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# Evidence for an eolian origin for the silt-enriched soil mantles on the glaciated uplands of eastern Upper Michigan, USA

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**Abstract**

We provide textural, geochemical, and mineralogical data on a thin, silty deposit that unconformably mantles glaciated uplands in the eastern Upper Peninsula of Michigan. Previous research on this deposit, which we hypothesize to be loess, is nonexistent. The uplands were islands or narrow peninsulas within one or more glacial lakes. We compare the distribution, likely source and nature of the 20–60 cm thick silty mantle by using the loess formation model of Mason et al. [Mason, J.A., Nater, E.A., Zanner, C.W., Bell, J.C., 1999. A new model of topographic effects on the distribution of loess. Geomorphology 28, 223–236], which focuses on the generation of eolian silt by saltating sand across upwind, barren surfaces. Parabolic dunes, with arms open to the NW, are common on former lake floors upwind of the silt-mantled uplands, attesting to the strength and direction of paleowinds. The abrupt termination of the dunes at the footslopes of the uplands, associated with silt deposition on upland soil surfaces in downwind locations, are both consistent with the model of Mason et al. [Mason, J.A., Nater, E.A., Zanner, C.W., Bell, J.C., 1999. A new model of topographic effects on the distribution of loess. Geomorphology 28, 223−236]. Sediments on former lake floors contain abundant strata of fine/medium sand and silt, and thus are likely sources for the silt and dune sand. The cap, dune and lake sediments are similar along many different geochemical axes, whereas the substrate sediment, i.e., the drift below the cap, is unique. Cap sediments, normally containing roughly 30% silt, are enriched in quartz and depleted in Ti and Zr, relative to dune sediment. The dune sediment, a more residual eolian deposit, is enriched in Ti and Zr, relative to the cap, probably due to its greater abundance of heavy minerals. Therefore, we conclude that the silty cap is loess that was deflated from abandoned lake floors after nearby glacial lakes drained, probably contemporaneously with dune migration across the former lake floors.


*Keywords:* Loess; Upper Peninsula of Michigan; Lake Minong; Soil survey; Soil geochemistry; Soil mineralogy

## 1. Introduction

Deposits of wind-blown silt (loess) are common in many parts of the world, usually in association with cold, arid and/or glaciated landscapes (Pye, 1987). In the Midwestern USA, loess sheets are thickest near, and generally associated with, large glacial meltwater valleys such as the Mississippi, Missouri, Illinois and Wabash Rivers where they can exceed 50 m in thickness (Smith, 1942; Olson and Ruhe, 1979; Fehrenbacher et al., 1986). Loess deposits near these source valleys also tend to be texturally coarser than at sites farther downwind (Smith, 1942; Ruhe, 1969; Frazee et al., 1970; Fehrenbacher et al., 1986).

The predominant theory explaining the origin of most loess in North America involves the dynamics of meltwater valleys which are filled with silt-rich discharge in summer, but become dry and unprotected in winter. Strong winds associated with the steep pressure gradients that developed near the margins of ice sheets would have been capable of blowing dry silt out of the valleys and onto the adjoining uplands in winter. Because the cloud of eolian silt got progressively less dense with distance from the valley proper, loess deposits become finer textured and thinner, away from

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the valleys. Residual sands, sometimes expressed as dunes, tend to accumulate in the topographically lower outwash valleys.

Other, non-glaciogenic models of loess deposition, e.g., Mason (2001), place greater emphasis on topography and vegetation responses to climate change. Mason et al. (1999) proposed a loess generation/deposition model in which eolian sand and silt are first generated on, and move along, a low-relief, geomorphically unstable, and minimally vegetated landscape, e.g., one undergoing solifluction or recently uncovered by ice or water. Sand and silt can both be transported by wind across such landscapes until a topographic barrier is reached. The barrier forces deposition of the saltating sand while silt transport continues downwind via suspension. In the study area of Mason et al. (1999), the topographic barriers consist primarily of deep valleys running transverse to the direction of wind transport. In this model, saltation of eolian sand is viewed as not only preventing silt deposition upwind of the topographic obstructions, but also as a silt-generating mechanism.

While both glaciogenic and non-glaciogenic models of loess generation suggest a downwind facies model in which loess is produced by eolian deflation in a lowland source area and deposited downwind, on nearby uplands, the Mason et al. (1999) model emphasizes loess deposition downwind of clear topographic obstacles. The latter model also emphasizes the importance of saltating, eolian sand in the entrainment of finer-grained eolian silts by abrasion, rather than by direct entrainment of pre-existing fine particles from a silt-rich substrate, e.g., an outwash valley train, by wind alone. Lastly, the Mason et al. model also invokes the presence of widespread but sparse, tundra-like vegetation during loess deposition, as a trapping mechanism.

This paper provides data on a silty deposit common on the uplands of eastern Upper Michigan, USA. The deposit has many of the characteristics of loess; it may have been deflated from a nearby glaciolacustrine plain that is floored with abundant sediment rich in silt and fine sands, and contains abundant sand dunes. Our study, therefore, presents a regional test or application of the model of Mason et al. (1999) to glacial terrain in eastern Upper Michigan; we provide data that are relevant to mechanisms of eolian silt entrainment and deposition, and our study area has dunes and topographic obstructions upwind of a possible loess deposit. It is also the first study that documents and describes a regionally extensive silt deposit in Upper Michigan.

## 2. Regional setting

### 2.1. Glacial and geomorphic history

The study area, in the eastern part of the Upper Peninsula of Michigan, was last deglaciated between ~15,500 and 11,500 cal y BP (Drexler et al., 1983; Farrand and Drexler, 1985; Blewett et al., 1993; Lowell et al., 1999). With one exception (Blewett and Rieck, 1987), the glacial history of this region has been minimally studied.

One unresolved geomorphic issue in this region is the configuration of glacial lakes and their connecting channels during and after final deglaciation. Most or all of the lowlands in the region was inundated by a series of glacial lakes, initially by Glacial Lake Algonquin and its associates (Taylor, 1895; Futyma, 1981; Karrow and Calkin, 1985; Larsen, 1987; Schaetzl et al., 2002) and then, later, by Glacial Lake Minong (Drexler et al., 1983; Farrand and Drexler, 1985). Isostatic rebound has tilted the shorelines of these lakes, however, and complicated our understanding of their evolution (Futyma, 1981; Schaetzl et al., 2002). Further confounding matters is the possible catastrophic meltwater flux from Glacial Lake Agassiz to the Superior Basin between ~10,500 and 9000 cal y BP. The flow paths of this meltwater out of the Superior basin and across the Upper Peninsula are as yet unclear, but these waters probably did inundate large areas across northern Michigan. Surges of meltwater may have temporarily raised lake levels, stirred up bottom sediments, eroded pre-existing uplands and downcut lake outlets (Clayton, 1983; Drexler et al., 1983; Teller, 1985; Phillips and Fralik, 1994; Leverington and Teller, 2003). Although the shorelines and history of these lakes is still being investigated, certain parts of the study area were likely below the waters of both lakes, while other areas had continually remained subaerial, as islands or coastal highlands, even during the Agassiz overflows (Fig. 1).

Small, parabolic sand dunes are common on the broad lake plains of eastern Upper Michigan (Bergquist, 1936; Arbogast et al., 2002). Their orientation suggests that they formed on northwestly winds. The ages of these dunes vary (Arbogast et al., 2002; Loope et al., 2003), but at least some date to the period immediately after the draining of Lake Minong, suggesting that shortly after the lake drained, lake bed materials were occasionally dry and unvegetated and that winds were strong enough to move sand on the lake bed (Bergquist, 1936).

