, and valleys. (B) Digital elevation model of the region with Finger Names; some names from Burgis (1977, 1981). Lighter shades imply higher elevations.

Fig. 2. Image of the summit of the Perch Lake Finger, showing flat top and abrupt edge. Image taken by RJS, along Mancelona Road, Section 13, T. 29 N., R. 4 W., Otsego County.

Contrary to the name, the High Plains have a significant amount of relief, such that local elevation differences between incised valleys and nearby uplands often exceed 50–80 m. Deeply and heavily kettled areas are also common, especially on outwash plains. Dry, sandy soils dominate this landscape, although many bogs and swamps are also present (Werlein, 1998).

The High Plains district is dominated by the large outwash plain of the Port Huron readvance of the Laurentide ice sheet (Leverett and Taylor, 1915). The Port Huron ice advanced to its farthest point ca. 13 ka (Blewett, 1991; Blewett et al., 1993; Blewett and Winters, 1995). The Port Huron head of outwash forms a conspicuous ridge on three sides of the Fingers. The valleys between the Fingers are generally graded to the Port Huron outwash plain; the Fingers rise above the Port Huron outwash surface. Set within the middle of the High Plains, the Grayling Fingers are the highest part of this northern Michigan landscape that serves as the drainage divide for the southern peninsula. Two of the largest rivers in Michigan—the Au Sable and Manistee—head in the northern part of the Fingers and exist as small streams within the otherwise overdeepened and underfit Finger valleys (Fig. 1). Indeed, large parts of the High Plains are devoid of flowing water; no streams originate outside of the region and flow entirely through it. Depth to bedrock in the Fingers region ranges from 200–300 m, based on oil and gas well log data.

To the south of the Grayling Fingers are several high, E–W trending ridges composed of coarse-textured, stratified sediment. Burgis (1981) referred to these uplands as kamic ridges. Unlike the Fingers, which are generally flat at the highest points, these ridges have acute apices and do not form a continuous upland.

Soils in the region reflect two major pedogenic processes: podzolization and lessivage. In the former, translocation of Fe, humus, and Al is promoted by coarse-textured parent materials and acidic forest litter (Lundström et al., 2000). In lessivage, clay-sized particles are translocated from the upper to the lower profile, forming a Bt horizon. Podzolization varies in strength across the Fingers region, being strongest in the NW (Mokma and Vance, 1989; Schaetzl, 2002). This pattern primarily results from climatic and vegetative patterns and is not reflective of parent materials. Thus, similar parent materials can have developed into sandy Entisols in the east and Spodosols in the west (Table 1). For the purposes of this research, podzolization does little to alter the

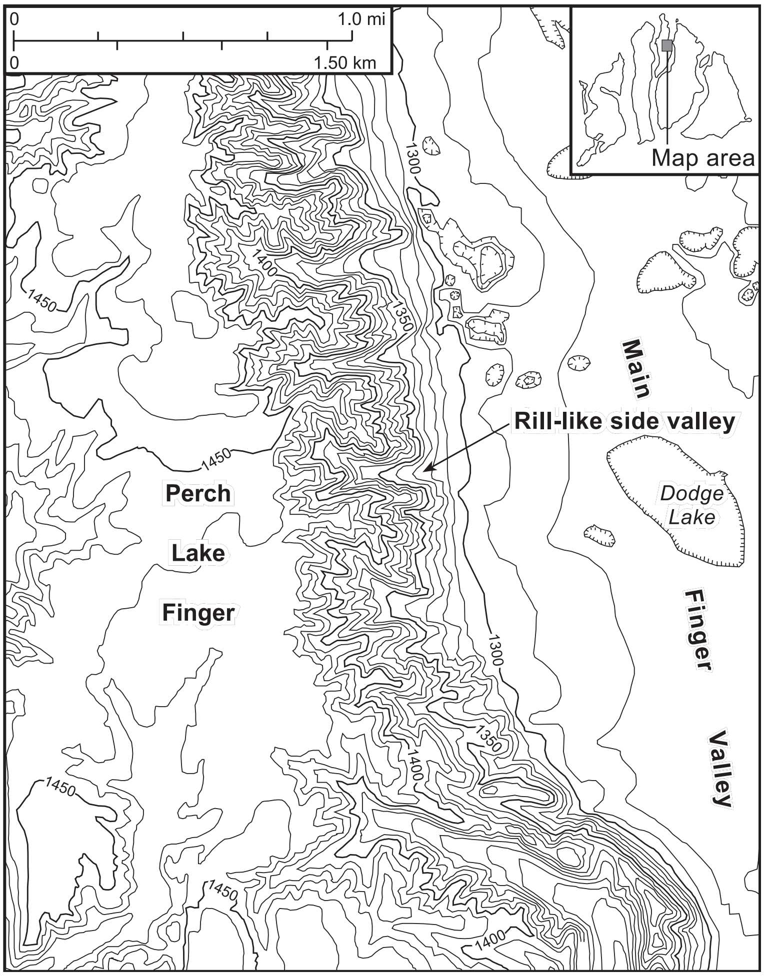

Fig. 3. Contour lines showing the topography on the top, along the side, and in the main valley that separates this Finger from its neighbor. The area shown is the eastern edge of the Perch Lake Finger. These types of steep side slopes with many rill-like valleys are common in the region.

distinguishing physical characteristics of the parent material. Lessivage is an ongoing process in all but the sandiest soils of the region. The morphology of the resultant Bt horizons varies as a function of clay content of the parent material (Schaetzl, 1992; Rawling, 2000). In sands with almost no clay, a Bt horizon does not form. In soils with 1–8% clay, illuvial bands of clay (lamellae) form, becoming thicker and closer to the surface as the amount of clay in the parent material increases. In still finer-textured parent materials, illuvial clay exists as continuous, rather than lamellic, Bt horizons (Khakural et al., 1993).

3. Methods

Our methods primarily involved field observation and measurement, followed by analysis of soils and sediment samples in the laboratory. We also employed a significant amount of map interpretation and field-checking. Because sandy soils dominate this landscape, roadbed materials only rarely have to be brought in from outside; hence, few gravel or borrow pits exist, within which deep stratigraphy can be observed. Only two large gravel pits exist in the ≈ 1500 km^2 that comprises the Fingers. Most subsurface data were therefore obtained at

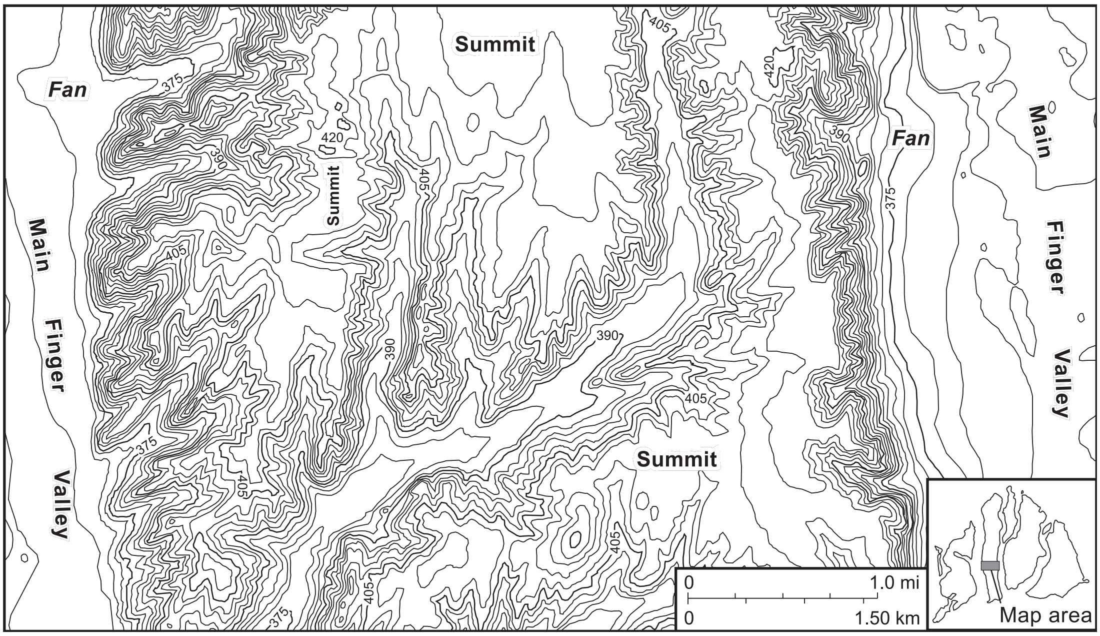

Fig. 4. Contour lines showing the topography across the Fayette Finger. Some of the isolated, flat summit areas and the side valleys have small fans at the ends, while others do not.

backhoe pits (2 m deep) and by hand-augering (5+ m deep).

Over 100 sampling locations were eventually selected based on geomorphology and soils data. Digital soils data from 1:20,000 maps were obtained from the NRCS. The soils of the Fingers span four counties which were mapped over different time periods. Therefore, some soil series are not mapped in all counties, even though they may exist in all. Thus, we determined which series correlated to others across county boundaries. As representative soils and the subjacent C horizons were sampled and described according to USDA procedures (Schoeneberger et al., 2002), the physical characteristics (e.g., stratification, texture, content of gravel, color, etc.) were noted, samples taken, and further quantification later performed in the laboratory. Using this information, each soil series was initially characterized as to parent material, e.g., sandy outwash. Continued research on the soils and stratigraphy helped refine our "field calls" regarding type of parent material. Because multiple, stacked parent materials exist [the contact between which is called a lithologic discontinuity (Schaetzl, 1998)], soils—based information was highly useful in identifying parent materials and contacts between them. Because the parent materials for the soils in this region were originally calcareous, it was a simple matter to determine the depth to "unaltered" parent material in the field, using weak HCl. In the laboratory, soil samples were submitted to particle size analysis (PSA) 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 (Beshay and Sallam, 1995; Tsai and Chen, 2000). Once the various stratigraphic layers were identified as to physical (but not necessarily genetic) characteristics, and the nature of the contacts determined, presence/absence and thickness were determined for various sites throughout the Fingers, usually by excavation and coring.

At 17 sites where sediment exists that had been determined to be basal glacial till, fabric data were generated by determining the alignment of 50 elongate gravel and cobble clasts that were >1 m below the surface (Mark, 1974; Dowdeswell and Sharp, 1986; Schaetzl, 2001).

