



# A new depositional model for sand-rich loess on the Buckley Flats outwash plain, northwestern Lower Michigan



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## ABSTRACT

Loess was first studied in Michigan on the Buckley Flats, where outwash, overlain by  $\approx 70$  cm of loamy sediment, was originally interpreted as loess mixed with underlying sands. This paper re-evaluates this landscape through a spatial analysis of data from auger samples and soil pits. To better estimate the loamy sediment's initial textures, we utilized "filtered" laser diffraction data, which remove much of the coarser sand data. Textures of filtered silt data for the loamy sediment are similar to loess. The siltiest soils are found in the low-relief, central part of the Flats. Spatial analyses revealed that many silt fractions are nearly uniformly distributed, suggesting that the loess was not derived from a single source. The previous depositional model for the loamy mantle relied on loessfall followed by pedoturbation, but does not explain (1) the variation in sand contents across the Flats, or (2) the abrupt contact below the loamy mantle. This contact suggests that the outwash was frozen when the sediments above were deposited. Deep gullies at the western margins of the Flats were likely cut as permafrost facilitated runoff. Our new model for the origin of the loamy mantle suggests that the sands on the uplands were generated from eroding gullies and saltated onto the uplands along with loess that fell more widely. Sands saltating to the west of the Flats may have entrained some silts, facilitating loessfall downwind. At most sites, the loamy mantle gets increasingly silty near the surface, suggesting that saltation ended before loess deposition.

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## 1. Introduction

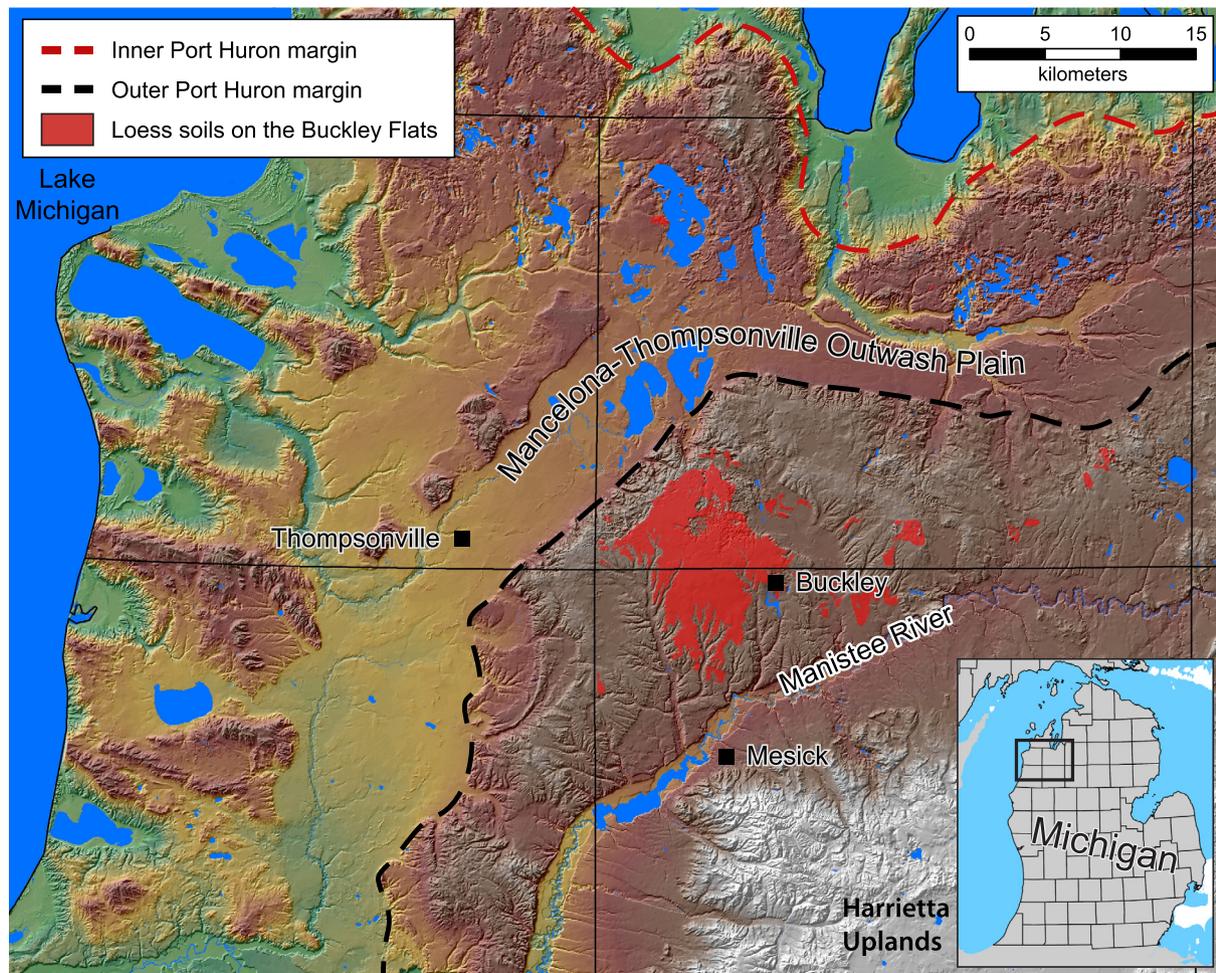
Loess is a silt-dominated sediment, deposited by aeolian processes. In the humid, glaciated areas of North America and Europe, loess is often derived from proglacial outwash or valley-train deposits (Grimley, 2000; Frechen et al., 2003; Haase et al., 2007; Buggle et al., 2008; Muhs, 2013; Schaetzl et al., 2014). Some of the thickest and most extensive loess deposits in North America were derived from large outwash valleys that were active for long periods of time, e.g., the Mississippi, Missouri, Illinois and Wabash Rivers (Bettis et al., 2003). Such deposits have been highly useful for determining paleowind direction and strength. However, recent studies have documented and focused on smaller, thinner, and sometimes spatially discontinuous, loess deposits, which may provide important paleoenvironmental information for more localized areas (e.g. Schaetzl and Attig, 2013). Much of this loess may have been derived (at least in part) from smaller source areas that were potentially active for relatively short periods of time (Schaetzl and

Hook, 2008; Schaetzl and Loope, 2008; Luehmann et al., 2013). Many of these thinner loess deposits however, are often partially mixed with the underlying sediment. If the underlying sediment is sandy, the resultant surficial sediment often has surface textures that classify as loamy, rather than silty (Schaetzl and Hook, 2008; Schaetzl and Luehmann, 2013; Luehmann et al., 2016). Historically, the loamy textures of these loess deposits have sometimes resulted in (1) incorrect geologic interpretations, in the literature and on soil and geologic maps, or (2) erroneous thickness estimates and textural characterizations.

The first study of loess in Michigan occurred on the Buckley Flats outwash plain, in the northwestern Lower Peninsula, named for the nearby village of Buckley (Fig. 1). The soils on the Flats are loamy in their upper profiles, and sandy to gravelly at depth (Weber et al., 1958; Buchanan, 1985). The Flats area supports a prosperous cash grain industry (Fig. 2A, B), in a region that otherwise is dominated by forests and swamps, on comparatively infertile, sandy soils. The presence of agriculture here is generally attributed to the extensive areas of low relief, on loamy soils. (Luehmann et al., 2016), soils at the Flats were not initially thought to be loess-derived.

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**Fig. 1.** Regional elevation map of the Buckley Flats in Michigan's northwestern Lower Peninsula. Soils interpreted as formed in loess over outwash (Coventry, Hodenpyl and Karlin series) are shown in red. County boundaries are shown as black lines.