### 2.2. Sediments and soils

The majority of the glacial sediments in the study area are sandy (Whitney, 1992). Many are dominated by fine sand, and some also contain abundant silt. To the SE, beyond the study area but still within Upper Michigan, sediments attributable to ancient lake floors are dominated by thick, red or pink (5YR Munsell hue), silts and clays. Fine-textured, lacustrine sediments (including abundant clay) have also been mapped along the Lake Superior shore in Alger and Luce Counties along the northwestern edge of the study area (Farrand and Bell, 1987). Within the study area, however, most of the glaciolacustrine deposits are dominated by medium, fine, and very fine sands; frequently they are finely interbedded with silts. Histosols, some very thick, are widespread on the very poorly-drained areas of former lake beds, where they overlie lake sediment. Spodosols and Alfisols are the most common upland soils, on sandy and loamy parent materials, respectively (Whitney, 1992). Many upland soils have a silty cap that varies in thickness but is typically 20–60 cm thick; in some soils, the cap can exceed a meter in thickness. The silty cap has, in many areas, promoted the formation of a strong fragipan near the

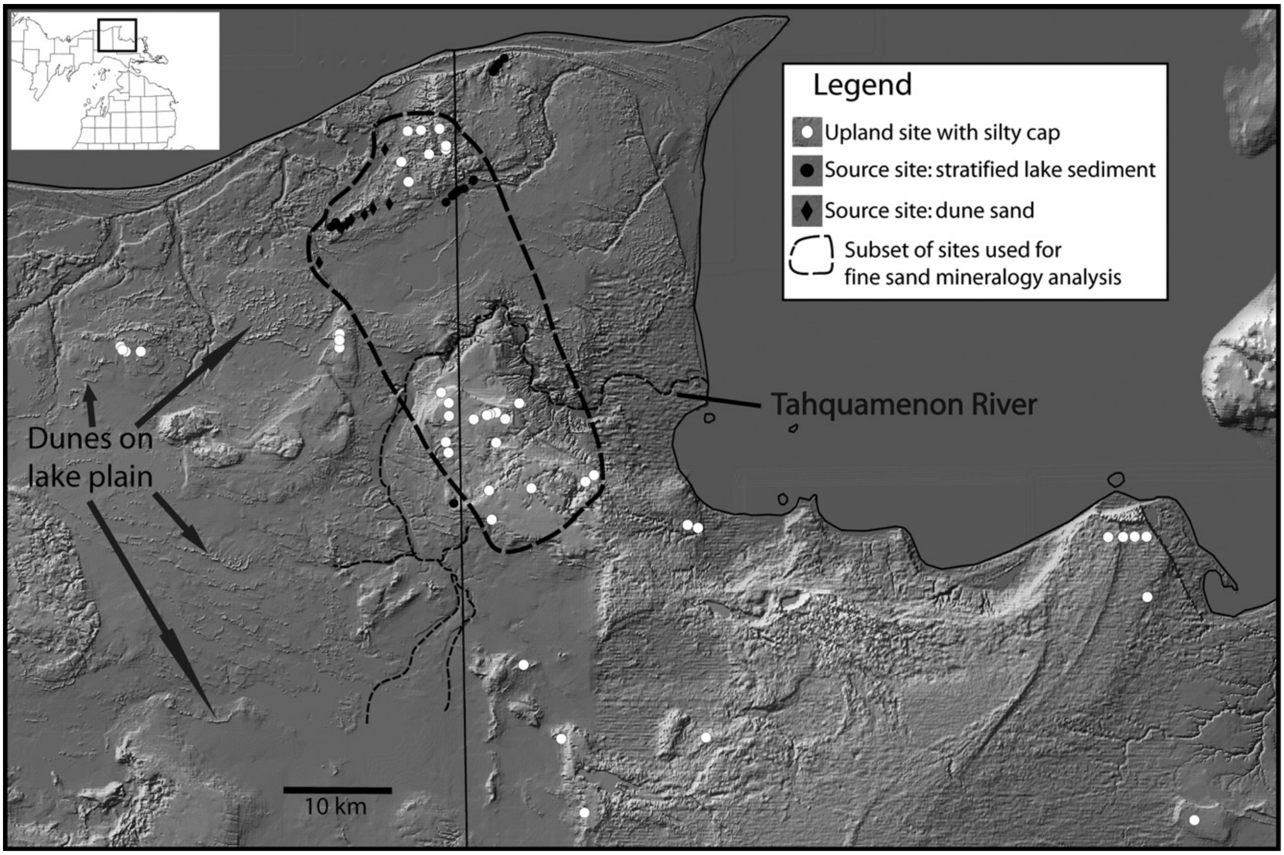


Fig. 1. Study area map on a DEM base, showing the locations of all sampled sites. Also shown are the locations of the subset of sites analyzed for fine sand mineralogy.

lithologic discontinuity with the underlying sandy drift (Weisenborn and Schaetzl, 2005).

Mixed coniferous–deciduous forest dominates the study area, except for bog and marsh sites that are too wet for trees to grow. Many of these areas have standing water at the surface, even into summer. Lowland areas tend to have more conifers, whereas upland forests are commonly dominated by broadleaf hardwood species (Whitney, 1992).

## 3. Materials and methods

### 3.1. Background

Our prior knowledge of the study area derives from several years of fieldwork, as well as information gleaned from NRCS (Natural Resources Conservation Service) mapping projects in Luce and Chippewa Counties within Eastern Upper Michigan (Whitney, 1992). Using digitized forms of this information, we stratified the soil series present in Luce and Chippewa Counties, based upon their parent sediments, horizonation and topographic position, into

(1) “cap” sites, uplands with prominent silty caps,
(2) “source” sites, lake plain locations with abundant silt and fine sand that could have served as sources of silty, eolian material, and
(3) dunes (Table 1).

Soils with silty caps on uplands are usually mapped within the Pence, Bodi, Amasa, Sporley, and Chesbrough series (Table 1), although in parts of western Chippewa County some areas with caps are mapped within the Rousseau series. If the silty caps are eolian, as we hypothesize, then possible sources include the broad, wet glaciolacustrine plains that contain abundant silt and very fine sand, usually in finely interstratified layers (Table 1). We assume that winds that might have winnowed silt from these lake bed deposits would have also left much of the sand behind in small dunes, as has been documented for parts of Iowa and Minnesota (Mason et al., 1999) and southern Michigan (Arbogast et al., 1997). The presence of many small, parabolic dunes on the former lake floor is consistent with this assumption. For this reason, we also sampled several dunes on the lake floor (Table 1).

Our strategy was to selectively sample sediment from (1) a number of the silty caps spread widely across the study area, (2) the substrate directly beneath them, (3) dunes on the lake floor, and (4) lake sediment windward of the caps, in order to ascertain if the silty cap is loess or not, and if so, determine the source(s) of the silt. Our hypothesis-testing framework focused on determining the degree to which the silty cap sediment is alike or different from lake plain, substrate, and dune sediment, along various textural, mineralogical and geochemical axes.

### 3.2. Field sampling

Using digital soil and topographic databases and a GPS we were able to navigate, in the field, to soil map units that we had deemed as a possible source or cap sites (Fig. 1). Most of the source sites were only accessible at the *edges* of large, broad glaciolacustrine flats. For source and dune sites, we took one bulk sample of 200–500 g from below the solum (i.e., in the C horizon) using a hand auger. At upland cap sites, we sampled both the cap and the material below (hereafter "substrate"). At two sites where the cap was particularly silty and thick we excavated a pit and described and sampled the pedon, according to NRCS guidelines (Schoeneberger et al., 2002). One of these pedons was mapped within the Amasa series, one within the Pence series (Table 1).