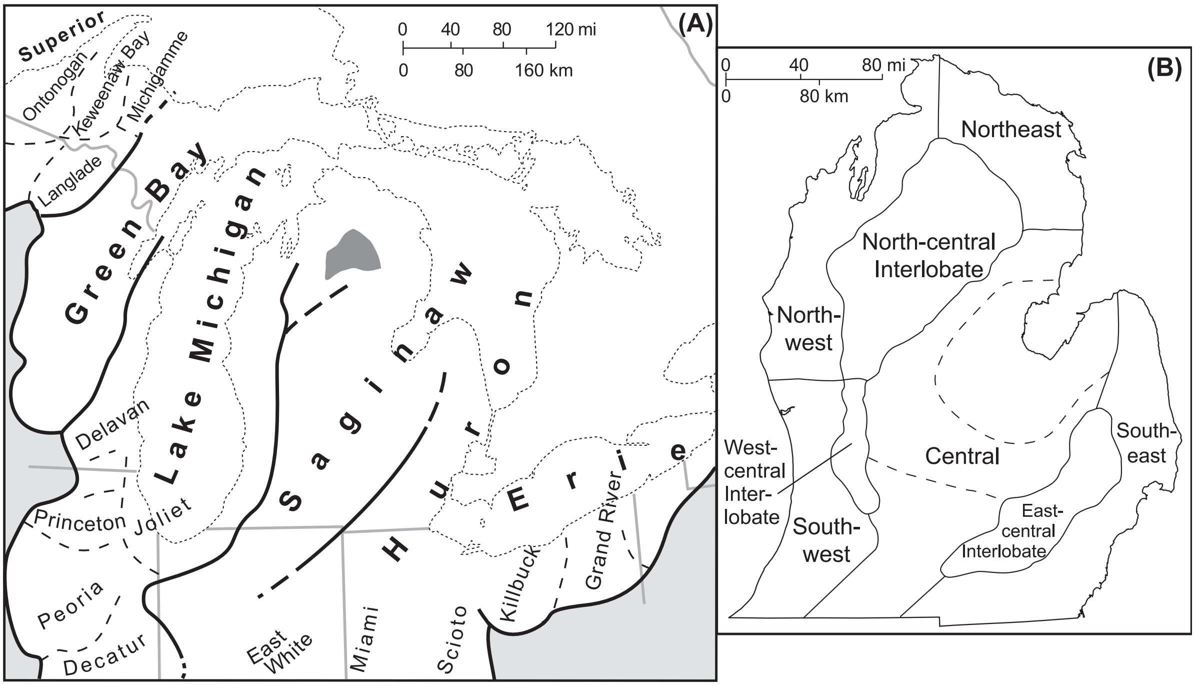

Fig. 5. Ice provinces in the Great Lakes region. (A) The major ice lobes of part of the Great Lakes region, with the location of the Grayling Fingers superimposed upon it. (B) Drift realms in Michigan's southern peninsula, with boundaries based on surface morphology; after Rieck and Winters (1993).

Data on subsurface geology were obtained by viewing core data from over 4000 water well logs, cataloged by the Michigan Department of Environmental Quality at http://www.deq.state.mi.us/well-logs/default.asp. Data on well depth and subsurface stratigraphy, specifically presence or absence of gravel and/or distinct clay strata, were determined for over 1000 wells that also provided specific USPLS coordinates. These data were then entered into a GIS. Data from wells that were located only to lot number, and those in Finger valleys, were noted but not included in the GIS database.

At six sites in and near the Fingers that had been determined to be on glacial outwash, samples were selected for optimally stimulated luminescence (OSL) dating (Forman, 1989; Aitken, 1994). Samples were collected from the deepest part of 2-m-deep soil pits, in the dark, and analyzed at the Luminescence Dating Research Laboratory at the University of Illinois at Chicago (UIC), using multiple aliquot regenerative-dose (MAR) techniques. Two of these sites were on the Port Huron outwash plain, in glaciofluvial sediment, which dates to about 13 ka. Six other sites were at various locations within main Finger valleys or in the outwash core of the Fingers. No samples were found on in situ material that could have provided useful ^{14}C ages.

4. Results and discussion

4.1. Glacial stratigraphy and soils

Soils, near-surface stratigraphic data, and well log data were used to identify three main parent materials (sedimentary deposits) in the Fingers. These sediments appear to be stacked in a sequence that, while variously intact across the region, does not vary in vertical arrangement.

Water well logs and the two deep pit exposures confirmed that the lowermost material in the Fingers is stratified, well-sorted sand or gravelly sand; we interpret this material to be glacial outwash. It is best exposed near the village of Waters, just east of the

Table 1
Taxonomic classification and presumed parent materials of the major soils of the Grayling Fingers region

Soil series	Subgroup classification	Parent material(s)[a]	Comments
Kalkaska	Typic Haplorthods	Outwash	
Rubicon	Entic Haplorthods	Outwash	
Grayling	Typic Udipsamments	Outwash	
Graycalm	Lamellic Udipsamments	Outwash	
Feldhauser	Lamellic Udipsamments	Silt/till (outwash at depth)	Found on flat summits of Fingers
Klacking	Arenic Glossudalfs	Silt/till (outwash at depth)	Mapped only in eastern Crawford County
Blue Lake	Lamellic Haplorthods	Till or till/ outwash	In Crawford County, this series includes soils mapped as Islandlake in other, later surveys
Islandlake	Lamellic Haplorthods	Till or till/ outwash	Mapped only in Kalkaska and Otsego Counties
Lindquist	Lamellic Haplorthods	Shallow till/ outwash or outwash only	Mapped only in Kalkaska and Otsego Counties
Hartwick	Entic Haplorthods	Gravel lag/ outwash	Not mapped in Antrim County; usually located only in valley bottoms

[a] Where more than one parent material commonly exists in a soil series, the slash (/) is used to connote the order of occurrence, with the uppermost parent material listed first.

northbound I-75 exit ramp (Fig. 6). Exposed at Waters is over 10 m of well-stratified and cross-bedded sand, interbedded with layers containing small, highly rounded gravel fragments. The fine earth fraction (< 2.0 mm dia.) of the sediment at the Waters cut is 99.4% sand, 0.4% clay, and 0.2% silt. Most gravel within the exposure is < 8 cm in diameter. These data are suggestive of clean meltwater transport from a fairly distant ice margin. Sedimentology at the site indicates that the outwash was deposited in shallow, braided streams that flowed roughly north to south (G. Weissmann, Michigan State University, personal communication, 2000). The surface of the outwash, determined to be the elevation of the uplands minus the thickness of the till, has a gentle N–S slope, which corroborates the conclusion that the outwash accumulated under the influence of N–S flowing, proglacial streams. Fig. 7 illustrates that the outwash at Waters is typical of that found throughout the region—both deep within the core of the Fingers as well as that immediately below the soil profile in the Finger valleys. The 37 outwash samples taken from over 20 sites throughout the Fingers, all below the influence of pedogenesis, i.e., in the C horizon, illustrate the regional uniformity in outwash texture. The outwash is always "sand" in texture, averaging 1.1% silt and 0.6% clay (Table 2). The outwash is also very uniform in color; it is typically light yellowish brown (Munsell moist color: 10YR 6/4). It usually contains < 5% coarse fragments (>2 mm dia.) and is frequently entirely lacking in coarse fragments (Table 2). This is one reason that few gravel pits exist in the Fingers region. At depth, however, strata containing gravel and cobbles, usually labeled "sand," "sand and gravel," or "sandy gravel" on well logs, are frequent. Over 800 of the 1120 water well logs in the GIS database mentioned gravel or stones in the subsurface.

Outwash comprises by far the largest volume percentage of the core of the Fingers (Fig. 8). At a large sanitary landfill pit within the Maple Forest Finger, outwash sand is >70 m thick (J. Werlein, NRCS, personal communication, 1998). Most domestic water wells in the Fingers region are shallower than 70 m, limiting the amount of deep stratigraphic information that is obtainable. One well, however, located on the top of the northern part of the Fayette Finger, reported sand and gravel to a depth of 104 m. Indeed, seldom does any well log in the Fingers region report any sediment other than "sand," "gravel," or "sand and gravel," although ≈ 100 of the 1120 wells in the database reported thin (< 5 m) strata of "sandy clay" or "blue clay," usually below 40-m depth. Given the ubiquity of sand and gravel in water wells, the Fingers appear to be cored with thick sequences of glaciofluvial sediment. Given the depth of valley incision and knowing the thickness of the two sedimentary layers that lie above it (see below), it is likely well over 150 m of outwash comprise the core of the Fingers.

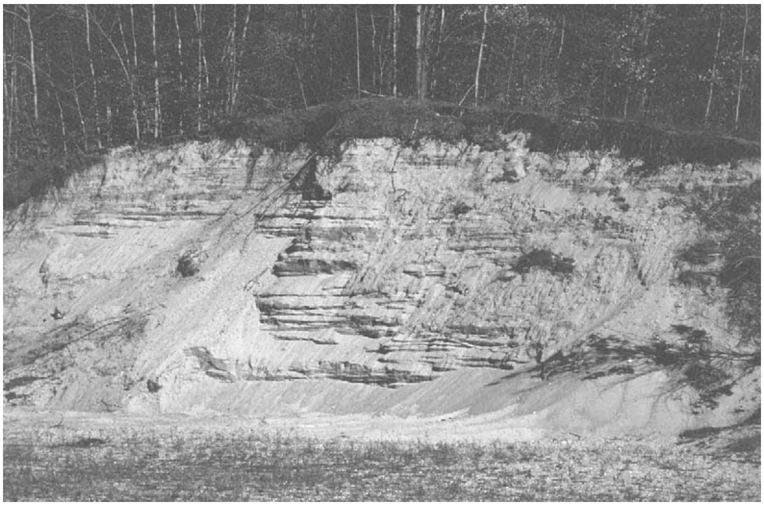

Fig. 6. Exposure of outwash sand near Waters, MI. This is the only significant exposure of the outwash that cores the Fingers proper.

Because outwash is exposed at the surface only where the overlying sediment has been eroded, soils formed in outwash exist primarily on sideslopes and in Finger valleys. Outwash-derived soils, e.g., Rubicon, Kalkaska, and Grayling (Table 1), comprise all areas of the Fingers except for parts of the uplands (Fig. 9). In side (rill) valleys, Hartwick soils are commonly mapped; these soils formed where fluvial erosion has cut into the outwash, leaving behind a lag concentrate of gravel and cobbles over outwash (Fig. 10A). In Finger valleys, this stone line is equally ubiquitous, although it is usually buried by 1–2 m of alluvium that may represent deposition immediately subsequent to the erosional episode that formed the stone line (Fig. 10). Stone lines are present in the valleys and continue uninterruptedly onto the side slopes above, gradually thinning until they become absent on the mid- to upper-backslopes. In most erosional settings in the Fingers, some sort of colluvial or lag deposit overlies the outwash.