Schaetzl and Hook's (2008) initial work on the soils of the Buckley Flats concluded that the loamy, upper part of the profile is loess, mainly derived from the Manistee River valley and floodplain to the southeast. They concluded that, the Flats provided a generally dry, stable and potentially vegetated upland capable of retaining any aeolian silt blow in from nearby sources. Aeolian silt retention occurred while the ice margin was in contact with the outwash surface, and later as the glacier retreated northward. They suggested that the loamy character of the mantle was due to pedoturbation of sands from below. As the first study of loess in Michigan, documenting the presence of loess on the Flats was, in and of itself, notable.

We use the generic term "loamy mantle" for the sediment that comprises the upper profile of these soils, i.e., above the contact with the outwash below. Schaetzl and Hook (2008) concluded that the loamy mantle formed as a result of pedoturbation of the thin loess with the sandy outwash below. Subsequent work has shown that many other thin loess deposits are often sandier than is typical for loess, displaying a bimodal particle size distribution (Schaetzl and Luehmann, 2013; Luehmann et al., 2016). Because of the frequent occurrence of such sediments, Luehmann et al. (2013) developed a "textural filtering" method, which they used to determine the textural characteristics of the original loess, before it had been mixed with sandy, underlying sediment (Schaetzl and Attig, 2013). The method determines the textural characteristics of the original loess by mathematically removing the data for the coarser, usually

sand-sized, sediment, modeling the distribution for the removed portion of the textural curve, and recalculating the proportions of the resulting data to sum to unity. This filtering technique has been applied to data from other thin and texturally modified loess deposits, which facilitated their successful textural analysis and mapping (Schaetzl and Attig, 2013; Schaetzl et al., 2014; Luehmann et al., 2016). Schaetzl and Hook (2008) based many of their conclusions on raw, non-filtered, textural data. In this study, we applied the filtering method, when necessary, to better characterize the textural character of the loamy mantle on the Flats. In addition to applying the textural filtering technique, the present study expands upon the initial work of Schaetzl and Hook (2008) by sampling across a larger area, including areas not technically on the Flats, and on flat uplands nearby that were not mapped as loamy soils but which could have nonetheless retained some loess.

A. Typical scene in the northern part of the Flats where the topography is slightly rolling. Here, some woodlots still exist. B. Typical scene of the center of the Flats, where the landscape has less relief, soils are siltier, and intensive agriculture, with irrigation, is more common. C. A view looking south, off the southern margin of the Flats, looking across the Manistee River valley. In the background is the large, forested, Harrietta Upland, dominated by sandy soils.

Through a more thorough mapping effort, and filtering the textural data as needed, our work re-mapped the extent, thickness, and original textural properties of the loamy sediment on the

Buckley Flats. Such data were then used to ascertain the source region(s) for the loess, to better inform paleocirculation models, and develop a depositional model for the generation, transport, and deposition of aeolian sediment in this region.

## 2. Study area

The Buckley Flats are a topographically high, dry, and sandy (at depth) outwash plain in northwestern Lower Michigan, covering  $\approx 90 \text{ km}^2$ , spanning 12 km north-south and 10 km east-west (Fig. 1). The Flats are highest in elevation on their northwestern edge, and slope gently to the southeast, at  $\approx 3.0\text{--}3.5 \text{ m km}^{-1}$ . The central section of this elevated upland is exceptionally flat (Fig. 2B). Despite the overall slope gradient to the south, the southern margins of the Flats are still perched, in places, as much as 80 m above the deeply incised Manistee River valley, which forms the southern border of the region. South of the Flats lies a large, hilly, interlobate region, the Harietta Upland, where forests and sandy soils dominate (Fig. 2C).

Geomorphically, the Buckley Flats are associated with the Port Huron readvance of the Laurentide Ice Sheet; this advance was extensive across all of Lower Michigan (Blewett, 1991). Deposits associated with this advance can be traced from Ontario, through

the Lower Peninsula of Michigan, across the bottom of Lake Michigan, and into Wisconsin (Blewett, 1991; Blewett et al., 1993; Syverson and Colgan, 2004). In the northwestern portion of the Lower Peninsula, the advance had two distinct intervals – an earlier (Outer Port Huron Moraine) that advanced farther into the center of the peninsula, and a later (Inner) advance (Fig. 1). The Flats comprise part of the Outer Port Huron morainic system. While ice was at the Outer Port Huron margin, meltwater flowed down the Manistee River valley to the southeast of the Flats. After withdrawing from the Buckley Flats, Port Huron ice later readvanced to the Inner Port Huron margin. At this time, meltwater flowed down the Mancelona-Thompsonville Outwash Plain to the northwest of the Flats (Fig. 1).

In northern Michigan, both advances are expressed by steep ice-contact slopes, grading outward along a morphosequence into broad, flat, outwash fans/plains (Blewett, 1991; Blewett and Winters, 1995; Blewett et al., 2009). The Outer Port Huron readvance reached its maximum extent between 12.7 and 13.5 k  $^{14}\text{C}$  yrs BP (Blewett et al., 1993), or between 15,100 and 16,470 cal yrs ago, based on the CalPal calibration curve (<http://www.calpal-online.de>). The “moraine” itself, at the northern edge of the Flats, is not a true moraine in this area. Rather, it is the steep, sometimes partially collapsed, ice-contact slope of an outwash fan (Figs. 1, 3). Meltwater flowed to the south and southeast across the outwash surface of the Flats, and eventually drained down the Manistee River. At this time, the Manistee valley aggraded considerably with sandy and gravelly outwash. Stream incision of these outwash deposits have since formed a series of alluvial terraces that mark the southern edge of the Flats. The eastern margin of the Flats is marked by a conspicuous Port Huron-aged meltwater channel, which is also incised below the Flats proper (Fig. 3).

Although the Flats are mainly a gently sloping surface, several parts are extremely kettled. Other areas, especially near the margins of the Flats, were deeply incised by fluvial gullies and channels which grade to one or more terraces of the Manistee River (Fig. 3). Because all except the largest parts (lower ends) of these channels are dry today and runoff across the Flats is minimal, these channels were likely cut in the immediate post-glacial interval, when permafrost may have been widespread in this part of Michigan (Schaetzl, 2008). Well-developed soils in the bottoms of the gullies also suggest that they are no longer undergoing incision. Similar gully patterns present on nearby landscapes have been interpreted as evidence for low permeability conditions and enhanced runoff, induced by widespread permafrost (Morgan, 1972; Johnson, 1990; Clayton et al., 2001; Lusch et al., 2009).

Most soils on the Flats are well- or moderately well-drained, and have developed under the influence of mixed coniferous-deciduous forest vegetation. The loamy soils of the Buckley Flats stand out in the landscape because most upland soils in the region are sandy, reflecting the nature of the glacial sediments (Schaetzl and Weisenborn, 2004; Schaetzl, 2002; 2009).

On the northern half of the Buckley Flats, in Grand Traverse County, soils with loamy upper sola are mapped within the Coventry (Coarse-loamy over sandy or sandy-skeletal, mixed, frigid Alfic Haplorthods) and Karlin (Sandy, mixed, frigid Entic Haplorthods) series. In the southern half of the Flats, in Wexford County, these same soils are mapped within the Hodenpyl (Coarse-loamy, mixed, active, frigid Haplic Glossudalfs) series (Fig. 3). The reason for the nomenclatural disparity stems from the age of the two soil surveys; Grand Traverse County was mapped nearly 30 years earlier, and series nomenclature and definitions had changed in the interim. All three series are indicative of similar parent materials; there is no noticeable change at the county line. Where deep gullies have incised into the Flats, sandy outwash is exposed at the surface. Here, soil series such as Kalkaska and Rubicon (both Sandy, mixed, frigid Haplorthods) are mapped.