### 3.3. Laboratory methods

All samples were air-dried and lightly ground in a ceramic mortar with a wooden pestle to pass a 2-mm sieve. The fine-earth (<2 mm fraction) portions of these samples were then passed through a sample splitter and recombined (four passes total) to maximize homogeneity. Particle size analysis was done on chemically dispersed (in a water-based solution with $(NaPO_3)_{13}\cdot Na_2O$ as the dispersant, after shaking for 2 h), 2-g samples, on a laser particle size analyzer.

Next, certain particle size fractions were isolated for mineralogical and geochemical analyses. To do this, approximately 10 ml of dispersing solution and about 50 ml of water were added to 10-g samples. The suspensions were shaken on an oscillating shaker for 4 h and then washed through a 45-um sieve; the finer silt and clay fractions were discarded. The 45–2000 µm fraction (remaining on the sieve) was dried and dry-sieved for 5 min to isolate the 45–630 µm and 63–1250 µm fractions.

#### 3.3.1. Coarse silt geochemistry

After about 2.0 g of the 45–63 µm fraction were accumulated via dry sieving, the sediment was then washed with a sodium citrate-dithionite solution to remove Fe and Al coatings (Mehra and Jackson, 1960). To accomplish this, 200 g of 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 into the solution. This mixture was allowed to stand for 1 h, 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 samples was

Table 1
Soils of the study area, relevant to this research

| Soil series | Taxonomic classification | Drainage class | Parent material | Typical geomorphic setting in the study area |
|---|---|---|---|---|
| *Soils series that are likely sources of eolian silt and fine sand* | | | | |
| Sugar | Coarse-silty over clayey, mixed, superactive, frigid Alfic Oxyaquic Haplorthods | Moderately well-drained | Loamy lacustrine sediments over clayey sediment | Glaciolacustrine plains |
| Fence | Coarse-silty, mixed, superactive, frigid Alfic Oxyaquic Haplorthods | Moderately well-drained | Stratified silty-to-sandy, glaciolacustrine sediments | Glaciolacustrine plains |
| Wainola | Sandy, mixed, frigid Typic Endoaquods | Poorly-drained | Fine sand-dominated, stratified sediments | Glaciolacustrine and outwash plains |
| Gogomain | Coarse-loamy over clayey, mixed, active, nonacid, frigid Aeric Epiaquepts | Poorly-drained | Stratified silty-to-sandy, sediments over clayey sediment | Glaciolacustrine plains |
| Alcona | Coarse-loamy, mixed, active, frigid Alfic Haplorthods | Well-drained | Stratified silty-to-sandy, glacial sediments | Drier parts of glaciolacustrine plains, and other uplands |
| Burleigh | Sandy over loamy, mixed, active, nonacid, frigid Mollic Endoaquents | Poorly- and very poorly-drained | Sands over stratified silty-to-sandy glacial sediments | Glaciolacustrine plains |
| Ingalls | Sandy over loamy, mixed, active, frigid Typic Endoaquods | Somewhat poorly-drained | Fine sands over stratified silty-to-sandy glacial sediments | Glaciolacustrine plains |
| Soo | Fine-silty, mixed, superactive, nonacid, frigid Aeric Epiaquents | Poorly- and very poorly-drained | Stratified silty-to-sandy glaciolacustrine sediments | Glaciolacustrine plains |
| Rousseau | Sandy, mixed, frigid Entic Haplorthods | Well-drained | Eolian sands | Sandy uplands and small dunes on lake plain |
| *Soil series with eolian silt and fine sand caps* | | | | |
| Pence | Sandy, isotic, frigid Typic Haplorthods | Somewhat excessively-drained | Loamy sediment, possible eolian, over stratified sandy outwash | Glaciated uplands |
| Bodi | Coarse-silty over sandy or sandy-skeletal, isotic, frigid Oxyaquic Fragiorthods | Moderately well-drained | Thick silt loam cap over sandy glacial drift | Glaciated uplands |
| Chesbrough | Sandy, isotic, frigid Typic Fragiaquods | Somewhat poorly-drained | Thin silt loam cap over sandy glacial drift | Glaciated uplands |
| Sporley | Coarse-silty, mixed, active, frigid Alfic Haplorthods | Well-drained | Thick silty cap over stratified silts and clays | Glaciated uplands |
| Amasa | Coarse-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Typic Haplorthods | Well- and moderately well-drained | Silts and fine sands over gravelly and cobbly, sandy drift | Glaciated uplands |

Based largely on soil series descriptions by the NRCS.

determined by X-ray fluorescence (XRF). Samples were diluted by adding 9.0 g of lithium tetraborate ($Li_2B_4O_7$) 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 in, 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 elemental analyses were reduced by a fundamental parameter data reduction method, while trace element data were calculated using standard linear regression techniques. Although the XRF unit is capable of analyzing for numerous major and minor elements, we chose to primarily use data for Ti and Zr, because of the mobility of the other elements in the udic, acidic soils of this area. Fortunately, silt- and sand-sized Ti and Zr have been shown to be nearly immobile in such soils (Chapman and Horn, 1968; Sudom and St. Arnaud, 1971; Pearce and Cann, 1973; Chadwick et al., 1990; Lichter, 1998).

### 3.3.2. Very fine sand mineralogy

The mineralogical composition of the 63–125 μm fraction was determined on a subset of samples from sites in the center of the study area (Fig. 1). After accumulating about 4 g of the 63–125 μm (very fine sand) fraction, the sediment was placed in a plastic vial and mixed with an epoxy resin. Heating the sediment-resin mixture to 70 °C facilitated hardening. The hardened resin block, with the sand grains embedded, was cut into thin sections, stained for K-spar with alizarin red, and examined under a petrographic microscope. At least 300 grains were counted per sample. The following minerals and mineralogy categories were routinely identified: quartz, potassium and plagioclase feldspar, hornblende, biotite, garnet, microcrystalline quartz, and dolomite/limestone, as well as lithic and opaque fragments. In the final analysis, we chose to use only data from the five most abundant minerals: quartz, K-feldspar, plagioclase feldspar, hornblende, and biotite.

Data on particle size fractions, fine sand mineralogy, and coarse silt geochemistry were compared using a Student's *T*-test to determine if the sediment samples came from similar or unique populations. In most of these tests, our data sets were derived from 9 dune samples, 17 lake sediment samples, 44 substrate samples, and 54 cap samples. Mineralogical comparisons were performed using a smaller data set (Fig. 1).

## 4. Results and discussion

### 4.1. Distribution of the silty cap

Most of the silty caps in the study area are on the flat crests or the footslopes (just above the uppermost shoreline) of the major islands (Fig. 2). The major island in the northern part of the study area locally known as the Crisp Point moraine contains large areas of soils with a silty cap, especially along its western edge. The thickest and most areally extensive caps, however, are on the broad upland known as Tahquamenon Island. At this site we described and sampled the two pedons with thick silty caps which are typical of the area (Table 2).

Silty caps were seldom mapped by NRCS personnel as continuous units across the uplands, although they may be more extensive than the maps show. Because the NRCS soil mapping here was done under difficult conditions, amidst dense forest and with poor road access, the silty caps are probably more extensive than is shown in Fig. 2 or in the county soil surveys.

The areal extent and thickness of mapped silty caps (Whitney, 1992) and our field observations support a picture of eolian silt deposition as a punctuated, local phenomenon whose influence diminishes rapidly with distance from the former shores of Lakes Algonquin and Minong. This contrasts with very thick and extensive loess deposits that bear signals of climatic change in the Great Plains during the Holocene, e.g., Miao et al. (2005).