On stable uplands, above the outwash, a sandy diamict interpreted as glacial till commonly exists. We have named this sediment the Blue Lake till for its unofficial type location near Blue Lake on the Kalkaska Finger (Table 2). This diamicton is interpreted as a till for several reasons: (i) it is unstratified and unsorted, (ii) it has a strong and consistent fabric

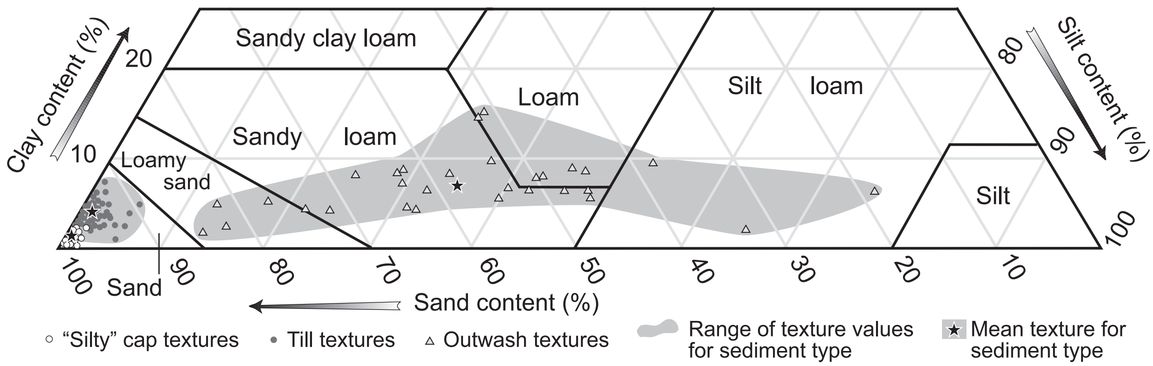

Fig. 7. Textural properties of the fine earth fraction (<2.0 mm dia.) of the three main sediment types in the Grayling Fingers, plotted on standard USDA textural triangles.

Table 2
Physical characteristics of the various sediments in the Grayling Fingers

	Units	Silt cap	Glacial till	Glacial outwash
Typical color	–	Varies, due to pedogenesis	10YR 4/4 (dark yellowish brown) and 10YR 5/4 (yellowish brown)	10YR 6/4 (light yellowish brown)
Gravel (>2 mm dia.)	Estimated % by volume	0–4	2–10 (6 is typical)	0–4
Sand (0.05–2 mm)	Mean % by weight	57.8	94.7	98.3
Silt (0.002–0.05 mm)	Mean % by weight	35.3	1.4	0.6
Clay (< 0.002 mm)	Mean % by weight	7.0	4.0	1.1
V Coarse sand (1.0–2.0 mm)	Mean % by weight	1.0	1.3	1.2
Coarse sand (0.5–1.0 mm)	Mean % by weight	9.4	13.9	14.4
Med sand (0.25–0.5 mm)	Mean % by weight	32.9	58.8	63.1
Fine sand (0.125–0.25 mm)	Mean % by weight	10.2	18.7	18.6
V Fine sand (0.005–0.125 mm)	Mean % by weight	4.4	2.0	1.1
Mean particle size	(um)	241 (fine sand)	381 (medium sand)	399 (medium sand)

across a wide area (Fig. 11), and (iii) it is superjacent to an obviously glacigenic sediment (outwash). Estimates of the volumetric content of coarse fragments, taken from numerous till exposures in the bottoms of soil pits, suggest that the till typically has from 2% to 10% coarse fragments. It has a slight pink hue, often exhibiting 10YR 4/4 (dark yellowish brown) or 10YR 5/4 (yellowish brown) Munsell colors (moist). The Blue Lake till has many similarities to the outwash below [e.g., the proportions of individual sand sepa-

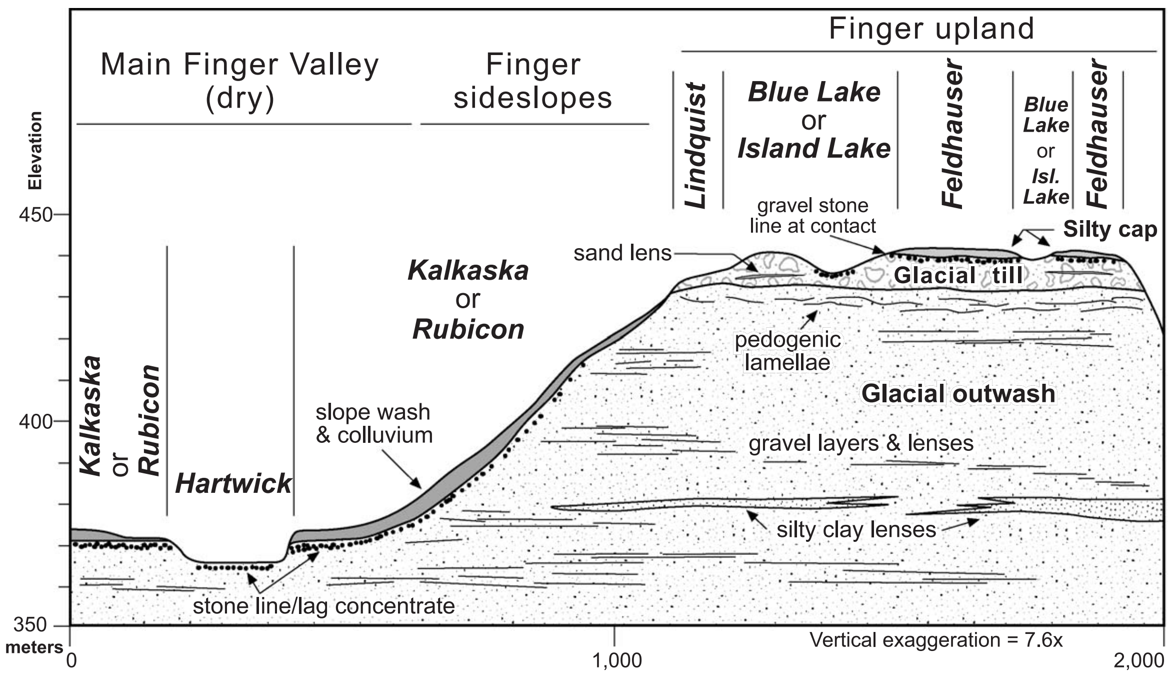

Fig. 8. Diagram of the internal stratigraphy and physiography of the Grayling Fingers, as exemplified by the three westernmost Fingers. Soil series names are shown above their representative landscape segments, in bold italics.

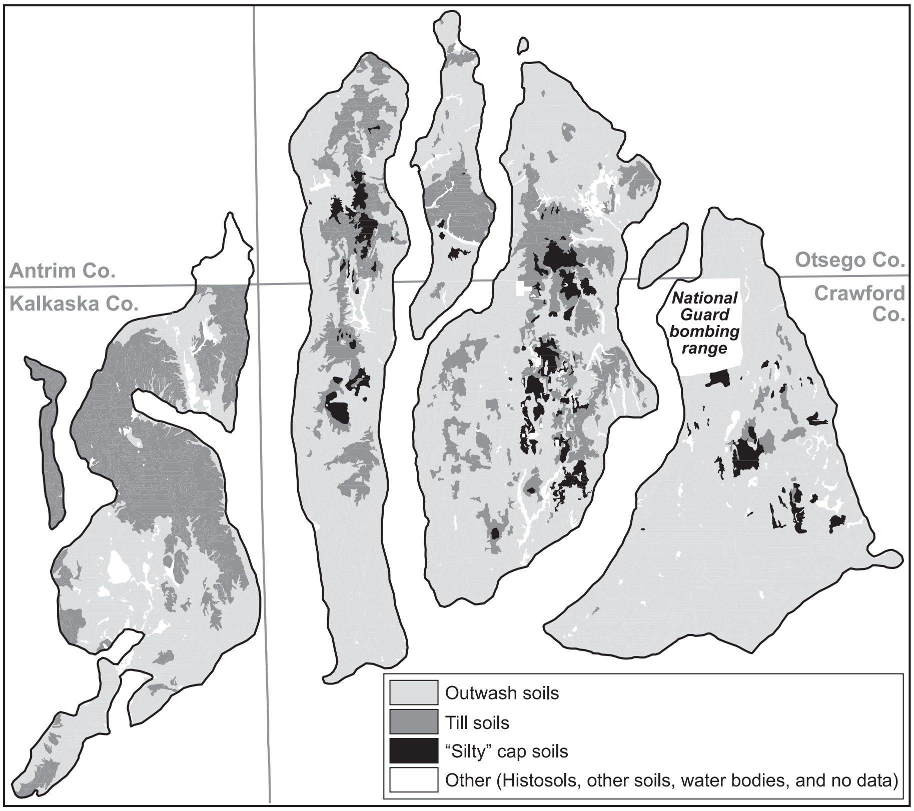

Fig. 9. Soils of the Grayling Fingers, grouped based on parent material.

rates in the till are remarkably similar to those in the outwash (Table 2)] and in the field the two can be confused. The till is pinker, however, contains more coarse fragments, is unstratified, and is also slightly finer textured, containing on average 1.4% silt and 4.0% clay (Fig. 7; Table 2). Of the 66 till samples analyzed, all have more clay than the typical outwash sample, and 42 are siltier. Thus, in the field, we used subtleties in color and texture to differentiate between these two sediments. Also, a stone line, gravelly zone, or sandy lens often coincide with the contact between the till and outwash, assisting in their differentiation. Sand lenses and gravelly zones also infrequently occur within the till.

We determined the distribution of the Blue Lake till based on maps of soils that had till parent materials (Table 1; Fig. 9). Specifically, Blue Lake, Islandlake, Feldhauser, and Klacking soils have all formed in till; some of these soils also had a thin (< 90 cm) silty cap above the till. The till is found only on high, stable Finger uplands; it is absent where these uplands have been incised (Fig. 8). The till is also frequently absent from Finger uplands, where they are generally lower in elevation (e.g., parts of the Kalkaska and Bucks Fingers), suggesting that in such locations, the till has been eroded across large segments of the upland landscape (Fig. 12). Lastly, it is absent in the southern part of the Fingers region, where the uplands are topographically lower than they are in the north (Fig. 12). Beneath geomorphically stable Finger uplands, the Blue Lake till is usually < 5 m in thickness, although on the far western edge of the Fingers, it attains thicknesses >10 m (Fig. 12). Based on till fabric data, which are remarkably consistent and strong across such a large area (Fig. 11), this till appears to have been deposited by a glacier that was moving generally from north to south.