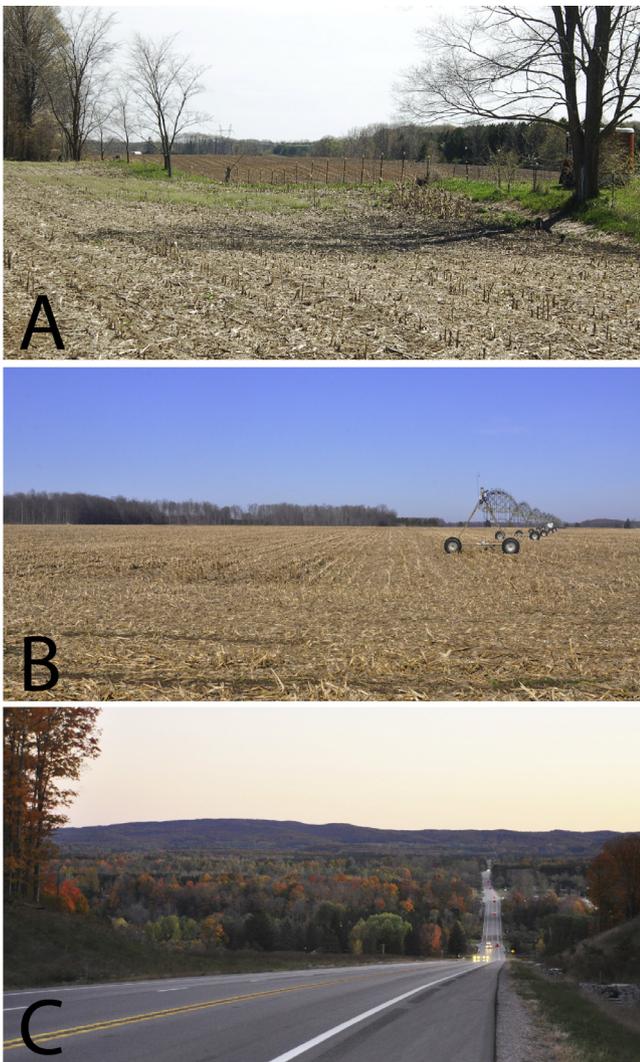
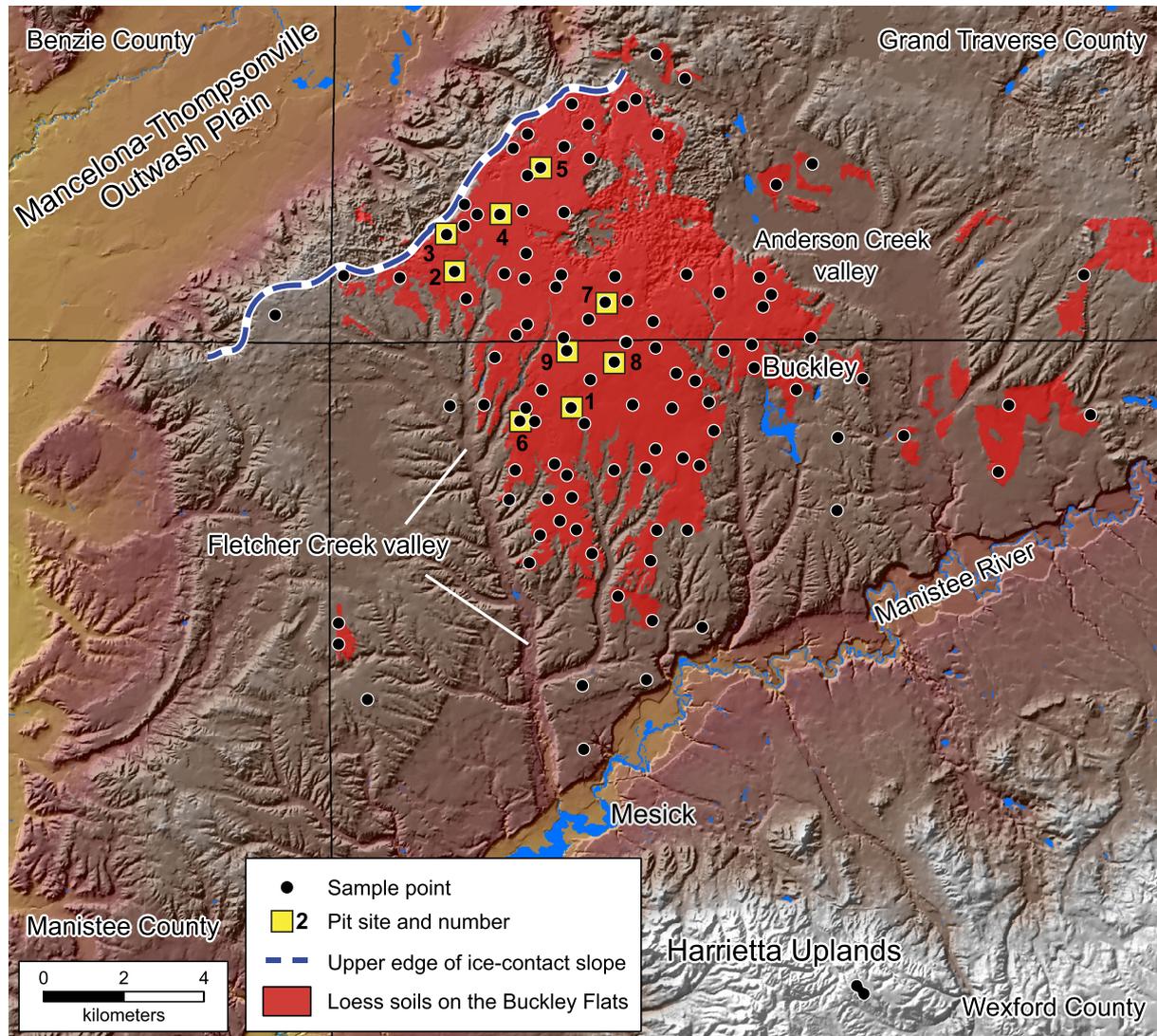


Fig. 2. Images of the Buckley Flats region.



**Fig. 3.** Elevation map of the Buckley Flats, showing the locations of the 105 sample points, and other features referenced in the text.