Because mobilization of sand can facilitate silt entrainment by wind (Bagnold, 1941; Mason et al., 1999), the spatial arrangement of uplands (e.g., Tahquamenon Island; Fig. 2), relative to windward sand-rich littoral zones, was probably an important circumstance leading to emplacement of many of the silty caps. Indeed, the greatest concentration of silty soils mapped by Whitney (1992) lies downwind (southeast) of topographic swales between high-standing former islands, along the trend of the strongest effective winds. Upon lake drawdown, sand dunes were probably mobilized along emergent littoral zones of lakeward islands and, in turn, helped entrain leeward silt and very fine sand. Topographic barriers, e.g., the gorge of the Tahquamenon River or the steep NW face of the Tahquamenon Island, apparently arrested the south-easterly movement of these dunes. Any silt in the air column would have then been deposited in the lee of the barrier, as per the model of Mason et al. (1999).

At present, no absolute age control has been established for the deposition of the silt. However, optically stimulated luminescence (OSL) ages of dune sand in and near the study area suggest that the many of the dunes last stabilized between 10,500 and 8500 cal y BP, depending upon the draining of glacial Lake Minong (Loope et al., 2003). These dates may provide the likely median age of the silt, if its genesis can be linked to dune migration and formation on the lake plain. However, it is also possible that some of the silt was deposited over a much longer time span, dating to the initial decline of Lake Algonquin, Minong's immediate predecessor, and the exposure of its lake bed. This would place the exposure of the potential loess source between ~13,500 and 8500 cal y BP. The influence of vegetation upon the areal extent and thickness of the loess caps is also unknown, but vascular plants probably did occupy these rolling uplands during the period of loess deposition, possibly acting as vegetation traps (Webb et al., 1983).

### 4.2. Particle size data

In the study area, many of the uplands have soils with silty caps of varying thickness, overlying sandy glacial drift (Tables 1, 2; Figs. 1, 2). For the 55 cap samples we analyzed, the mean amount of silt is 30% (Table 2). The mean clay contents from this same set of samples is only 4.0%, and

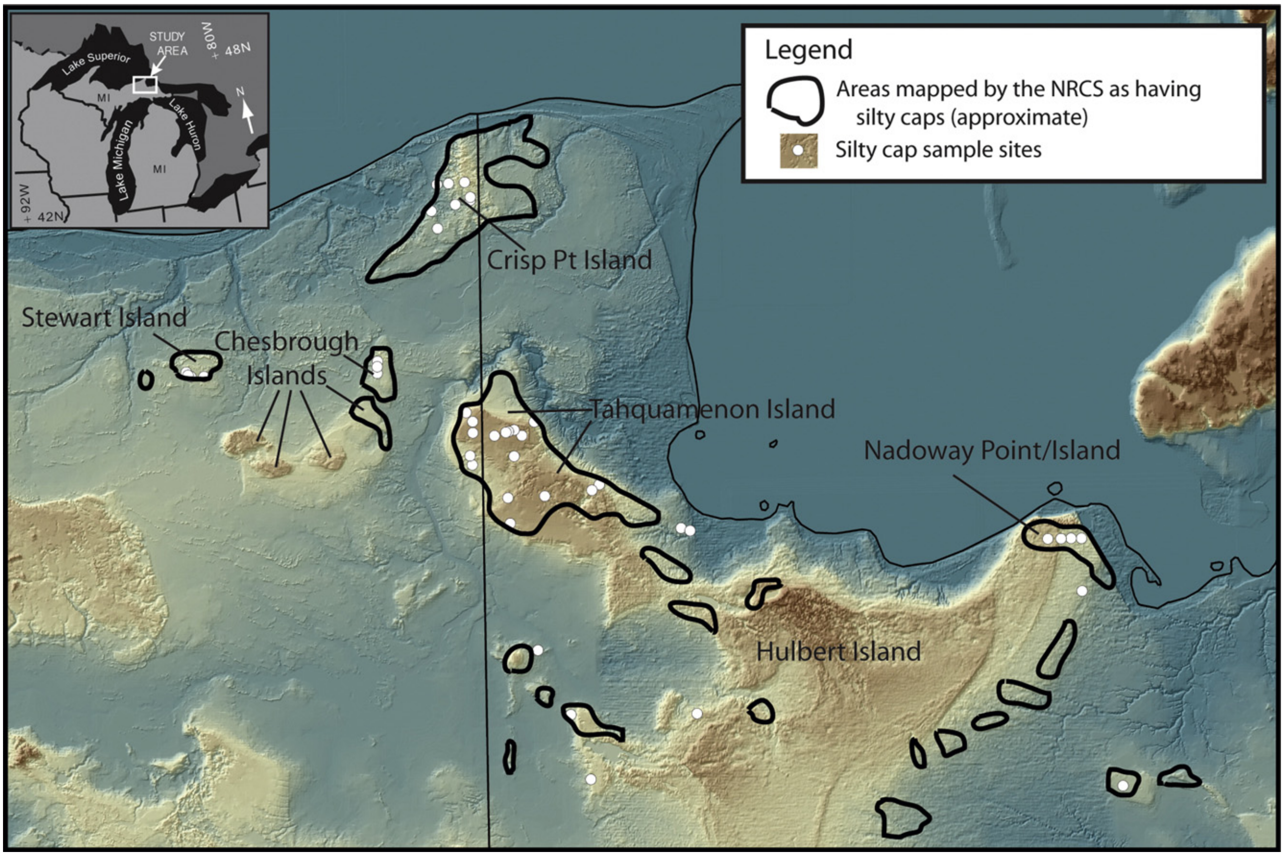


Fig. 2. Study area map on a DEM base, showing the generalized locations of the silty cap soils on the major uplands and (where possible) the names of the islands/uplands.

whereas sand contents are high (66.1%), over 84% of the sand is within the medium and finer fraction. Indeed, the average cap sample has 21.2% very fine sand – almost as much as it has silt (Table 2). Most silty caps here are 20–60 cm in thickness and have clear and discernable contacts to the underlying drift. The most common soil texture classes encountered in cap sediments were loamy sand, fine sandy loam and very fine sandy loam (Table 3; Fig. 3A). Because of pedoturbation and the thinness of the cap, occasional pebbles and gravels are found within it.

The substrate (glacial drift) on the uplands, sampled only at locations where it is overlain by a silty cap, is considerably coarser and sandier, especially with regard to the coarser sand fractions (Tables 2, 3; Fig. 3C). Cobbles and pebbles are very common in the drift, much of which probably has complex glaciofluvial origins. Medium and coarse sand fractions dominate the substrate sediments. Of the 44 substrate samples analyzed (less than the number of cap samples because, in places, coarse fragments prevented deep augering and sampling), the most common texture classes encountered were sand and coarse sand (Table 2; Fig. 3C). The variation in particle size, as indicated by the standard deviation data in Table 2, is large for this type of sediment (drift), attesting to

Table 2
Physical and morphological data for a typical upland soil developed in a thick silty cap overlying glacial outwash parent material

| Horizon | Depth (cm) | Munsell color (moist) | Coarse fragments (>2 mm dia.) (est. vol.%) | Structure | Sand (%) | Silt (%) | Clay (%) | Texture class[a] |
|---|---|---|---|---|---|---|---|---|
| Latitude–longitude coordinates: 46° 32′ 13′′ N. 85° 12′ 2′′ W | | | | | | | | |
| Oi | 0–2 | – | 0 | – | – | – | – | – |
| A | 2–6 | 10YR 4/3 | 0 | Weak, fine, granular | Not sampled | | | |
| Bs | 6–24 | 7.5YR 3/4 | 0 | Weak, fine and medium, subangular blocky | 45.3 | 49.8 | 4.8 | Sandy loam |
| Bw1 | 24–47 | 10YR 5/4 | 2 | Weak, fine and medium, subangular blocky | 50.2 | 45.4 | 4.4 | Fine sandy loam |
| 2Bw2 | 47–74 | 7.5YR 4/4 | 2 | Structureless | 83.3 | 15.3 | 1.5 | Loamy sand |
| 3BC | 74–102 | 7.5YR 4/4 | 6 | Structureless | 95.7 | 3.8 | 0.5 | Coarse sand |
| 3C | 102–139+ | 10YR 5/4 | 2 | Structureless | 96.6 | 2.6 | 0.9 | Sand |

Textures according to the Soil Survey Division Staff (1993). In this pedon, the A, Bs and Bw1 horizons would be considered as cap material.
[a] S: Sand; LS: Loamy Sand.