The uppermost sedimentologic unit in the Fingers occurs only on the flattest, highest summits. Local soil scientists refer to this unit as a "silty cap," and so (for

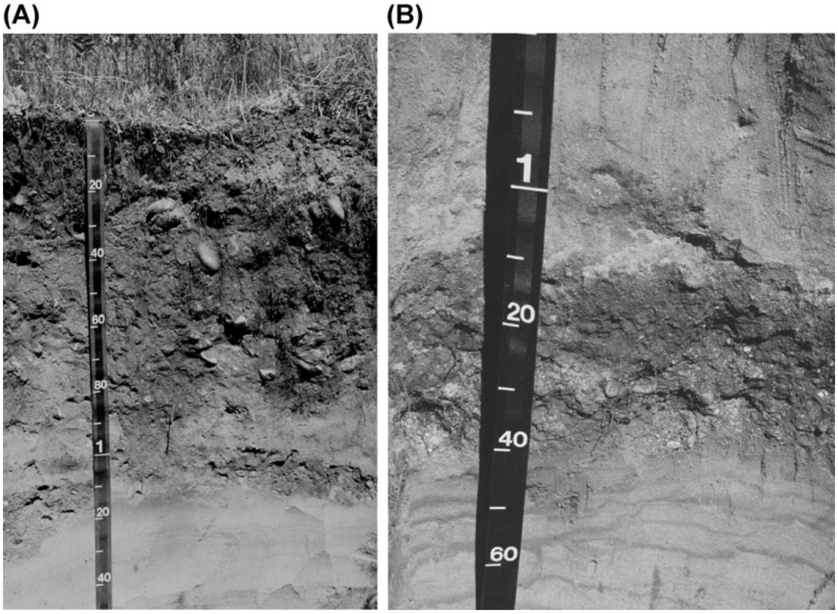

Fig. 10. Images of soils and sediments from the Grayling Fingers. Tape increments are in cm. Images by RJS. (A) Hartwick soil with a stone line of lag gravels at the surface, overlying clean outwash sand. This soil series is typically found in fluvially eroded side (rill) valleys and lower order dry valleys. (B) Closeup of a stone line that typically exists in the subsurface of soils in the bottoms and sides of the Finger valleys.

now) do we. The silty cap is seldom thicker than 90 cm and contains much more silt than do either of the two sediments below (Fig. 7; Table 2). In the 31 samples, we analyzed from silty caps at 14 different sites, only eight had silt contents of < 25%, and 12 had >40% silt. Only rarely does the cap have more than 9% clay. The color of the silty cap is not a distinguishing characteristic, since its ‘‘inherited’’ color has been largely masked by pedogenesis. Everywhere in the Fingers, the cap is within the soil profile. Where it contacts the till below, at a lithologic discontinuity, a stone line can occur, which has been accentuated by pedogenesis into a layer of illuvial humus. More commonly, however, the cap simply grades into the till below. The gradual transition between the two may, in these cases, reflect the original sedimentology of the units and/or millenia of bioturbation, especially by earthworms.

As we did with the Blue Lake till, we were able to determine the general distribution of the silty cap within the Fingers based on the soil series that contain it. Two series—Feldhauser and Klacking—contain the silty cap and both are mapped only on stable Finger uplands (Table 1). Soil maps verified our field observations that the cap is absent on sideslopes and in rill valleys. It is found only on the flattest, most stable uplands; even in slight swales or incised channels on the uplands, the silty cap is thinner or absent. We sampled and traced the cap along the top of the Fayette Finger upland, off the shoulder and into a rill valley. Along this, transect the cap, which at the top of the Finger was >75 cm thick and contained ≈ 40% silt, became thinner and sandier until at the shoulder (edge) of the upland, it was discontinuous and contained only about 12% silt. As the cap thins in this manner, pedoturbation mixes increasingly greater amounts of sand (from below) into it, making it sandier and rendering it less sedimentologically distinct. Eventually, on the upper backslope and below, the cap is missing, presumably due to erosion.

4.2. Geomorphic evolution of the Grayling Fingers

The Grayling Fingers are a plateau-like landscape with deeply incised N–S trending valleys. These landforms are composed of three distinct sediment packages, the largest which, by volume, is a sandy glacial outwash that makes up the core. It is generally

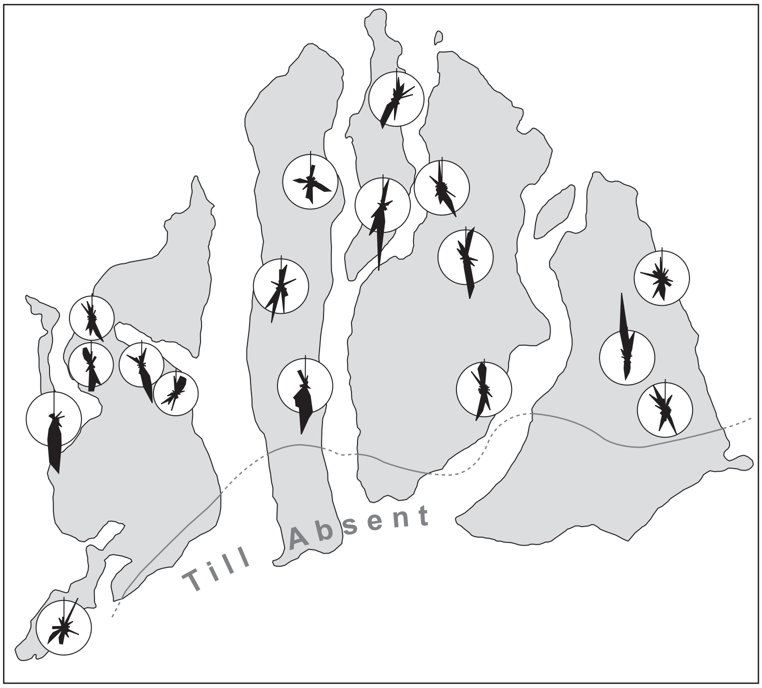

Fig. 11. Rose diagrams showing the till fabric for several sites within the Grayling Fingers. Each diagram is based on a count of at least 50 elongate stones.

clean (>98.5%), stratified sand with varying, although not large, amounts of coarse fragments. Well log data suggest that this sediment package extends more or less continuously across the entire landscape and attains thicknesses >100 m below uplands. Above the outwash is a sandy glacial till that, sedimentologically, very closely resembles the outwash. Informally named the Blue Lake till, this unit is typically <5 m in thickness. Till fabric data point to deposition from a glacier moving north to south. The till is preserved only on uplands; it is absent in the valleys and in the southernmost parts of the Fingers, presumably because it has been eroded from these sites. Lastly, on isolated locations on the very flattest parts of the Finger uplands, a thin (<1 m) cap of silty sediment forms the uppermost stratigraphic layer. On the sides of these valleys, the entire stratigraphic package is preserved, although it is usually buried by >1 m of colluvium and slopewash.

This sedimentologic–geomorphic relationship suggests that the genesis of this landscape involves, first, large-scale constructional processes, followed by incision and erosion. The almost ubiquitous presence of lag concentrate deposits and stone lines in the valleys attests to their erosional origins. The remainder of this paper is a discussion of the most likely geomorphic scenarios that were involved in the development of this landscape. Our discussion begins with the first sediment that was deposited and ends with the most recent processes that have shaped the landscape.

4.2.1. The outwash core

The bulk of the Fingers consists of stratified, sandy glaciofluvial sediment. Gravel content within this sediment is generally low and the gravel fragments are small; well logs indicate that by far the largest volume of material is simply "sand." Local residents refer to this sediment as "sugar sand." Data from samples taken in backhoe pits excavated into the outwash revealed that the fine earth fraction of the outwash is almost pure sand, with virtually no silt and clay (Fig. 7; Table 2).

The sandy outwash was almost certainly deposited by a glacier that had its margin north of the

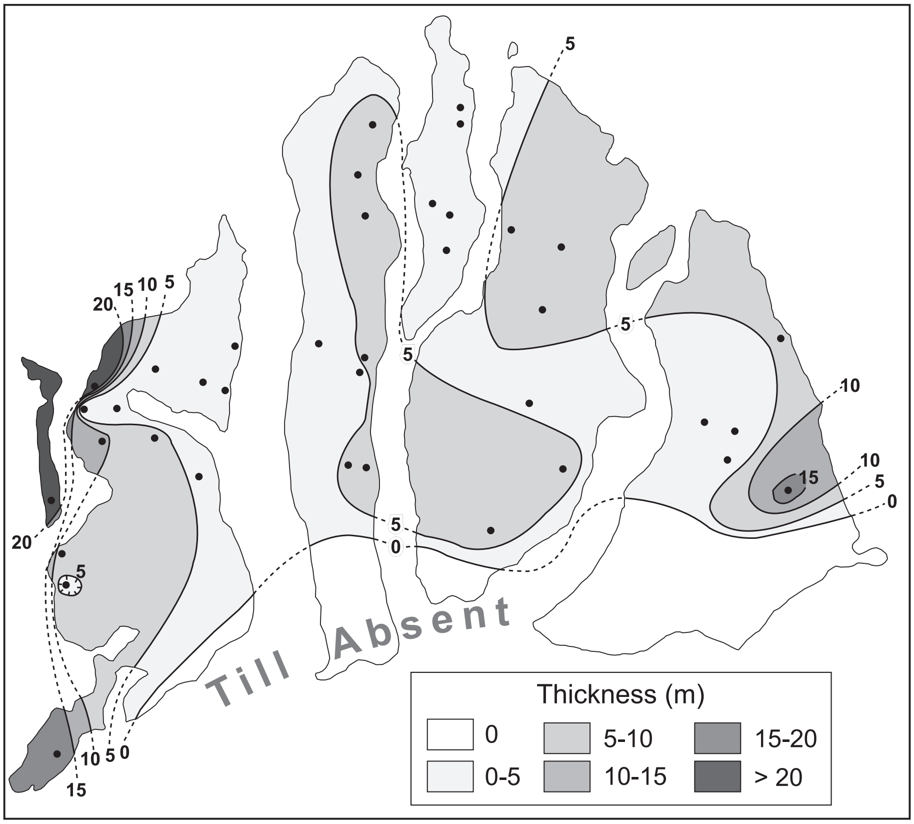

Fig. 12. Generalized maximum thickness of the sandy till unit on the uplands of the Grayling Fingers. Dots represent data points on flat uplands where core data established the actual thickness of the till.

region. This interpretation is based on the sedimentology of the outwash, at the one exposure large enough to show an adequate amount of sedimentary structure (i.e., near Waters), and corroborates with the current understanding that Pleistocene glaciers advanced into the region generally from the north (Farrand and Eschman, 1974; Larson and Schaetzl, 2001).