### 3. Methods

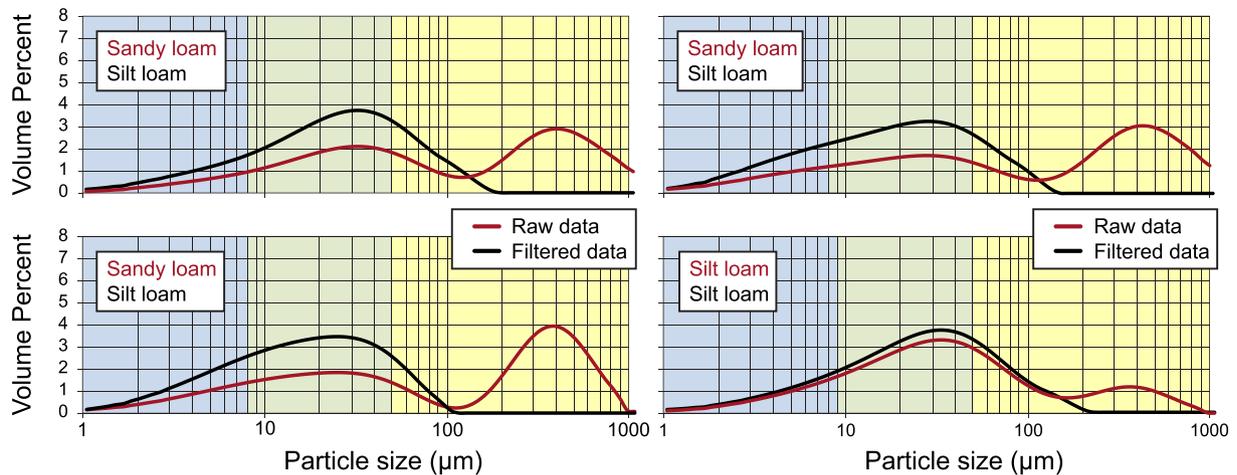
The goal of this work was to systematically reassess the upper, loamy sediment, on geomorphically stable sites across the Buckley Flats, and on stable but sandy upland sites immediately outside of the Flats (Fig. 3). To accomplish this, we developed a point-based shapefile in ArcMap v. 10.2 that identified over 125 “target” locations, all of which were on level, or nearly level, terrain, and mapped within the Karlin, Coventry, or Hodenpyl series. Each target site, was inspected to ensure that it was not disturbed or eroded. Then, using a standard hand auger, the thickness of the loamy mantle was estimated and  $\approx 900$ – $1200$  g of the loamy upper material was collected, more-or-less evenly distributed through the loamy mantle. In all, 96 point-locations across the loamy mantle were sampled, a greater sampling density with better coverage around the margins of the Flats, as compared to the initial work by Schaeztl and Hook (2008), with only 67 sites. At 12 of the 96 sites, we also recovered a sample of outwash from below the loamy mantle.

At nine additional, uncultivated sites, where the loamy mantle was particularly well developed or at a key location, a deep (2 meter) pit was excavated with a backhoe, to examine the stratigraphy and sedimentology of the soil parent materials. Soils at each

pit were sampled incrementally and by horizon. From the pit face we collected one composite sample of the entire column of loamy sediment, and added these data to that of the 96 samples taken by hand auger, to arrive at a final sample count of 105 (Fig. 3). None of Schaeztl and Hook’s (2008) original samples were reused for this study.

All 105 samples were air-dried, lightly ground, and passed through a 2-mm sieve. The remaining fine earth fraction was then passed through a sample splitter three times, in order to assure full homogenization. The homogenized samples were prepped for particle size analysis by chemically dispersing them (with a mass of ca. 2 g) in a water-based solution of  $[\text{NaPO}_3]_{13}\text{-Na}_2\text{O}$ , and shaken for at least 40 min. Particle size analysis on the dispersed samples was performed by laser diffraction, using a Malvern Mastersizer 2000E unit. Resulting textural profile data for the sand fraction were then filtered from each sample’s particle size distribution using the methodology of Luehmann et al. (2013). Examples of the results from this analysis on samples collected from the Buckley Flats are shown in Fig. 4.

In subsequent analyses, we examined spatial thickness patterns for both the original (raw) and filtered particle size data. These data were interpolated across the Flats, using ordinary kriging. A proximity analysis was also conducted using ArcMap to determine



**Fig. 4.** Examples of textural curves for samples of the loamy mantle, both raw data (red line) and after filtering (black line). The particle size ranges for clay, silt and sand are shown in blue, green, and yellow, respectively.

the nearest distance from sampled points to gullies around the Flats. Sand contents (included in raw data) were of particular interest in this analysis.

## 4. Results and discussion

### 4.1. Assumptions and hypothesis

Based on the initial work of [Schaeztl and Hook \(2008\)](#), and the findings from other Midwestern sites with similar soils ([Schaeztl and Luehmann, 2013](#); [Luehmann et al., 2016](#)), we assumed that the Buckley Flats are mantled with loess that had been mixed with sand from the outwash below, resulting in loamy textures (sandy loam most commonly). The loessial origin of the silts here, and the subsequent pedoturbation of sand up and into the loess, was then viewed as a testable, working hypotheses, using the new “textural filtering” method developed after the initial work was performed in 2008.

### 4.2. Data and landscape exploration

This landscape re-analysis confirmed that the NRCS (soils) data in this area is generally accurate. Areas mapped within the three series thought to contain loess ([Fig. 1](#)) consistently had a loamy upper profile of varying thickness, whereas nearby upland areas mapped within sandy soil series, even if they are flat or gently sloping, almost always lacked a loamy mantle. These latter soils often had “sand” or “coarse sand” textures and minimal amounts of silt in the upper profile, although they usually did get slightly siltier near the surface. Very few sites outside of the originally mapped “loess soils” area ([Fig. 1](#)) had a loamy mantle with considerable amounts of silt. Therefore, we consider NRCS soils data to be a good approximation of the extent of the loamy mantle on the Buckley Flats ([Fig. 3](#)).

### 4.3. Thickness of the loamy mantle

In most places, the thickness of the loamy mantle is apparent, because its lower boundary is abrupt and thus, can be accurately estimated with an auger. In their initial work, [Schaeztl and Hook \(2008\)](#) determined that the loess-rich mantle on the Buckley Flats was 35–45 cm thick. Our work pointed to a considerably thicker mantle:  $72.3 \pm 32.4$  cm mean thickness ([Fig. 5](#)). The thickness difference is probably due to variations in field interpretation. The

mantle is thinnest in the east-central parts of the Flats. Thickness values are maximal along the northern edge of the Flats, where they commonly exceed 80 cm. Here, the mantle is sometimes stony and contorted, and thus may have a more complicated depositional history. The thick mantle ends abruptly at the ice-contact slope on the northwestern edge of the Flats, whereas at the other marginal areas, it gradually thins and becomes sandier. For example, on level uplands near deep gullies the mantle thins and becomes coarser. At the edge of most gullies there is no loamy mantle at all, and the soils are sandy throughout. This spatial relationship is suggested by the NRCS data, and has been repeatedly verified in the field.

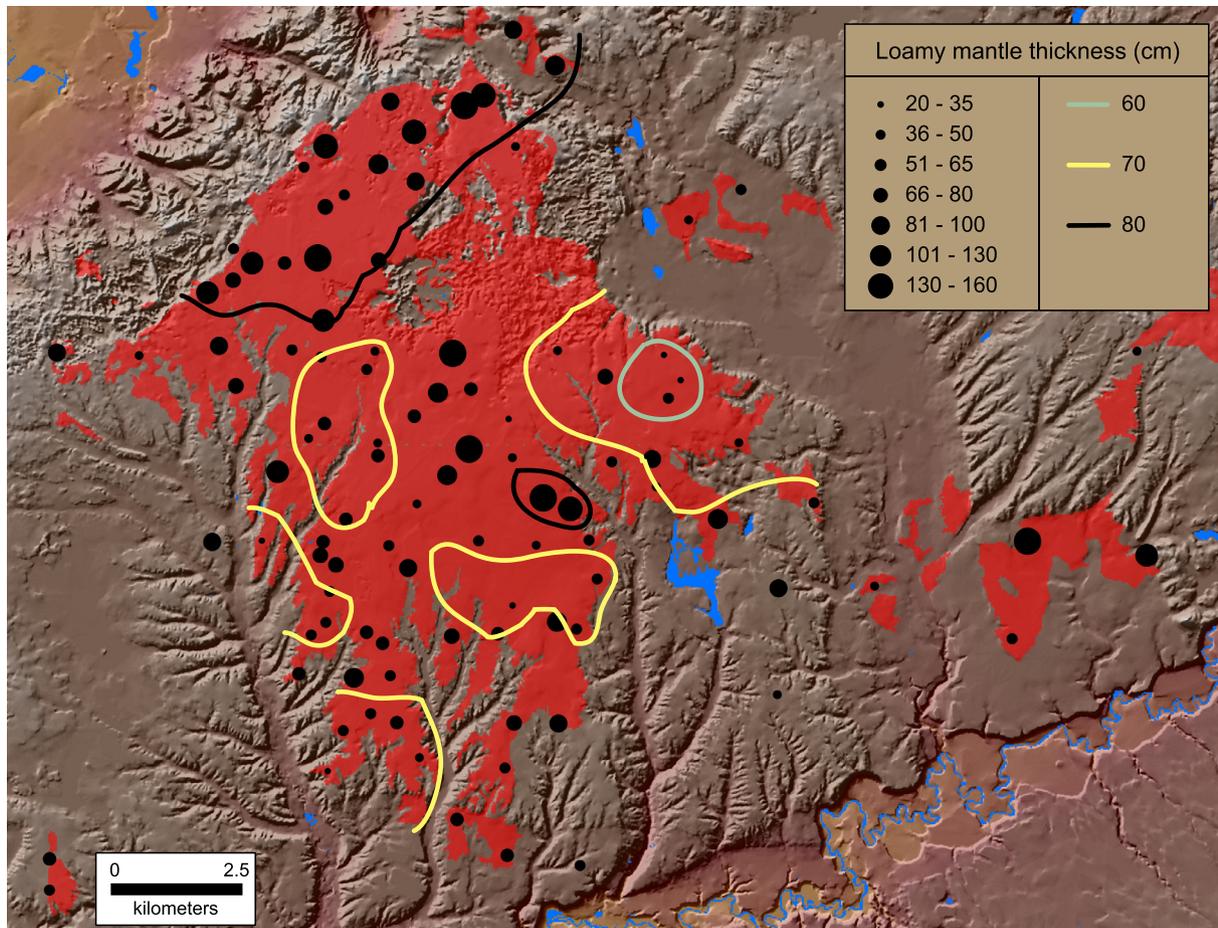
### 4.4. Textural characteristics of the loamy mantle