Table 3
Summary particle size data for the various soil groups sampled in this study

| Parameter | Silty cap samples | Substrate samples | Dune samples | Lake sediment samples |
|---|---|---|---|---|
| Clay content[a] (mean %) | 4.0±2.0 | 4.3±6.7 | 0.1±0.3 | 4.3±3.7 |
| Silt content (mean %) | 30.0±13.3 | 13.4±18.1 | 1.0±1.5 | 41.4±16.1 |
| Sand content (mean %) | 66.1±14.9 | 82.3±23.7 | 98.9±1.8 | 54.3±18.6 |
| Very fine sand content (mean %) | 21.2±9.6 | 10.6±13.9 | 6.7±4.6 | 27.8±13.3 |
| Fine sand content (mean %) | 15.9±7.5 | 18.5±13.1 | 41.4±10.7 | 14.2±8.9 |
| Medium sand content (mean %) | 18.7±10.7 | 33.6±18.6 | 44.1±8.8 | 9.1±8.3 |
| Coarse sand content (mean %) | 9.7±7.4 | 18.6±16.3 | 6.6±5.9 | 3.1±5.5 |
| Very coarse sand content (mean %) | 0.5±0.5 | 1.0±1.3 | 0.0±0.1 | 0.1±0.4 |
| Most common soil textural class | Loamy sand | Sand | Sand | Silt loam |
| Second most common soil textural class | Fine sandy loam | Coarse sand | Fine sand | Fine sandy loam |
| Zr content[b] (mean g/kg) | 914 | 1276 | 2636 | 658 |
| Ti content[b] (mean %) | 0.44 | 0.58 | 0.78 | 0.33 |
| Quartz content[c] (%) | 79.5 | 71.7 | 73.9 | 74.3 |
| K-feldspar content[c] (%) | 7.1 | 7.2 | 11.3 | 8.3 |
| Plagioclase feldspar content[c] (%) | 8.8 | 10.8 | 10.0 | 12.4 |
| Hornblende content[c] (%) | 1.5 | 3.1 | 1.9 | 1.4 |
| Biotite content[c] (%) | 1.0 | 3.0 | 0.2 | 1.5 |

[a] Particle size breaks follow the USDA (Soil Survey Division Staff 1993). Clay: <2 um; silt: 2–50 μm; very fine sand: 50–125 μm; fine sand: 125–250 μm; medium sand: 250–500 μm; coarse sand: 500–1000 μm; very coarse sand: 1–2 mm.
[b] For the 45–63 μm fraction.
[c] For the 63–125 μm fraction.

the variability in origin, e.g., sandy till and different facies of glaciofluvial sediment.

Areas of sand with minimal amounts of silt do occur on the lake plain, and spatial variation in texture is reasonably high across the lake bed. We focused our sampling efforts in areas of the lake bed that had significant amounts of silt in order to obtain enough silt-sized sediment for later analysis. For this reason, the sediments that we sampled from the lake plain (26 sites total) had large amounts of silt (41.4%) and finer sands (Table 3; Fig. 3B). Silt loam and fine sandy loam are the dominant texture classes in the samples we obtained, although even within one pit any of a number of textures can be observed, because of their stratified nature. Strata tended to be thin (<5 cm) and varied between the finer sand and silt fractions; very little coarse (3.1%) and very coarse sand (0.1%) were present in the lake bed sediments we sampled. Some sediment on the lake plain is almost pure sand (Fig. 3B).

As expected, the nine small dunes that we sampled on the lake plain are dominated by fine (41.4%) and medium sands (44.1%) and have almost no silt (1.0%), clay (0.1%), or very coarse sand (0.0%) (Table 3). The most common texture classes for the dune samples were sand and fine sand.

### 4.3. Geochemical and mineralogical data

We examined the Ti and Zr geochemical data not only as individual elements but as a combined group (Table 4). The goal was to examine which of the four groupings of soils/sediments (caps, substrate, dunes and lake sediments) were geochemically, statistically unlike the other, assuming that this knowledge would shed light on their geomorphic origins and enable us to accept or reject our hypothesis of an eolian origin for the silty cap. To this end, an informal *dissimilarity index*, which rates each of the geochemical and mineralogical variables, in pairs,

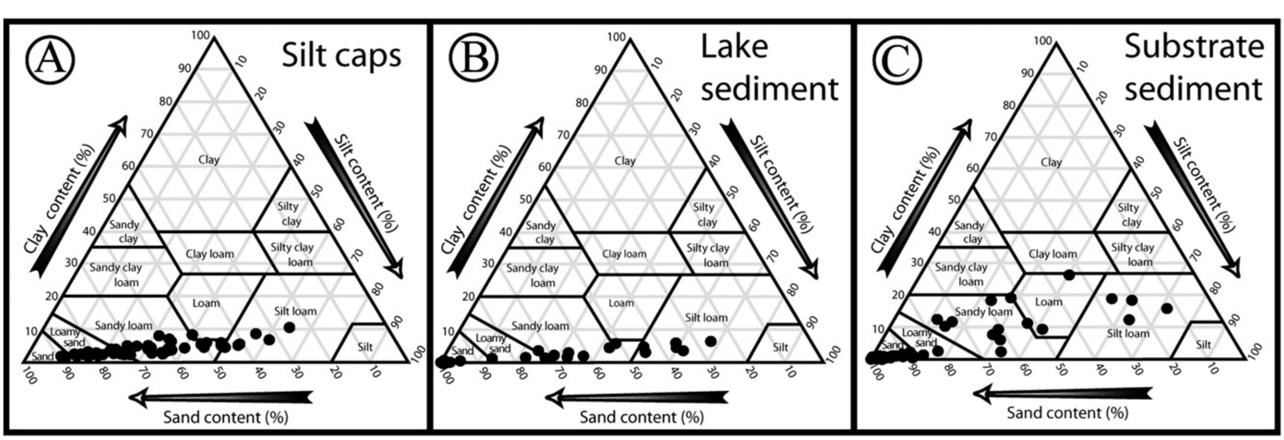


Fig. 3. Texture data plotted on standard, USDA textural triangles, for samples from the (A) silty caps, (B) lake sediment, and (C) substrate materials (drift).

based on their statistical dissimilarity, was also developed and applied (Table 4). The sediment that is most unlike all the others, i.e., has the highest dissimilarity index, is the substrate material, when compared to the cap (9; Table 4). The substrate material is statistically unlike the cap sediment on all mineralogical and geochemical axes, except for K-feldspar content. The dissimilarity index (Table 4) and texture data (Table 3) clearly indicate that the cap and substrate materials are not geochemically or sedimentologically linked. This finding, coupled with the common observation that the cap lies unconformably upon the substrate material and maintains an abrupt boundary to it, confirms that the cap is not genetically linked to its substrate, as would be expected for an eolian deposit.