This proglacial outwash was later overridden by ice; several meters of till lies stratigraphically above it (Figs. 8 and 12). Large but muted flute-like structures on the Bucks Finger, which align with the till fabric data (Fig. 11), also point to a glacigenic origin for the surface morphology of the Fingers. The till is generally continuous across the Finger uplands, except where it has been removed by postglacial erosion (e.g., in incised valleys and near the topographically lower, southern end of the region) (Fig. 12). The till is also texturally so similar to the outwash (Fig. 7) that it is reasonable to assume that the till was derived locally. The primary source for the till was, therefore, the outwash below, which was entrained as the ice overrode it. This conclusion is supported by the strong till fabric, suggesting that it was primarily subglacial in origin. The lack of outwash deposits *above* the till indicates that, during ice recession, large-scale areas of proglacial deposition were centered outside of the Fingers.

Ascertaining the age of the outwash and the general ice sheet configuration at the time of its deposition is important to the interpretation of the origins of the Grayling Fingers. The large volume and areal extent of the outwash in High Plains district of Michigan, especially in the Fingers, imply that the period of proglacial, glaciofluvial deposition in this interlobate area was lengthy. One of two possible scenarios best explains the formation of the thick outwash sequence in the Fingers.

(i) It accumulated during various retreats of Middle and Late Pleistocene glaciers. Under this scenario, the outwash is primarily pre-Woodfordian in age, including Altonian and Illinoian advances, and the till above it is Woodfordian (stage 2) age.
(ii) It accumulated largely during the Middle to Late Wisconsinan, having formed in association with ice margins that generally stagnated in this area during marine isotope stages 4, 3, or 2.

The outwash cannot be associated with the *retreating* Woodfordian ice sheet (i.e., it is Late Woodfordian), for to be so would require that it then be overridden by that same ice; enough time probably did not elapse for this sequence of events to occur. Thus, we conclude that, eventually, a till-poor Woodfordian ice sheet advanced over a thick outwash sequence and buried it with basal till derived locally from the outwash below. Regardless of which of the above scenarios is most accurate, little or no outwash was deposited on this landscape by the retreating Woodfordian ice, because no known locations exist where outwash overlies till. Rather, the Woodfordian retreat in this area was likely associated with rapid erosion or non-deposition by meltwater.

Evidence in favor of the first scenario includes the knowledge that many glacial landscapes in Michigan and the Great Lakes region are palimpsest; a recent, increased emphasis on topographic inheritance has occurred within midwestern geomorphology (Winters and Rieck, 1982; Flint and Lolcama, 1986; Rieck and Winters, 1991; Kehew et al., 1999). By virtue of its interlobate location, this area would have been a locus of deposition for pre-Woodfordian glaciers (Rieck and Winters, 1993), making it logical to assume that the advancing Woodfordian ice would have encountered an overthickened area of drift in this region. Also, it seems unlikely that the large volume of glaciofluvial sediment in the Fingers could be associated with only one ice sheet.

Evidence in favor of the second scenario is equally compelling. First, sedimentologic data suggest that much of the upper 100 m of outwash could be similar in age, for if the outwash "uplands" were highly palimpsest, then buried soils, pockets of organic sediment, or weathered zones should be present in the subsurface. Such deposits have not been encountered. Nor have they been reported in published water well logs, although they are known to exist at many other locations in Michigan that literally surround the Fingers (Rieck and Winters, 1982; Rieck et al., 1991).

Finite radiocarbon dates on buried organic materials in the region have repeatedly indicated that the southern peninsula of Michigan was an ice-free tundra or boreal steppe during part of marine isotope stages 3 and 4 (Rieck and Winters, 1980; Gephart et al., 1982; Eschman and Mickelson, 1986). For example, Rieck et al. (1991) reported on a buried, ≈ 46,000-year-old peat in Manistee County, several tens of kilometers SE of the Fingers, indicating that the Fingers was almost certainly ice-free in late stage 4. These data suggest that stage 4 Altonian ice was slow to enter the center of the southern peninsula of Michigan. Instead, it was being diverted around the topographically high areas in the center of the peninsula; more rapid advances may have occurred along lobe streamlines, such as at the southern end of the Lake Michigan and Erie basins, and along the Saginaw Bay axis. Thus, the High Plains area may have been a topographically high, glacial "backwater" during the Late Pleistocene. This area may have been covered much later in time by the Woodfordian ice than were other areas of Michigan and also may have formed an ice-free inlier at a much earlier time during deglaciation than has been heretofore postulated. The high, interlobate, High Plains–Fingers region would have been the logical place for an advancing Woodfordian ice margin to stagnate as it slowly advanced onto the peninsula, providing opportunity for outwash deposition late in stage 3 and early in stage 2. The Late Woodfordian Port Huron readvance (ca. 13 ka) also stagnated in this region, with roughly the same ice-marginal configuration as the northern edge of the Fingers. The spatial coincidence between the Port Huron head of outwash and the northern margin of the Fingers is striking, again suggesting that ice streams were diverted around this region rather than over it because of its high elevation coupled with the large scour basins that already existed to the west and east. Although advancing glaciers are seldom associated with thick sequences of outwash, this part of Michigan is unique enough to warrant this possibility for at least three reasons: (i) glacial energy would have been focused in areas around the region, leading to a prolonged period of subaerial exposure during early stage 2; (ii) the area would have been one of the topographically higher areas in the Great Lakes region and perhaps the highest in southern Michigan; and (iii) ice stagnation landforms and sediments are common in the area (Blewett, 1991; Blewett and Winters, 1995).

The OSL dates reported for outwash from the Fingers (Table 3) are not highly precise but they are reasonable and useful when one realizes that they provide maximum constraining ages on the sediment. For example, the OSL ages on the Port Huron outwash, which is generally accepted to be ≈ 13k radiocarbon YBP (Blewett et al., 1993), are constrained by the OSL method but overestimated by about 10 ka (Table 3). OSL dates from the main core of the Fingers provide a maximum constraining age of about 28 ka, which is reasonable and fits within the scenario of early Woodfordian deposition—at least for the upper parts of the outwash core. The maximum constraining OSL ages on sands from the Finger valleys are younger than similar ages on outwash from the core of the Fingers, suggesting that the sands in the valleys may contain a luminescence signal that has been partially reset during the Holocene.

Table 3
Optically stimulated luminescence dates on outwash sand from sites within and near the Grayling Fingers

Site context	UIC sample number	Multiple aliquot additive dose (MAAD) age (ky)
Samples from near the top of the outwash core, near the top of the Finger uplands		
Top of Fayette Finger	799	28.7 ± 2.0
Top of Kalkaska Finger	800	38.4 ± 2.7
Samples from below the stone line in the incised outwash core, bottoms of Finger valleys		
Finger valley, east of Bucks Finger	795	19.9 ± 1.4
Finger valley, between Fayette and Maple Forest Fingers	811	23.2 ± 1.7
Samples from the Port Huron outwash plain		
Outwash plain, east of the Fingers	1016	23.8 ± 1.7
Outwash plain, west of the Fingers	1017	20.8 ± 1.5

Applying the OSL ages in a relative age assessment manner indicates that the outwash in the Fingers is no younger than that of the Port Huron readvance (as it cannot be) and likely is older. The implication is that the Fingers outwash is likely to be associated with early (advancing) stage 2 Woodfordian ice. Because the retreating Woodfordian ice could not have deposited the Fingers outwash, the next most logical age assessment would be an advancing but stagnant Woodfordian ice margin as the source of the outwash—at least the upper portions that were dated with OSL. The widespread presence of buried organic deposits along the margins of the southern peninsula of Michigan, dating between 30 and 50 ka (Rieck et al., 1991), illustrates that the center of the peninsula was subaerial during much (if not all) of stages 3 and 4. Thus, association of the outwash with a Middle Wisconsinan, Altonian ice sheet is unlikely; the terminus of this ice may have been much closer to the edges of the peninsula than the middle. Lastly, if the outwash were Illinoian or older, it would have been capped with a Sangamon paleosol or weathering zone; evidence of the existence of such a zone has not yet been unearthed.

Thus, although a definitive age cannot be assigned to the outwash, it is clearly older than the Port Huron advance (13 ka), and we suggest that much of it is likely associated with a slowly advancing and intermittently stagnant Woodfordian ice margin, placing it within the ≈ 38–28 ka window. The implications for this conclusion are that the Fingers region was ice-free much later into the Woodfordian than was heretofore assumed, and that it functioned as a locus of outwash deposition during that time.

4.2.2. The Woodfordian till

The sandy, Woodfordian till that overlies the outwash displays a very strong and uniform fabric, suggesting that it is a basal till. Its maximum thickness across most of the area is < 10 m, which is expected in this interlobate ‘‘backwater’’ area where ice flow—a process that brings large amounts of subglacial drift into a region—would have been infrequent or almost nonexistent. Till fabric data suggest that the Woodfordian ice that deposited this till advanced across the region from north to south (Fig. 11). Thus, the most correct genetic nomenclature for the Fingers region, based upon its widespread covering of till, is a dissected ground moraine.

Kettle chains are generally assumed to form when ice overrides preexisting valleys, leading to over-thickening of the ice and, upon retreat, a higher likelihood of ice blocks remaining on the landscape. Kettles and kettle chains are common across the Fingers uplands; they extend through the thin till cap and into the outwash below (Fig. 13). The kettle chains tend to run N–S, paralleling the direction of ice advance and aligning with the Finger valleys. In the Fingers region kettle chains document the existence of preexisting fluvial valleys; many even exhibit meandering forms (Fig. 14). The meandering morphology of many of these kettles cannot be relict from immediate post-glacial streams because ridges lie between the kettles. Thus, the kettle chains are interpreted as clear evidence that the landscape that the ice overrode—an outwash plain—contained a network of generally N–S flowing, braided and anastomosing streams.