Roughly half (55 of the 105 samples) of the loamy mantle had sandy loam textures, in accordance with [Schaeztl and Hook's \(2008\)](#) original data. The remainder of the samples had loamy sand (20), loamy coarse sand (10), loam (9), fine sandy loam (4), coarse sandy loam (3) and coarse sand (3) textures. Only one site had a silt loam texture. Silt contents of the loamy mantle samples averaged  $27.0 \pm 9.4\%$ , with an average silt mode of  $34.7\ \mu\text{m}$ . The overall “sandiness” of the mantle is best indicated by the large value for mean weighted particle size, with an overall average of  $250.0 \pm 61.0\ \mu\text{m}$  and an overall average sand mode of  $374.9 \pm 40.7\ \mu\text{m}$ . All but one (coarse sand) of the 12 outwash samples recovered from below the mantle had “sand” textures.

The textural curves for the sediment in the loamy mantle are almost always bimodal, with peaks in both the sand and silt fraction ranges ([Fig. 4](#)). This type of texture is common where thin deposits of loess overlie sandy sediment ([Scull and Schaeztl, 2011](#); [Schaeztl and Luehmann, 2013](#); [Luehmann et al., 2013](#); [2016](#)), and often suggest a mixture of aeolian silts (loess) and sands from the underlying outwash. The textural filtering operation developed by [Luehmann et al. \(2013\)](#) allows us to determine the “original” textural characteristics of the silty component of such samples.

### 4.5. Origin of the loamy mantle: Background

Based on previous work, here ([Schaeztl and Hook, 2008](#)) and elsewhere ([Schaeztl and Luehmann, 2013](#); [Luehmann et al., 2016](#)), we initially hypothesized that the sand in the upper profiles on the Flats was an autochthonous sediment, originating as lower



**Fig. 5.** Isoline and graduated circle map of the thickness of the loamy mantle on the Buckley Flats. In this and other maps the data are shown as graduated symbols; the kriged surface is shown as isolines.

subsoil (outwash) sediment that had been mixed into the upper profile via pedoturbation. This hypothesis appears to hold for some soils in the northern parts of the Flats, where the boundary between the outwash and the loamy mantle is diffuse, changing texture gradually over a 20–50 cm interval. In these soils, the loamy mantle gets progressively siltier toward the surface, without noticeable stratification and with a diffuse boundary to the underlying material. In many places, however, the boundary between the outwash and the loamy mantle above is somewhat to extremely abrupt, indicating that pedoturbation of outwash materials with any overlying sediment has not been an important process (Fig. 6). The abrupt nature of the boundary was often apparent while augering. Such data imply that pedoturbation processes alone cannot explain the sand in the upper material, at least for most locations on the Flats.

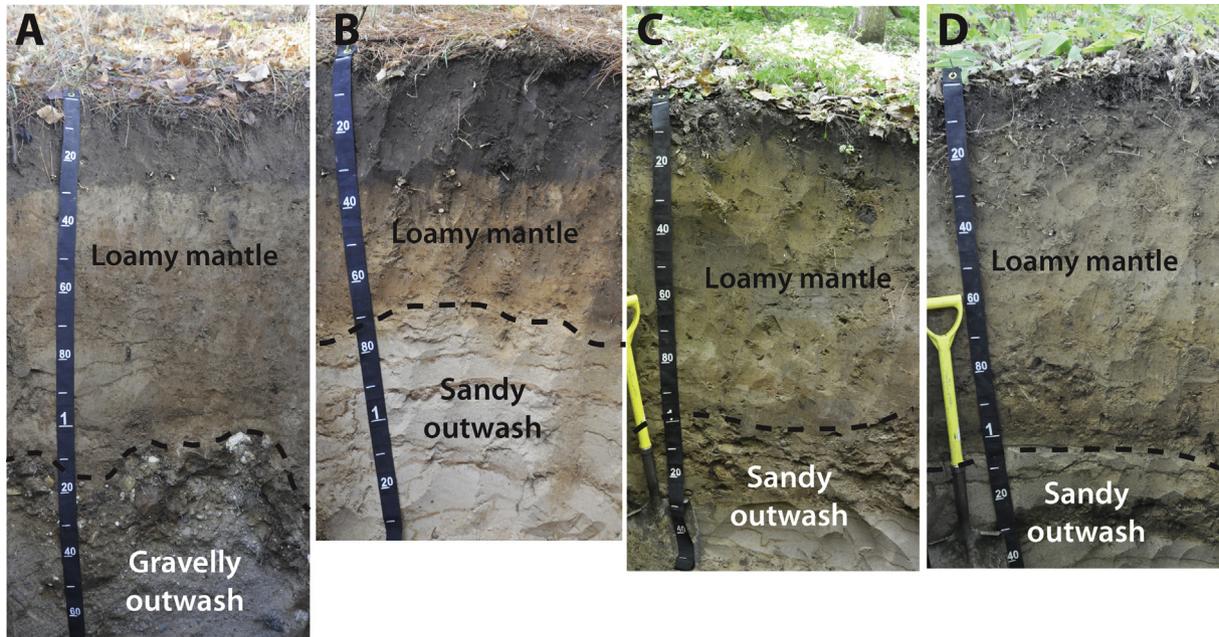
- A. Site #1, with  $\approx 118$  cm of loamy material over outwash, which is very gravelly in its upper part.
- B. Site #4, with  $\approx 62$  cm of loamy material over sandy outwash.
- C. Site #6, with  $\approx 97$  cm of loamy material over sandy outwash.
- D. Site #9, with  $\approx 103$  cm of loamy material over sandy outwash.

All four sites have an abrupt contact between the upper material and the outwash below, as shown by a dashed line. Textural lamellae in the outwash, especially prominent in photo B, are a product of pedogenesis, and are not geogenic features.