The next most dissimilar pairing includes the cap and dune sediment (Index of dissimilarity = 6; Table 4). The dunes are enriched in K-feldspar, Zr and Ti, relative to the cap sediment. This finding probably stems from the winnowing and sorting effects of eolian transport; the dunes became relatively enriched in heavy minerals *vis a vis* the cap, rendering the dunes more likely to include more of the minerals that contain Zr and Ti. The lake floor dunes have been derived from glaciolacustrine sediment that was, at one time in the past, presumably devegetated and dry enough to be moved by wind and accumulate into dunes; others have observed this relationship in various parts of Michigan (Arbogast et al., 1997, 2002; Albert, 2000). Relative to the lake sediment, dune sand is also enriched in Ti and Zr (Table 4; Fig. 5). Taken as a whole, these geochemical and mineralogical values are to be expected for sediment like dune sand, which is partially residual, having been winnowed of its lighter minerals by wind, thereby enriching it in heavy minerals and elements. The cap sediment, which presumably was transported farther than dune sand, and in suspension rather than saltation, would be expected to show a relative depletion in heavy minerals, i.e., Ti and Zr, and it does (Table 4; Fig. 5).

The 63–125 μm (very fine sand) fraction of all samples is strongly dominated by quartz, potassium and plagioclase feldspars, hornblende, and biotite. Statistical analyses were, therefore, restricted to these minerals (Table 4). In most cases, the mineralogical data were in support of the geochemical data. For example, the strong dissimilarity between the cap and substrate sediments, supported based on Zr and Ti data, was reinforced by the mineralogical data (Table 4). The high degree of cap vs. substrate dissimilarity is strongly influenced by quartz content, of which the cap sediment is greatly enriched, vs. the substrate (79.5 vs. 71.7%). For all four other minerals, each with a higher specific gravity than quartz, the cap is impoverished, relative to the substrate. The cap sediment is statistically enriched in quartz, even with respect to the dunes, and contains less of the heavy mineral hornblende, although not at a statistically significant level (Table 4). Conversely, the cap sediment is strongly impoverished in hornblende, relative to the substrate (Table 4). Theory would suggest that long-distance transported, eolian sediments like loess would be enriched in quartz and impoverished in heavy minerals and elements, and therefore these data support our hypothesis of an eolian origin of the cap.

It is also interesting to note that the dunes are greatly impoverished in biotite, relative to the substrate (0.2 vs. 3.0%), perhaps due to the ease with which biotite is physically weathered during saltation. The platy shape of biotite may also render it more easily entrained and transported by the wind than minerals of other shapes, which may partially explain why the

Table 4
Summary results of *T*-test analyses for geochemical and mineralogical parameters of the four groups of sediment samples

| Sediment group | As compared to what group? | Statistically different[a] ($p=0.05$) on what variables? | Not statistically different on what variables? | Dissimilarity index[b] |
|---|---|---|---|---|
| Cap | Substrate | **Ti**, Zr, (**Zr+Ti**), ***Quartz*** Plagioclase, Hornblende, Biotite | K-feldpsar | 9 |
| Cap | Dunes | Ti, **Zr**, (Zr+Ti), ***Quartz***, K-feldspar, *Biotite* | Plagioclase, Hornblende | 6 |
| Cap | Lake sediment | ***Ti***, (***Zr***+**Ti**), *Quartz*, **Plagioclase** | Zr, K-feldspar, Hornblende, Biotite | 4 |
| Substrate | Cap | ***Ti***, *Zr*, (***Zr***+**Ti**), **Quartz**, *Plagioclase,* **Hornblende**, *Biotite* | K-feldspar | 9 |
| Substrate | Dunes | Zr, K-feldspar, ***Biotite*** | Ti, (Zr+Ti), Quartz, Plagioclase, Hornblende | 0 |
| Substrate | Lake sediment | ***Ti***, ***Zr***, (***Zr***+**Ti**), ***Hornblende*** | Quartz, K-Feldspar, Plagioclase, Biotite | 4 |
| Dunes | Cap | *Ti,* **Zr**, (*Zr*+*Ti*), **Quartz**, *K-feldspar*, Biotite | Plagioclase, Hornblende | 6 |
| Dunes | Substrate | *Zr, K-feldspar*, **Biotite** | Ti, (Zr+Ti), Quartz, Plagioclase, Hornblende | 0 |
| Dunes | Lake sediment | ***Ti***, ***Zr***, (***Zr***+**Ti**), **Biotite** | Quartz, K-Feldspar, Plagioclase, Hornblende | 4 |
| Lake sediment | Cap | **Ti**, (**Zr+Ti**), **Quartz**, ***Plagioclase*** | Zr, K-feldspar, Hornblende, Biotite | 4 |
| Lake sediment | Substrate | **Ti**, **Zr**, (**Zr+Ti**), **Hornblende** | Quartz, K-Feldspar, Plagioclase, Biotite | 4 |
| Lake sediment | Dunes | **Ti**, **Zr**, (**Zr+Ti**), ***Biotite*** | Quartz, K-Feldspar, Plagioclase, Hornblende | 4 |

[a] Mean values for the variable in italics are *larger* for the first group than for the one it is being compared to. Bolded values in column three indicate that the statistical differences in the *T*-test values are significant at $p=0.01$.

[b] The "dissimilarity index" rates the two variables being compared based on their statistical dissimilarity. Two points are awarded for each parameter in column three that is significantly different at $p=0.01$; one point is awarded for parameters that are different at $p=0.05$. Then the number of entries in column four is subtracted from this sum to arrive at a final dissimilarity index. Larger values of the dissimilarity index imply that the two sediments are more dissimilar. The index is set at a minimum value of zero.

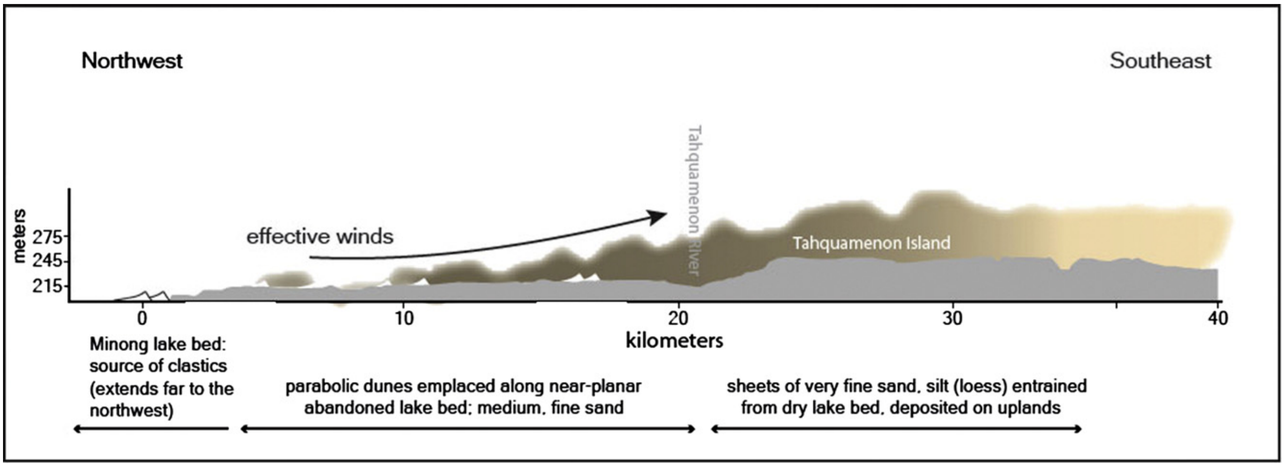


Fig. 4. Diagram illustrating a likely scenario for the origin of the silty cap on the former islands of eastern Upper Michigan's lake plains.

cap sediments contain more biotite than the dunes. Instead of transport by saltation might corrode the thin, platy biotite grains in the dunes, whereas transport in suspension, as would have occurred in the cap sediments, might favor the preservation of biotite because of fewer inter-grain contacts during transport.