In addition to kettle chains, the Finger uplands also contain numerous dry valleys (Fig. 15). Although some of the dry valleys are interconnected in a sort of crude

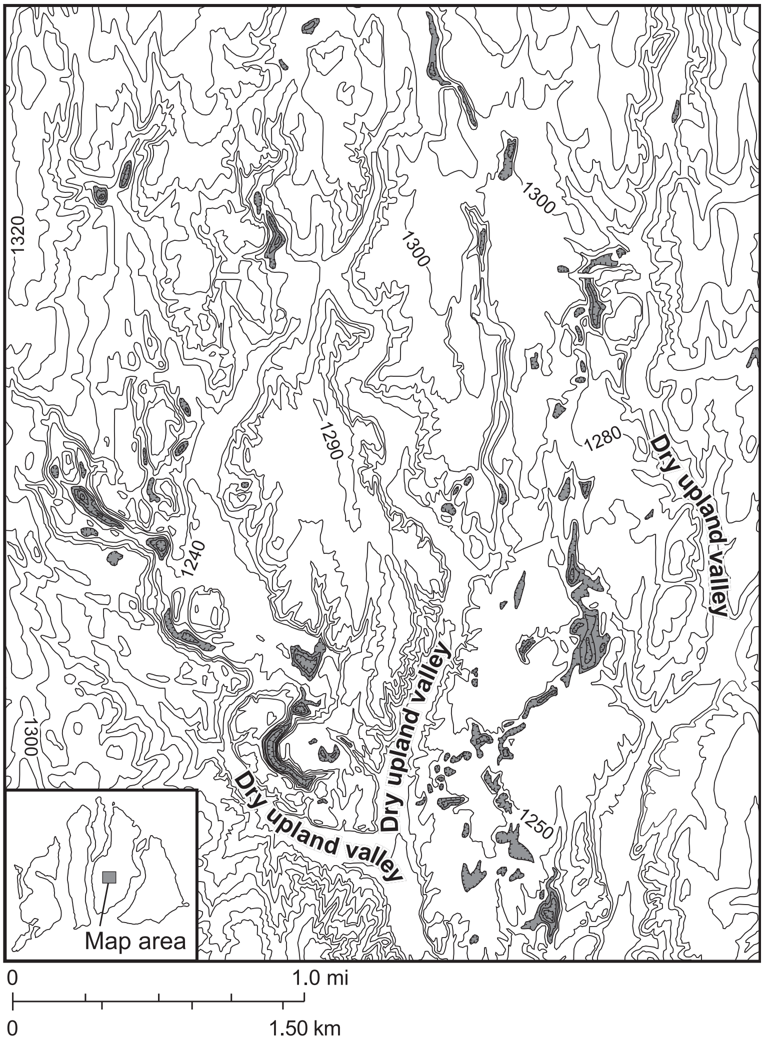

Fig. 13. Typical examples of kettle chains from the uplands in the Grayling Fingers. For ease of visualization, all kettles have been shaded with a gray fill.

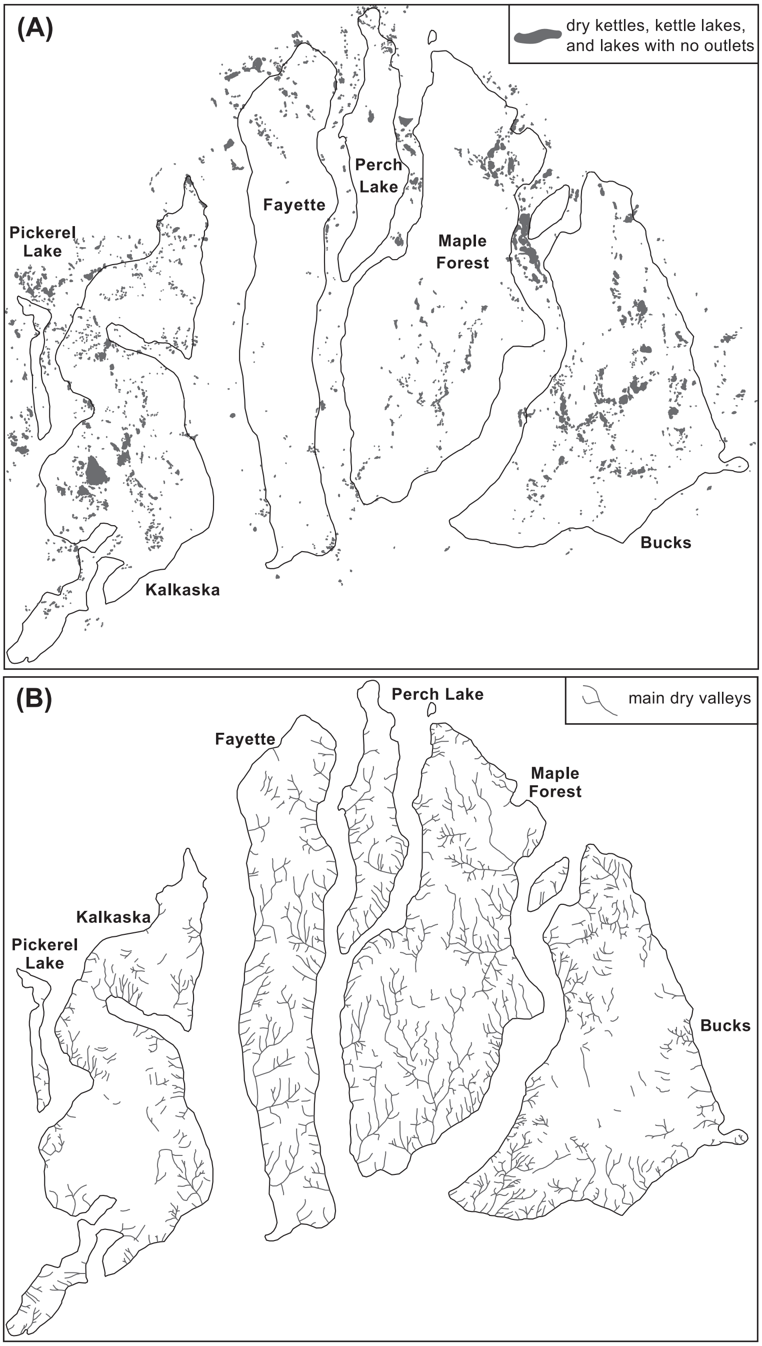

Fig. 14. Possible palimpsest features in the Grayling Fingers. (A) Dry kettles and kettle lakes. Lakes are included only if they have no outlet. (B) The main dry valleys on the Finger uplands.

but spatially broken drainage network, many are simply segments of larger valleys that end abruptly. Many of the dry valleys connect to kettle chains, again suggesting that the latter are linked to preexisting fluvial channels on the outwash surface (Winters and Rieck, 1982). As the ice margin began to retreat across the Fingers, meltwater may have reoccupied some of the preexisting meltwater valleys that were palimpsested onto the subaerially exposed till surface. Although these valleys may have formed subglacially, as tunnel channels during final deglaciation, direct morphological or geomorphic evidence of this, such as eskers or other stagnation features within the valleys, is lacking (Fisher and Taylor, 2002; Sjogren et al., 2002).

The deep Finger valleys that developed during and after ice retreat, coupled with the lack of outwash above the till, indicate that at this point in time, the glacial meltwater was not fully charged with sediment. Erosion, subaerial and also possible subglacial, was the dominant process during this period. Meltwater was occupying valleys that were manifested onto the till surface because of palimpsest reasons. Some of these valleys became preferentially enlarged, capturing most of the drainage and becoming Finger valleys, while others carried meltwater for only a short period of time. These latter types of valleys remain today as dry valleys on the Finger uplands (Fig. 14).

4.2.3. Silty sediment in the Grayling Fingers

The silty cap on stable, generally uneroded upland sites in the Fingers is, texturally, quite different from

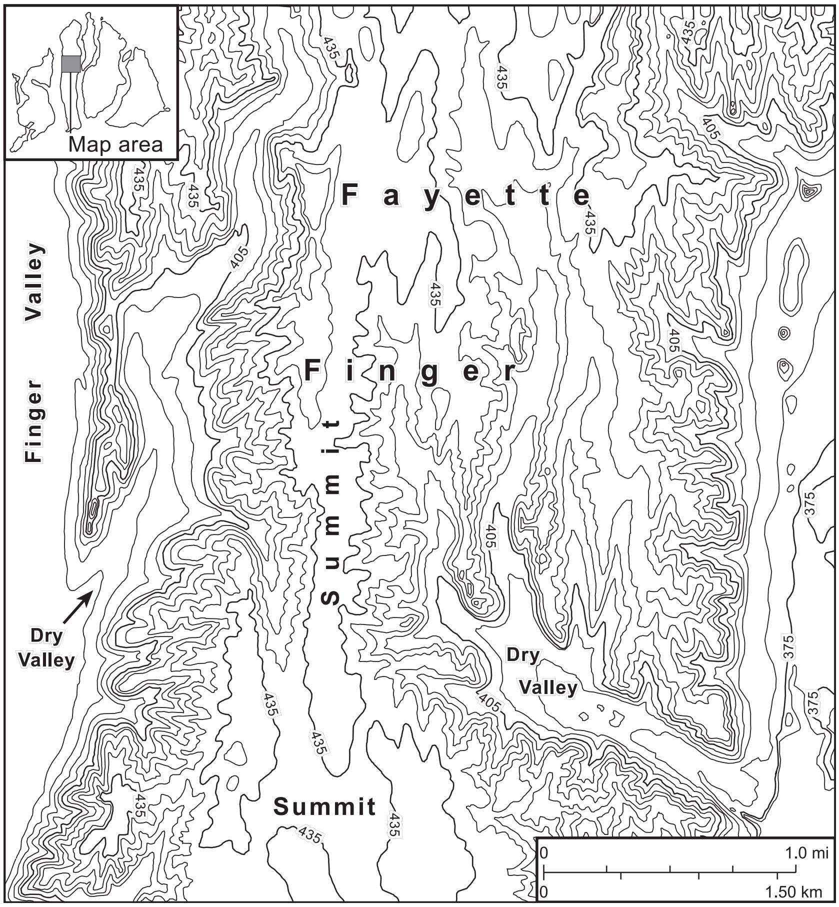

Fig. 15. Topographic expression of the dry valleys on the Fingers uplands, showing their relationship to the Finger valleys. Contour interval 6 m.

the outwash or till below. Unlike the outwash and till, which average < 1.5% silt, the cap sediment is over a third (35.3%) silt (Fig. 7). Thus, it is not likely that the silt is an ablation till, or that it was even brought into the region englacially.