At the peak of the Port Huron advance, the Flats would have been between the ice sheet and the Harrietta Uplands (Fig. 1). After

the ice withdrew from the ice-contact slope at the northwestern edge of the Flats, large parts of the outwash plain may have become subaerial and free of meltwater; the incised channels to the east and south of the main part of the Flats support this hypothesis. Under this setting, the climate would likely have been cold enough to develop permafrost across the Flats, as has been suggested for similar sites in Lower Michigan (Schaetzl, 2008). Permafrost, which likely persisted for a period of time after the ice withdrew and meltwater stopped flowing across the Flats, provides the best explanation of the lack of mixing between the outwash and the sediment above during and after deposition. A frozen substrate could have preserved the sharp upper contact of the outwash sediment, even while additional (aeolian) sediment was being deposited. Permafrost would still have allowed for some vegetation to colonize the surface and trap aeolian sediment within the active layer. The surface morphology of some farm fields also suggests a type of patterned ground and other types of topographic irregularities, much like high-centered polygons (Lusch et al., 2009). In the northern Flats, where the mantle is thick and near the former glacial margin, highly irregular and contorted horizonation was noted in the soil profile at pit site 4 (Fig. 3), and interpreted as being the result of cryoturbation.

Taken together, these observations led to the rejection of the initial hypothesis for the origin of the loamy mantle on the Flats. In particular, the abrupt contact between the upper, loamy sediments in the soils on the Flats and the outwash below necessitated a model wherein an upbuilding event occurs with minimal disturbance to the underlying outwash, and where post-depositional pedoturbation is also minimal. Thus, our working model posits that



**Fig. 6.** Photographs of four representative soil profiles from the Buckley Flats. See Fig. 3 for locations. The photos are stacked so that each is portrayed with the same vertical scale.

the last depositional interval on the Flats, i.e., the deposition of the loamy mantle sediment, occurred while at least the northern part of the landscape was underlain by permafrost. Using this model, the abrupt transition to underlying outwash can be interpreted as representing the paleopermafrost table, or more specifically, the transient layer. Where the transient layer is an ice-rich layer indicating the long-term position of the permafrost table, thawing on the order of decades and centuries (Shur et al., 2005), this layer could therefore have acted as a cap on the underlying sediment.

#### 4.6. Origin of the loamy mantle: Silt component

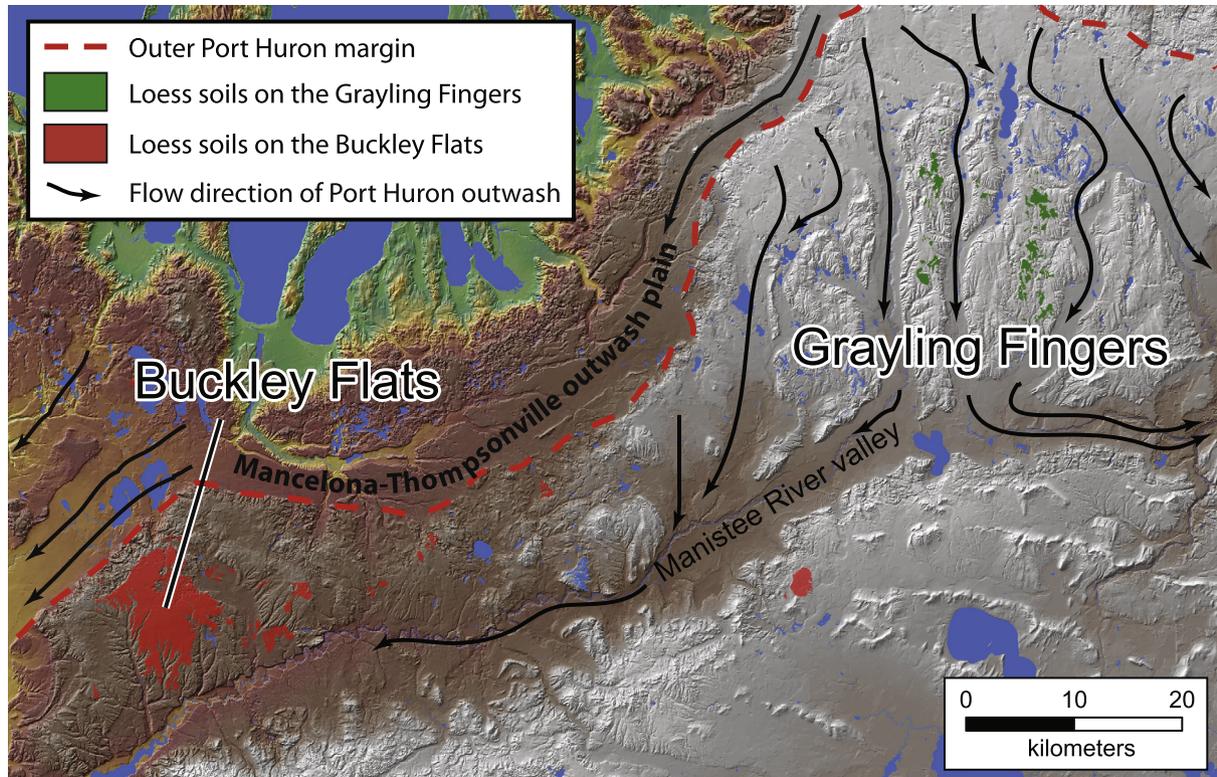
In a previous paper, Schaetzl (2008) reported evidence for Late Pleistocene permafrost on the Grayling Fingers, a large upland only 90 km to the northeast of the Flats, and only slightly farther from the outer Port Huron moraine (Schaetzl and Weisenborn, 2004; Fig. 7). Flat, stable, upland sites in the Fingers are capped with <90 cm of silt-rich, loamy sediment, which Schaetzl (2008) interpreted as loess, subsequently mixed with sand from the underlying till. The loamy mantle in the Fingers often lacks the abrupt boundary observed on the Flats. The loess source for the Fingers was determined to be the Port Huron outwash surface, which surrounds the Fingers on all sides, and is also confluent with the valleys between the Finger uplands (Schaetzl et al., 2006). This same outwash surface continues uninterrupted to the southeast, where it merges with the Manistee River valley south of the Flats (Fig. 7). It seems likely that this outwash surface would have been a loess source along its complete extent - from the Fingers to the Buckley Flats

Testing the hypothesis that the silt component of the loamy mantle is loess, we examined *filtered* particle size data to determine its textural characteristics, and mapped them in ArcGIS. Recall that filtered data do not include any sand component (Fig. 4). Filtered data for the 105 loamy mantle samples are dominated by silt, averaging 64.4% silt, with an average content of 39.3% fine silt (6–25  $\mu\text{m}$ ). Medium (25–35  $\mu\text{m}$ ) and coarse silt (35–50  $\mu\text{m}$ ) comprise much smaller percentages of the sediment (average contents: 14.4% and 10.7%, respectively). The mean weighted particle size of the filtered fraction is 32.9  $\mu\text{m}$  (medium silt). The

relative paucity of coarser silt fractions in the loamy mantle suggests that the silt/loess sources were not immediately adjacent to the Flats, or that the loess was brought in on generally light winds.

Filtered data from previous work (Schaetzl and Loope, 2008; Scull and Schaetzl, 2011; Schaetzl and Attig, 2013; Schaetzl et al., 2014) on >1900 loess samples from across Wisconsin and the Upper Peninsula of Michigan confirm that loess on the Flats is similar to loess in the region at large (after the sand peak data are filtered out). The filtered data for this large suite of Midwestern loess samples show an average mode of 36.2  $\mu\text{m}$  and a median of 30.8  $\mu\text{m}$ . Data for the silts on the Flats are comparable, with a mean of 34.7  $\mu\text{m}$  and a median of 33.8  $\mu\text{m}$ . Midwestern loess data average at 36.9% fine silt, whereas medium and coarse silt contents average 14.6% and 10.4%, respectively. This comparison illustrates that most loess deposits in the upper Midwest are very similar to the silts in the loamy mantle on the Flats thereby reinforcing the original loess interpretation made by Schaetzl and Hook (2008).