### 4.4. Fit of the data to the Mason et al. (1999) loess generation model

We applied the loess generation model of Mason et al. (1999) to our data by assuming that, in the past, barren areas of dry lake sediment were winnowed by wind, with coarser and heavier fractions retained on the lake floor as dunes and finer, lighter fractions deflated and deposited as silty caps on nearby uplands (Fig. 4). The data generally support the model in the following ways. First, cap sediment can be clearly shown to be different, texturally, mineralogically and geochemically, than the substrate below (Tables 3, 4). The cap is enriched in silt and very fine sand fractions, relative to the substrate. Likewise, the cap has a very high index of dissimilarity, relative to the substrate. The cap has, without question, not been derived from the substrate below; it has a different origin.

Second, the model would suggest that the lake sediment is the source for both the dunes and the cap sediment, the latter simply having been transported farther because of its smaller particle size characteristics. This aspect of the model is also supported by the data. The dunes are dominated by medium and fine sand-sized particles, as is typical for most dunes, while the cap contains finer and very fine sand, as well as silt (Table 3). The dune sand and lake sediment have a relatively low index of dissimilarity (4; Table 4), with the main difference being that the dunes are relatively enriched in Ti and Zr. Given that Ti and Zr are mainly contained in heavy minerals, their relative enrichment in a residual eolian sediment like dune sediment is expected. Conversely, the cap is impoverished in Zr and Ti, relative to the dunes, perhaps reflective of its greater distance, and different mode, of transport (Table 4). Also in support of the eolian origin of the cap is its very high quartz content, even relative to the dunes (Tables 3, and 4). The cap contains more 5.3% quartz than the lake sediment, 7.8% more than the

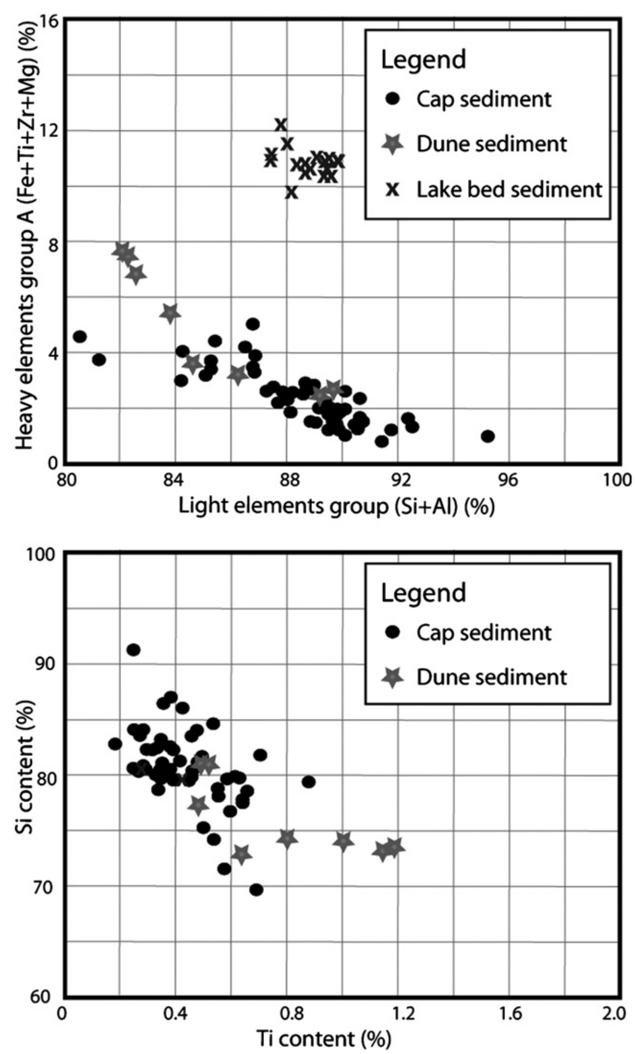


Fig. 5. Examples of two binary diagrams, showing the relationships between elemental variables for some representative sediment groups. (A). Heavy vs. light elements, for the cap, dune, and lake sediment groups. (B). Si vs. Ti for the cap and dune groups.

substrate, and 5.6% more than the dunes. These data all suggest that the lake sediment is the source of the dune and cap sediment, and that the dunes are mainly a residual accumulation of lake sediment, but enriched in many of the heavier minerals that were unable to be fully deflated. Taken as whole, the data in Table 3 and 4 support the hypothesis that the dunes are composed mainly of heavier, residual minerals, while the cap has been concomitantly enriched in light elements and minerals, again suggestive of an eolian origin, with the lake sediment and dunes as its main sources. (Fig. 5)

The loess generation model of Mason et al. (1999) appears to fit/explain precisely the geomorphic scenario that is extant on the lake plains and former islands in the eastern Upper Peninsula. Exposure of a sandy lake bed, following the demise of Glacial Lake Minong (and also, possibly, some earlier lakes), provided a widespread source of unconsolidated fine sands and silts, with little or no vegetation cover to stabilize them. Wetness may have been a factor in preventing some areas from incurring extensive deflation, but based on the widespread occurrence of dunes on other, equally wet, lake plains in Michigan (Arbogast et al., 1997, 2002; Arbogast and Jameson, 1998; Loope et al., 2003), ample opportunity for deflation may exist at times, on even the wettest of sites. With the advent of dune migration by saltation across the lake plain, silt was entrained and transported farther downwind, much of it landing on distant uplands, where it persisted on the most stable sites. Today, these uplands have 20–60 cm (or more) of silty material above a sandy, gravelly substrate. Taken together, the lake bed, dune and cap sediment represent a facies change, with respect to texture and mineralogy, consistent with that predicted by the Mason et al. (1999) model. Therefore, we interpret the silty material on the uplands in our study area as loess, derived from the nearby lake bed, and assisted by the migration of dunes and concomitant saltation processes.

## 5. Conclusions

Uplands in the eastern Upper Peninsula of Michigan, former islands in one or more large, proglacial lakes during the late Pleistocene and early Holocene, contain a previously unstudied cap of sediment that is enriched in silt and very fine sand, relative to the substrate material. Although discontinuous and spatially variable with respect to texture and thickness, this silty cap is almost certainly loess that has been deflated from the former lake bed that surrounds the uplands, in a manner consistent with the loess generation model of Mason et al. (1999). Eolian mobilization of sand on abandoned lake floors in the Midwest has been previously documented, and our study is just another documented example of lake bed dunes in Michigan. Our study takes this finding one step further, however, by underscoring the fact that the mobilization of eolian sand also generates substantial quantities of eolian silt, which, if nearby stable uplands and/or other barriers to sand dune migration are present downwind, can be deposited there as loess. Our research, therefore, provides important verification data for the loess generation model of Mason et al. (1999) outside of the Great Plains region and, in so doing, also documents a unique and previously unstudied loess sheet in northern Michigan.

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## References

Albert, D.A., 2000. Borne of the wind: an introduction to the ecology of Michigan sand dunes. Michigan Natural Features Inventory. MI, Lansing. 63 pp.

Arbogast, A.F., Jameson, T.P., 1998. Age estimates of inland dunes in east-central Lower Michigan using soils data. Phys. Geogr. 19, 485–501.