Although the outwash and till are texturally (and genetically) dissimilar to the cap sediment, another silty sediment can be found in the Fingers. In the bottoms of many dry kettles, up to a meter of silty sediment forms the uppermost mantle, usually overlying outwash sand. The silt does not extend up the sides of the kettles. It can also be found on landscapes where the uplands lack the silty cap and are capped only by the silt-poor till. The lack of appreciable sand in the kettle silts points to an origin not directly associated with the sand-rich glacier discussed earlier; a similar conclusion can be made for the silty cap material.

The silty cap and the silt in kettle bottoms may have related origins because they both overlie glacigenic sediment but are not directly associated with the glacial system, and they were the last sediment to be deposited on the respective geomorphic settings. Because these two silty sediments overlie but do not occur within glacial deposits, it is reasonable to conclude that they were imported into the Fingers via a non-glacial system. 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 the kettles has no upslope source. Fluvial transport can be eliminated for the same reasons. The one remaining geomorphic system, and the one that seems likely, is eolian. Long-distance transport of eolian silts onto the ice sheet is a scenario that appears to answer many sedimentologic and geomorphic disconnects associated with the stratigraphy and sediments in the Fingers. It answers and explains a number of questions that exist regarding the evolution of the Fingers and the sediments therein: (i) why sediment of such different texture could have accumulated on the upper parts of this predominantly sandy landscape—it came from outside the landscape; (ii) why the silt is the *uppermost* sediment on the Fingers uplands and in many kettles—it had accumulated as a carapace on the ice surface and was let down as the ice ablated; (iii) why silt exists in kettles surrounded by sand uplands that contain almost no silt—the silt was present on the surface of the ice and in its uppermost parts, and as the ice melted the silt was retained in the kettle; and (iv) why the silty cap exists only on the flattest, highest uplands—on lower sites, it was eroded by meltwater, leaving behind only till or in cases of greater erosion, outwash.

Long distance eolian transport of loess onto the ice surface was occurring during the period in time when the Fingers region was ice-covered, as regional winds at this latitude, during the Woodfordian maximum, were strong and westerly (Fehrenbacher et al., 1965; Putman et al., 1989; Muhs and Bettis, 2000). Most of these loesses had as a source region the meltwater-fed flood plains of the Mississippi and Missouri valleys (Forman et al., 1992; Mason, 2001; Bettis et al., 2003; Fig. 16). Small amounts of any of these loesses could have been brought into the region on westerly winds. The Roxana silt and its correlatives the Pisgah Formation and Gilman Canyon Formation are generally assumed to date to the interval 34–23 ka (Forman et al., 1992; Maat and Johnson, 1996). Peoria Loess, the dominant and thickest loess in the upper Midwest, has basal dates of about 27–22 ka (Forman et al., 1992). Loess deposition could have ended as early as 14 ka, but certainly did by 11 ka (Muhs and Bettis, 2000). If one operates on the assumption that the Fingers became ice-free shortly before the Port Huron readvance, ca. 13 ka, then the High Plains would have been ice-covered during the bulk of the period of Peoria Loess deposition interval and during at least some of the period of Roxana silt deposition. Because Roxana silt deposits are so thin and confined to areas near the source regions (Johnson and Follmer, 1989; Leigh, 1994), it is unlikely that measurable amounts of Roxana were transported into the Fingers region. The blanket of Peoria Loess, which is meters thick in western Wisconsin, thins considerably across Wisconsin (Fig. 16); many have long assumed, therefore, that any Peoria silt deposited in Michigan was so thin as to be undetectable. A small amount of silt, however, was probably deposited here. Given that the Fingers region was a regional low—a col between the Lake Michigan and Saginaw lobes—on the ice sheet surface, it is a likely place for any eolian, superglacial deposits to collect, perhaps even within ephemeral superglacial lakes. Generally, such carapace deposits never survive the chaotic events associated with deglaciation. In the Fingers region, however, deglaciation may have been relatively benign compared to locations nearer the

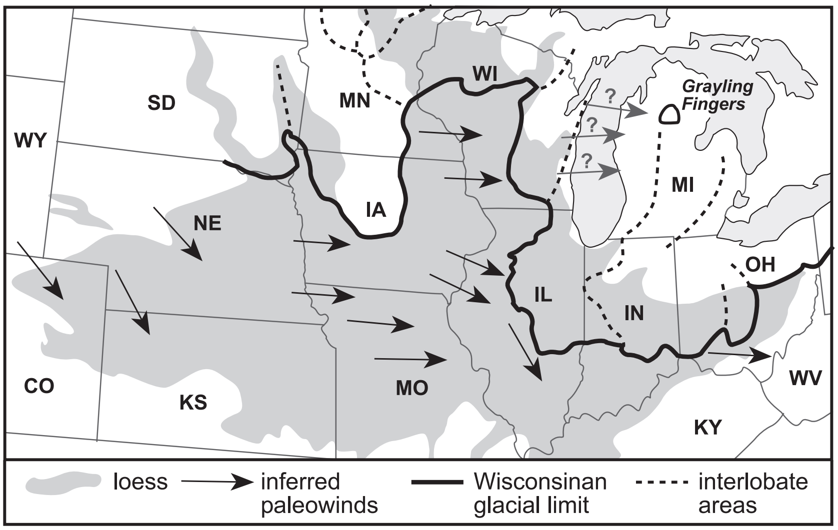

Fig. 16. Peoria loess occurrence and thickness in the upper Midwest, USA; after Grimley (2000) and Muhs and Bettis (2000).

axes of the main ice lobes. Whereas most of the superglacial, eolian/lacustrine silt was washed off the ice during deglaciation, some appear to have remained on upland sites where it was protected from disturbance by meltwater and debris flows.

4.2.4. The Finger valleys

The many dry upland valleys and Finger valleys must date to postglacial incision events, because they are cut into only known till in the region. By the principle of ascendancy and descendancy, an erosion surface (such as are in these valleys) must be younger than the youngest deposit or surface that it truncates (Hallberg et al., 1978). The sides of the Finger valleys, which contain lag gravels, cut the outwash, till and silty cap sediments, implying that the erosion (or collapse) of the valleys post-dates the deposition of these sediments. Because the sediment and soils in the region are so sandy and permeable, the valleys were most likely cut in immediate postglacial time by glacial meltwater. Field observations indicate that runoff is rare in this highly permeable landscape; even on the steep Finger sideslopes where rill valleys are common, runoff is minimal or nonexistent in all but the very largest storms. Soil development in the bottoms of the rill and Finger valleys is comparable to that on the uplands, indicating generally similar ages for both surfaces and pointing to erosion in immediate post-glacial time. Thus, we conclude that meteoric water, even when taken cumulatively over the past 14 ka, did not induce enough runoff to carve valleys of the size and scale seen in the Fingers. The only water source that could have existed at the northern end of the Finger valleys that would have been large enough to cut these valleys is a melting glacier. The floors of the Finger valleys also grade imperceptibly to the highly constructional Port Huron outwash plain that surrounds the Fingers on the north, east, and west, again suggesting a meltwater connection.

How much erosion or infilling occurred in the Finger valleys during the Port Huron readvance and stillstand is not known, but because of the gradient connections between the two surfaces (the floors of the Finger valleys and the Port Huron outwash plain), some Port Huron meltwater did flow through the Finger valleys. Indeed, the Finger valleys vaguely connect to cols on the Port Huron moraine. Any sediment eroded off the Finger uplands and transported to the Finger valleys as fan deposits would have been removed from the region by Port Huron meltwater that filled the valleys wall to wall. This scenario explains why there are so few fan deposits where side and upland valleys intersect the Finger valleys. Burial, rather than erosion, of these fans by Port Huron outwash would imply a large aggradation event during Port Huron time. This scenario seems unlikely because no partially buried fans exist, and onlap of outwash sediment onto valley-side fans was neither indicated on topographic maps nor observed in the field.

The dry upland valleys, which are at least partly palimpsest from the underlying outwash surface, provide additional information about the formation of the Finger valleys. Many of these valleys parallel the Finger valleys for some distance, even though the dry valleys are within a few hundred meters from the much deeper Finger valleys (Fig. 15). In an unconstrained fluvial system, this type of pattern would not have developed; the upland stream would have taken the shorter and steeper path to the Finger valley. Two possible explanations exist for this pattern: (i) the Finger valleys were cut after the upland valleys, or (ii) the Finger valleys were ice-filled but the Finger uplands were subaerial when the upland valleys were cut. Both are likely to have occurred during deglaciation. The most likely scenario of the two involves incision of an assemblage of upland valleys by meltwater as the ice margin retreated across the Fingers; the locations of these valleys would have been largely dictated by palimpsest relationships to the outwash valleys that had preexisted. As this network of valleys is revealed on the surface and reinforced by meltwater from the receding ice margin, several of the larger, north–south trending ones became more deeply incised and widened as they capture increasing amounts of meltwater. These became the Finger valleys. Several examples of valleys of intermediate size, larger than the dry upland valleys but smaller than the Finger valleys occur in the region (Fig. 15); had the meltwater event lasted longer, these, too, would have been incised to same the degree as the Finger valleys.

The deglacial-meltwater period in the Fingers was one of rapid erosion and transport of sediment out of the region. Valley incision was intense, but quickly slowed as the source of meltwater withdrew to the north.

5. Conclusions

The Grayling Fingers are a highly palimpsest landscape that may be older than many late Woodfordian landscapes in Michigan. Although detailed interpretations are difficult because of lack of precise dates, the general sequence of geomorphic/sedimentologic processes that formed the region is known.

The Fingers area was probably a topographically high, sandy region prior to the advance of the marine isotope stage 2 (Woodfordian) ice. Given that the region was ice-free during at least part of stage 4, it is unlikely that Altonian ice could have contributed large amounts of outwash here. We suggest that the uppermost part of the thick (>100 m) deposits of glacial outwash accumulated as an advancing Woodfordian ice margin stagnated in the region. The implications of this conclusion are that this part of Michigan remained ice-free and ice-marginal for longer periods of time during stage 2 than has been previously recognized—perhaps even as much of southern lower Michigan was covered with ice. Eventually, the region and its thick outwash deposits were buried by Woodfordian ice, which advanced from the north and generally deposited 5–10 m of sandy basal till. Kettle chains, many of which have meandering forms, are common on Finger uplands, indicating that ice advanced over an outwash surface that had a fully developed drainage network. These river valleys were palimpsested onto the till surface as the ice retreated, as kettle chains and as continuous, dry, upland valleys. These valleys were reoccupied by meltwater; the larger ones were so deeply incised that they quickly captured the majority of the meltwater, forming the large, through-flowing Finger valleys.