In contrast to the previous study however, this re-analysis generated little evidence for a single nearby loess source, such as the Manistee River valley. If the Manistee valley were the primary silt source, we would expect larger contents of coarse silts in the mantle sediment, and a clearer south-to-north fining and thinning pattern, which is not evident (Fig. 8). Silt fractions actually do not show strong variation across the Flats (Fig. 8). Fine and medium silts are most common in the central Flats, whereas coarse silts are more common near the margins, although again, the variation across the landscape is low. More likely, the region was rife with broad, active outwash plains and moraines that slumped as buried ice melted during and after the Port Huron advance. New sediment would have been exposed and likely contributed to widespread dust generation and mobilization. Examples of local silt sources that contributed to this regional dust cloud could have been the Harrietta Uplands to the south, the Manistee River valley, the Mancelona-Thompsonville and Port Huron outwash plains, and even the wide Anderson Creek valley immediately east of the Flats. All of these landscapes could have been silt sources particularly as sand- and silt-rich meltwater “refreshed” the many outwash surfaces, or as silt settled out in temporarily ponded settings, and then deflated as the waters drained. Work on comparably thin loess in



**Fig. 7.** Map of northwestern Lower Michigan, showing the locations of the Buckley Flats, the Grayling Fingers, and the most distal extent of the Outer Port Huron moraine. Soil series with loess influence are shown as red on the Buckley Flats, and as green on the Grayling Fingers.

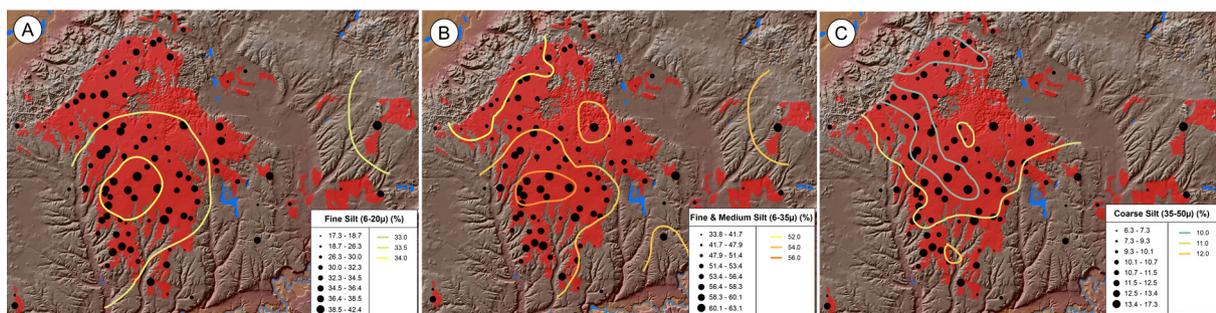
the western Upper Peninsula of Michigan concluded that small outwash surfaces like the ones surrounding the Flats a legitimate loess sources (Luehmann et al. 2013). Some silt was present in the Port Huron meltwater; outwash samples recovered from the Flats average 3.9% silt, and a fine-textured stratum in one outwash deposit contained 11.6% silt. As was the case with many other kinds of thick, silty loess deposits across the Midwestern US (Ruhe, 1984; Fehrenbacher et al., 1986; Mason et al., 1994; Grimley, 2000; Bettis et al., 2003), the presence of a single, prodigious, local loess source, coupled with strong winds from one main direction, is clearly lacking here.

#### 4.7. Origin of the loamy mantle: Sand component

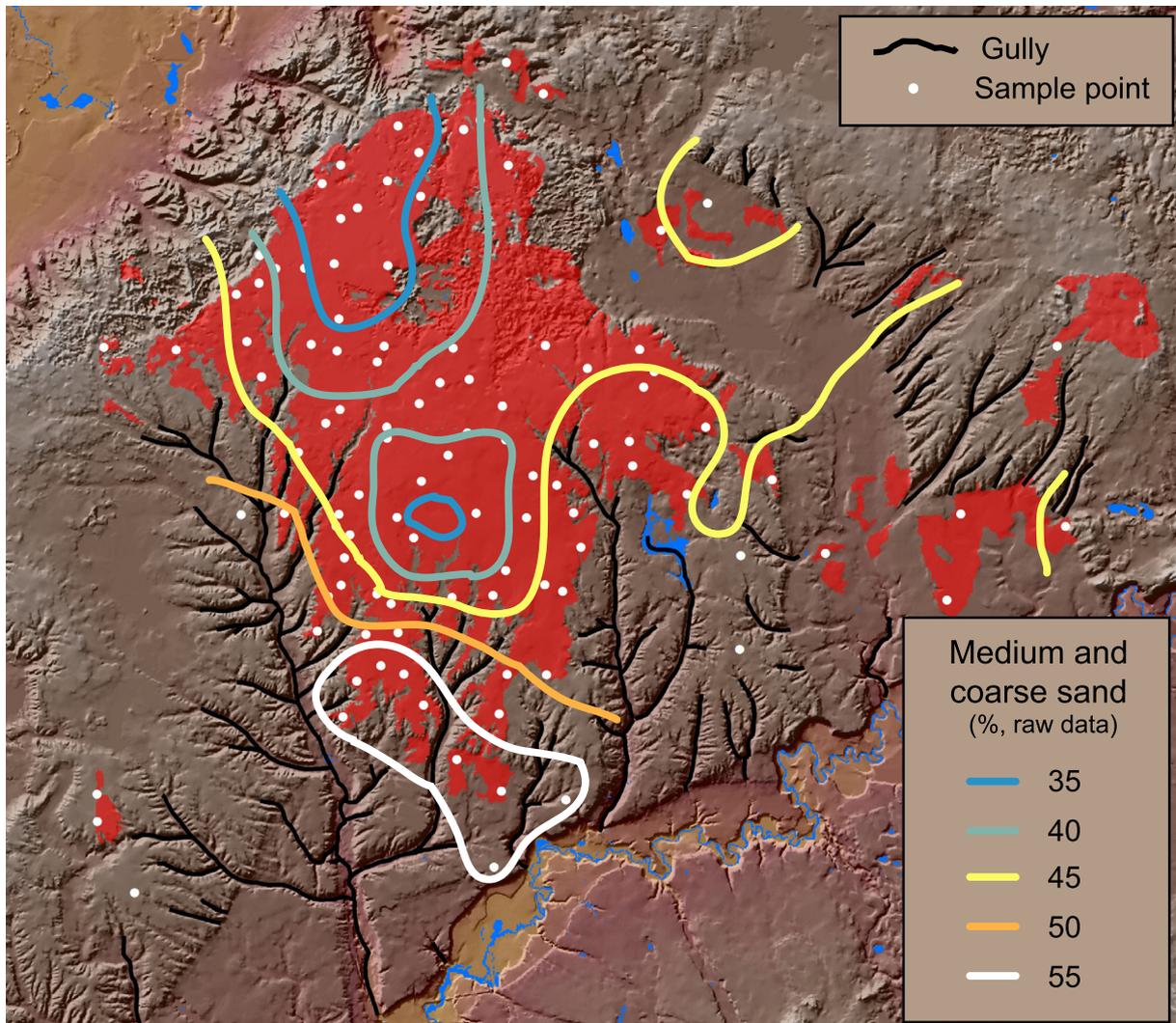
Although the silty component of the loamy mantle on the Buckley Flats appears to be loess, mantle sediments also contain considerable amounts of sand. The distinctly bimodal distribution of particle sizes in the loamy materials (peaks in both the silt and

sand fractions shown in Fig. 4) suggests two different sediment sources or origins. As discussed above, pedoturbation of underlying outwash sands into the upper profile seems unlikely, or at least does not apply universally across the Flats. Therefore, to better understand the possible origin of these sands, their spatial and textural characteristics were examined, as was done for silts, using unfiltered (raw) particle size data (Figs. 9 and 10). Depth functions for sand and silt contents were also examined from soil pits across the Flats.