Arbogast, A.F., Scull, P., Schaetzl, R.J., Harrison, J., Jameson, T.P., Crozier, S., 1997. Concurrent stabilization of some interior dune fields in Michigan. Phys. Geogr. 18, 63–79.

Arbogast, A.F., Wintle, A.G., Packman, S.C., 2002. Widespread middle Holocene dune formation in the eastern Upper Peninsula of Michigan and the relationship to climate and outlet-controlled lake level. Geology 30, 55–58.

Bagnold, R.A., 1941. The Physics of Blown Sand and Desert Dunes. Methuen, London.

Bergquist, S.G., 1936. The Pleistocene History of the Tahquamenon and Manistique Drainage Region of the Northern Peninsula of Michigan. Occasional Paper, Geology of Michigan. Mich. Geol. Survey Publ. vol. 40, Geol. Series 34, Part I. 137 pp.

Blewett, W.L., Rieck, R.L., 1987. Reinterpretation of a portion of the Munising moraine in northern Michigan. Geol. Soc. Amer. Bull. 98, 169–175.

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.

Chadwick, O.A., Brimhall, G.H., Hendricks, D.M., 1990. From a black box to a gray box–a mass balance interpretation of pedogenesis. In: Knuepfer, P.L.K., McFadden, L.D. (Eds.), Soils and Landscape Evolution. Geomorphology, vol. 3, pp. 369–390.

Chapman, S.L., Horn, M.E., 1968. Parent material uniformity and origin of silty soils in northwest Arkansas based on zirconium–titanium contents. Soil Sci. Soc. Am. Proc. 32, 265–271.

Clayton, L., 1983. Chronology of Lake Agassiz drainage to Lake Superior. In: Teller, J.T., Clayton, L. (Eds.), Glacial Lake Agassiz. Geol. Assoc. Canada Spec. Paper vol. 26, 291–308.

Drexler, C.W., Farrand, W.R., Hughes, J.D., 1983. Correlation of glacial lakes in the Superior basin with eastward discharge events from Lake Agassiz. In: Teller, J.T., Clayton, L. (Eds.), Glacial Lake Agassiz. Geol. Assoc. Canada Spec. Paper, vol. 26, pp. 261–290.

Farrand, W.R., Drexler, C.W., 1985. Late Wisconsinan and Holocene history of the Lake Superior basin. In: Karrow, R.F., Calkin, P.E. (Eds.), Quaternary Evolution of the Great Lakes. Special Paper, vol. 30. Geological Association of Canada, pp. 17–32.

Farrand, W.R., Bell, D.L., 1987. Quaternary Geology of Northern Michigan. Michigan Department of Natural Resources, Geological Survey Division. Lansing, MI. (Map).

Fehrenbacher, J.B., Olson, K.R., Jansen, I.J., 1986. Loess thickness in Illinois. Soil Sci. 141, 423–431.

Frazee, C.J., Fehrenbacher, J.B., Krumbein, W.C., 1970. Loess distribution from a source. Soil Sci. Soc. Am. Proc. 34, 296–301.

Futyma, R.P., 1981. The northern limits of glacial Lake Algonquin in Upper Michigan. Quat. Res. 15, 291–310.

Karrow, P., Calkin, P., 1985. Quaternary evolution of the Great Lakes. Geol. Assoc. Can. Spec. Paper 30.

Larsen, C.E., 1987. Geological history of Glacial Lake Algonquin and the Upper Great Lakes. U.S. Geol. Surv. Bull. 1801. 36 pp.

Leverington, D.W., Teller, J.T., 2003. Paleotopographic reconstructions of the eastern outlets of glacial Lake Agassiz. Can. J. Earth Sci. 40, 1259–1278.

Lichter, J., 1998. Rates of weathering and chemical depletion in soils across a chronosequence of Lake Michigan sand dunes. Geoderma 85, 255–282.

Loope, W.L., Loope, H.M., Goble, R.J., 2003. Latest Pleistocene and Holocene dune building in eastern Upper Michigan. Geol. Soc. Am. 35 (6), 169 Abstracts with Programs.

Lowell, T.V., Larson, G.J., Hughes, J.D., Denton, G.H., 1999. Age verification of the Lake Gribben forest bed and the Younger Dryas advance of the Laurentide Ice Sheet. Can. J. Earth Sci. 36, 383–393.

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.

Mason, J.A., Nater, E.A., Zanner, C.W., Bell, J.C., 1999. A new model of topographic effects on the distribution of loess. Geomorphology 28, 223–236.

Mehra, O.P., Jackson, M.L., 1960. Iron oxide removal from soils and clays by a dithionite–citrate system buffered with sodium bicarbonate. Clays Clay Mins. 7, 317–327.

Miao, X., Mason, J.A., Goble, R.J., Hanson, P.R., 2005. Loess record of dry climate and aeolian activity in the early- to mid-Holocene, central Great Plains, North America. The Holocene 15, 339–346.

Olson, C.G., Ruhe, R.V., 1979. Loess dispersion model, southwest Indiana, U.S.A. Acta Geol. Acad. Sci. Hung. Tomus 22, 205–227.

Pearce, J.A., Cann, J.R., 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses. Earth Planet. Sci. Lett. 19, 290–300.

Phillips, B.A.M., Fralik, P.W., 1994. A post-Lake-Minong transgressive event on the north shore of Lake Superior, Ontario – possible evidence of Lake Agassiz inflow. Can. J. Earth Sci. 31, 1638–1641.

Pye, K., 1987. Aeolian Dust and Dust Deposits. Academic Press, London. 334 pp.

Ruhe, R.V., 1969. Quaternary Landscapes in Iowa. Iowa State Univ. Press, Ames. 255 pp.

Schaetzl, R.J., Drzyzga, S.A., Weisenborn, B.N., Kincare, K.A., Lepczyk, X.C., Shein, K.A., Dowd, C.M., Linker, J., 2002. Measurement, correlation, and mapping of Glacial Lake Algonquin shorelines in northern Michigan. Annals Assoc. Am. Geog. 92, 399–415.

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.

Smith, G.D., 1942. Illinois loess: variations in its properties and distribution. Univ. Ill. Agric. Exp. Station Bull. 490 Champaign-Urbana.

Soil Survey Division Staff, 1993. Soil survey manual. USDA Handbook, vol. 18. US Government Printing Office, Washington, DC. 437 pp.

Sudom, M.D., St. Arnaud, R.J., 1971. Use of quartz, zirconium and titanium as indices in pedological studies. Can. J. Soil Sci. 51, 385–396.

Taylor, F.B., 1895. The Munuscong Islands. Am. Geol. 15, 24–33.

Teller, J.T., 1985. Glacial Lake Agassiz and its influence on the Great Lakes. In: Karrow Calkin, P.F., Karrow Calkin, P.E. (Eds.), Quaternary Evolution of the Great Lakes. Geol. Assoc. Canada Spec. Paper, vol. 30, pp. 1–16.

Webb III., T., Cushing, E.J., Wright Jr., H.E., 1983. Holocene changes in vegetation of the Midwest. Late Quaternary Environments of the United States, vol. 2. The Holocene. University of Minnesota Press, Minneapolis, pp. 142–165.

Weisenborn, B.N., Schaetzl, R.J., 2005. Range of fragipan expression in some Michigan soils: II. A model for fragipan evolution. Soil Sci. Soc. Am. J. 69, 178–187.

Whitney, G.D., 1992. Soil survey of Chippewa County, Michigan. USDA Soil Conservation Service. US Govt. Printing Office, Washington, DC.