The silt cap on stable upland sites is texturally unlike any of the glacigenic sediments in the Fingers, suggesting that it was imported into the region from outside—probably blown in as loess but also perhaps washed in as superglacial lacustrine sediment. The Fingers region, a col on the ice surface, could have acted as a superglacial collection basin, which was eventually let down as the ice melted and preserved only on certain geomorphically stable and fluvially isolated locations. Sediment of similar textural composition is also commonly found in the bottoms of dry upland kettles. In these settings, the only possible source of the silt was the ice block; the surrounding uplands are dominated by sand. However, the ice was carrying virtually no silt, as evidenced by its till, implying that the silt in the ice block was a superglacial sediment. This may be the first reported instance of superglacial loess inheritance on a landscape.

Our study of the Grayling Fingers is important because it suggests that Mississippi valley loess had impacted this region. We present the first evidence for silty, loess-like sediment in southern Michigan, as a carapace of superglacial silt was let down during deglaciation and preserved because of the unique geomorphic circumstances in the Fingers, whereby meltwater was largely and quickly diverted off the uplands and into the Main Finger valleys.

Acknowledgements

This study was supported by the National Science Foundation under Grant No. 9819148 made to R.J.S. We are thankful to the following people who assisted in the field and lab: Joe Hupy, Alan Arbogast, Dave Lusch, Grahame Larson, Kevin Kincare, and Laura Beeman. Steve Forman kindly agreed to run the OSL samples and read an earlier draft of the paper. The interpretations made in the paper, however, are ours.

References

Aitken, M.J., 1994. Optical dating: a non-specialist review. Quat. Geochronicle 13, 503–508.

Beshay, N.F., Sallam, A.S., 1995. Evaluation of some methods for establishing uniformity of profile parent materials. Arid Soil Res. Rehabil. 9, 63–72.

Bettis III, E.A., Muhs, D.R., Roberts, H.M., Wintle, A.G., 2003. Last glacial loess in the conterminous USA. Quat. Sci. Rev. 22, 1907–1946.

Blewett, W.L., 1991. Characteristics, correlations, and refinement of Leverett and Taylor's Port Huron Moraine in Michigan. East Lakes Geogr. 26, 52–60.

Blewett, W.L., Winters, H.A., 1995. The importance of glaciofluvial features within Michigan's Port Huron moraine. Ann. Assoc. Am. Geogr. 85, 306–319.

Blewett, W.L., Winters, H.A., Rieck, R.L., 1993. New age control on the Port Huron moraine in northern Michigan. Phys. Geogr. 14, 131–138.

Burgis, W.A., 1977. Late-Wisconsinan history of northeastern lower Michigan. PhD Dissertation, Univ. of Michigan, Ann Arbor.

Burgis, W.A., 1981. Late-Wisconsinan history of northeastern lower Michigan. Guidebook, 30th Midwest Friends of the Pleistocene Field Trip. Univ. of Michigan, Ann Arbor.

Davis, C.M., 1935. The High Plains of Michigan. PhD Dissertation, Univ. of Michigan, Ann Arbor.

Dowdeswell, J.A., Sharp, M.J., 1986. Characterization of pebble fabrics in modern terrestrial glacigenic sediments. Sedimentology 33, 699–710.

Eschman, D.F., Mickelson, D.M., 1986. Correlation of glacial deposits of the Huron, Lake Michigan and Green Bay lobes in Michigan and Wisconsin. Quat. Sci. Rev. 5, 53–57.

Farrand, W.R., Eschman, D.F., 1974. Glaciation of the southern peninsula of Michigan: a review. Mich. Acad. 7, 31–56.

Fehrenbacher, J.B., White, J.L., Ulrich, H.P., Odell, R.T., 1965. Loess distribution in southeastern Illinois and southwestern Indiana. Soil Sci. Soc. Am. Proc. 29, 566–572.

Fisher, T.G., Taylor, L.D., 2002. Sedimentary and stratigraphic evidence for subglacial flooding, south-central Michigan, USA. Quat. Int. 90, 87–115.

Flint, J.J., Lolcama, J., 1986. Buried ancestral drainage between Lakes Erie and Ontario. Geol. Soc. Amer. Bull. 97, 75–84.

Forman, S.L., 1989. Applications and limitations of thermoluminescence to date Quaternary sediments. Quat. Int. 1, 47–59.

Forman, S.L., Bettis III, E.A., Kemmis, T.J., Miller, B.B., 1992. Chronologic evidence for multiple periods of loess deposition during the Late Pleistocene in the Missouri and Mississippi River Valley, United States: implications for the activity of the Laurentide Ice sheet. Palaeogeogr. Palaeoclimatol. Palaeoecol. 93, 71–83.

Gephart, G.D., Monaghan, G.W., Larson, G.J., 1982. A mid-Wisconsinan event in the Lake Michigan basin. Abstr. Programs - Geol. Soc. Am. 15, 260.

Grimley, D.A., 2000. Glacial and nonglacial sediment contributions to Wisconsin episode loess in the central United States. Geol. Soc. Amer. Bull. 112, 1475–1495.

Hallberg, G.R., Fenton, T.E., Miller, G.A., Luteneggar, A.J., 1978. The Iowan erosion surface: An old story, an important lesson, and some new wrinkles. Guidebook, 42nd Annual Tri-State Geol. Field Conf., Geology of East-Central Iowa. Iowa Geological Survey, Iowa City, pp. 2-1–2-94.

Johnson, W.H., Follmer, L.R., 1989. Source and origin of Roxana silt and middle Wisconsinan midcontinent glacial activity. Quat. Res. 31, 319–331.

Kehew, A.E., Nicks, L.P., Straw, W.T., 1999. Palimpsest tunnel valleys: evidence for relative timing of advances in an interlobate area of the Laurentide ice sheet. Ann. Glaciol. 28, 47–52.

Khakural, B.R., Lemme, G.D., Mokma, D.L., 1993. Till thickness and argillic horizon development in some Michigan Hapludalfs. Soil Surv. Horiz. 34, 6–13.

Larson, G., Schaetzl, R.J., 2001. Origin and evolution of the Great Lakes. J. Great Lakes Res. 27, 518–546.

Leigh, D.L., 1994. Roxana silt of the upper Mississippi Valley: lithology, source, and paleoenvironment. Geol. Soc. Amer. Bull. 106, 430–442.

Leverett, F., Taylor, F.B., 1915. The Pleistocene of Indiana and Michigan and the History of the Great Lakes. U.S. Geol. Surv. Mon. 53 (529 pp.).

Lundström, U.S., van Breemen, N., Bain, N., 2000. The podzolization process: a review. Geoderma 94, 91–107.

Maat, P.B., Johnson, W.C., 1996. Thermoluminescence and new ^{14}C age estimates for late Quaternary loesses in southwestern Nebraska. Geomorphology 17, 115–128.

Mark, D.M., 1974. On the interpretation of till fabrics. Geology 2, 101–104.

Mason, J.A., 2001. Transport direction of Peoria loess in Nebraska

and implications for loess source areas on the central Great Plains. Quat. Res. 56, 79–86.
Mokma, D.L., Vance, G.F., 1989. Forest vegetation and origin of some spodic horizons, Michigan. Geoderma 43, 311–324.
Muhs, D.R., Bettis III, E.A., 2000. Geochemical variations in Peoria loess of western Iowa indicate paleowinds of midcontinental North America during last glaciation. Quat. Res. 53, 49–61.
Putman, B.R., Jansen, I.J., Follmer, L.R., 1989. Loessial soils: their relationship to width of the source valley in Illinois. Soil Sci. 146, 241–247.
Rawling III, J.E., 2000. A review of lamellae. Geomorphology 35, 1–9.
Rieck, R.L., Winters, H.A., 1980. Distribution and significance of glacially buried organic matter in Michigan's southern Peninsula. Phys. Geogr. 1, 74–89.
Rieck, R.L., Winters, H.A., 1982. Low altitude organic deposits in Michigan: evidence for Pre-Woodfordian Great Lakes and paleosurfaces. Geol. Soc. Amer. Bull. 93, 726–734.
Rieck, R.L., Winters, H.A., 1991. Paleotopography and present terrain in southwestern Michigan. Mich. Acad. 23, 241–256.
Rieck, R.L., Winters, H.A., 1993. Drift volume in the southern peninsula of Michigan—a prodigious Pleistocene endowment. Phys. Geogr. 14, 478–493.
Rieck, R.L., Klasner, J.S., Winters, H.A., Marlette, P.A., 1991. Glaciotectonic effects on a Middle-Wisconsin boreal fenland peat in Michigan, USA. Boreas 20, 155–167.
Schaetzl, R.J., 1992. Texture, mineralogy and lamellae development in sandy soils in Michigan. Soil Sci. Soc. Am. J. 56, 1538–1545.
Schaetzl, R.J., 1998. Lithologic discontinuities in some soils on drumlins: theory, detection, and application. Soil Sci. 163, 570–590.
Schaetzl, R.J., 2001. Late Pleistocene ice flow directions and the age of glacial landscapes in northern lower Michigan. Phys. Geogr. 22, 28–41.
Schaetzl, R.J., 2002. A Spodosol–Entisol transition in northern Michigan: climate or vegetation? Soil Sci. Soc. Am. J. 66, 1272–1284.
Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., Broderson, W.D. (Eds.), 2002. Field Book for Describing and Sampling Soils. Version 2.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.
Sjogren, D.B., Fisher, T.G., Taylor, L.D., Jol, H.M., Munro-Stasiuk, M.J., 2002. Incipient tunnel channels. Quat. Int. 90, 41–56.
Soil Survey Laboratory Staff, 1996. Soil survey laboratory methods manual. National soil survey center. Soil Survey Investigations Report, vol. 42. USDA-SCS, National Soil Survey Center, Lincoln, NE.
Tsai, C.-C., Chen, Z.-S., 2000. Lithologic discontinuities in Ultisols along a toposequence in Taiwan. Soil Sci. 165, 587–596.
Werlein, J.O., 1998. Soil Survey of Crawford County, Michigan. USDA Natural Resources Conservation Service U.S. Govt. Printing Office, Washington, DC.
Winters, H.A., Rieck, R.L., 1982. Drainage reversals and transverse relationships of rivers to moraines in southern Michigan. Phys. Geogr. 3, 70–82.