Sands within the loamy mantle are primarily within the medium sand (250–500  $\mu\text{m}$ ) fraction, with an average mode of 359  $\mu\text{m}$ . Maps in Figs. 9 and 10 show that, unlike silt contents, sand contents vary markedly across the Flats, with maximum values often occurring near the margins. In particular, sand contents increase considerably in areas near deep gullies that are immediately distal to the western and southern margins of the Flats (Fig. 9). Medium and coarse sand contents in the loamy mantles are 15–20% higher near the gullies than in the central Flats



**Fig. 8.** Maps of the content of various silt fractions (filtered) in the loamy mantle on the Buckley Flats. Note the general “bullseye” pattern made by the different silt fractions centered on the middle of the Flats, indicative of multiple surrounding or regional silt sources.



**Fig. 9.** Map of the Buckley Flats, showing the locations of the 105 sites used for analysis and the network of gullies that surrounds the periphery of the area. Isolines of medium and coarse sand contents of the unfiltered (native) data are also shown.

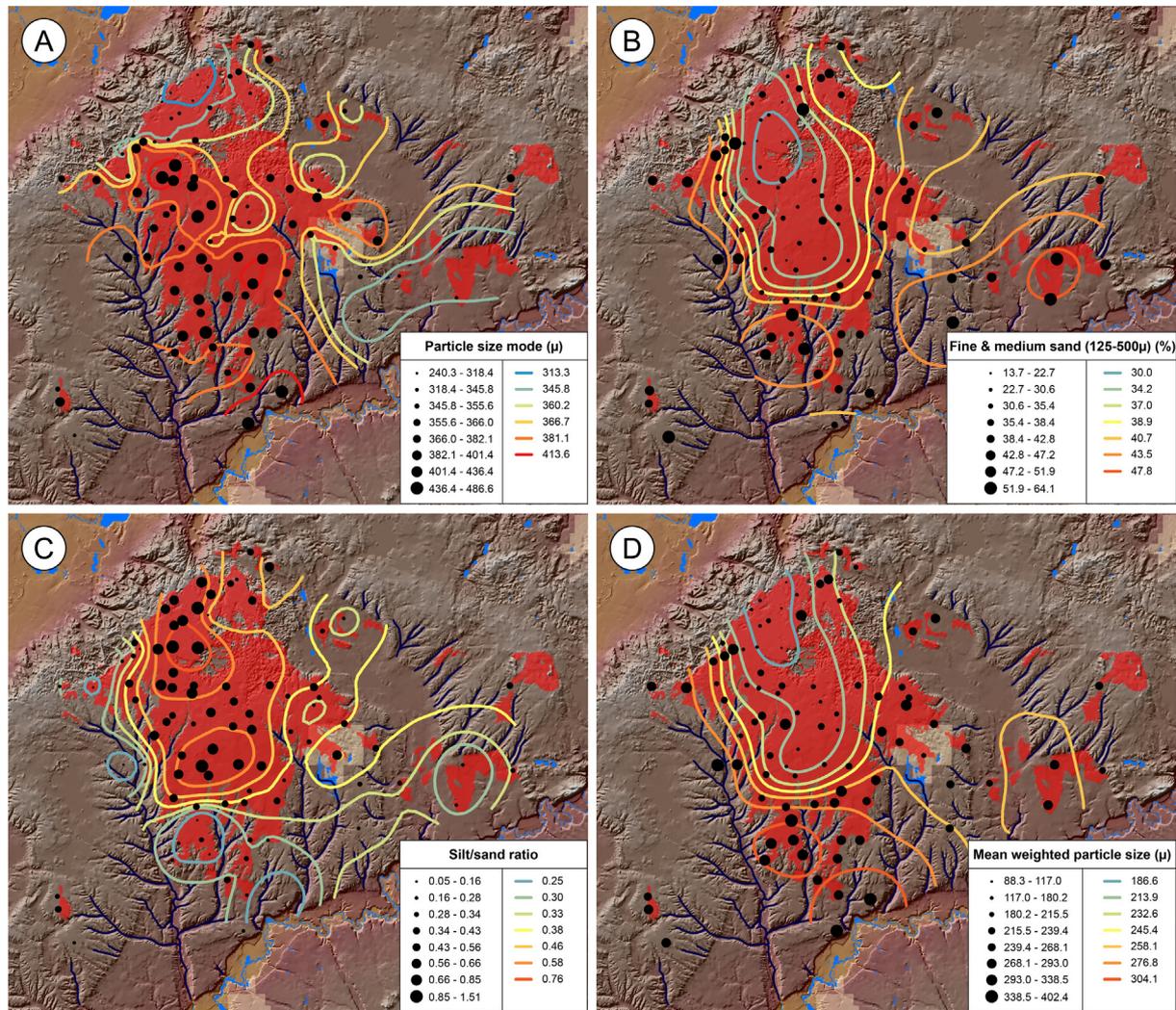
(Fig. 9). Similar patterns occur for the mean weighted particle size of the loamy mantle sediments, and for fine and medium sands (Fig. 10). Silt/sand ratios decline near these same gullies (Fig. 10C). Scatterplots (Fig. 11) illustrate that textural properties of the loamy mantle vary predictably with distance from the nearest gully, suggesting that the gullies may have been important sand sources. Medium and coarse sands decrease with increasing distance from gullies, probably because they were not able to be transported as far as fine and very fine sands, whose contents increase away from gullies (Fig. 11). Thus, sand/silt ratios decrease predictably away from gullies and attain their highest values in the flattest, central parts of the Flats.

#### 4.8. Depositional model for the loamy mantle on the Buckley Flats

Other models that were considered for the origin of the loamy mantle do not readily fit the data discussed above. For example, if the loamy mantle simply represented the last, finer-textured stratum within the outwash package, its textures should exhibit spatial trends that radiate primarily away from the former ice margin, rather than changing with respect to the gullies at the edges of the Flats. Likewise, a final, fine-textured outwash deposit on the Flats should be focused in small valleys and lowlands, rather than being spread continuously across the surface. A second possibility

is that the mantle is the product of an erosional-depositional system, in which fluvial erosion and loess deposition were generally contemporaneous across the Flats. In this model, loess gets mixed in with the sediments being reworked by fluvial erosion, as may have occurred on the lowan Erosional Surface (Hallberg et al., 1978). The advantage of this model is that erosion would have likely been more pronounced near the margins of the Flats and especially near the gullied areas, which would have enhanced the loss of silt there and hence, lead to sandier mantles. Elements of such a model do, indeed, fit for the Flats upland. Nonetheless, if this model is the only one used to explain the loamy mantle, then stone lines and other evidence of erosion surfaces would likely be present within the mantle proper. In the nine pits excavated, there were no stone lines or other evidence of erosional surfaces within the mantle sediment.

Like other areas in northern Lower Michigan (Schaeztl, 2008), the presence of permafrost on the Flats would have accentuated runoff and formed gullies. The largest and deepest gully system is associated with Fletcher Creek, which along most of its extent is a dry valley (Figs. 3 and 9). Soil development in gully bottoms is equivalent to that on side slopes and uplands, pointing to their current geomorphic stability, and confirming that they were cut in the immediate post-glacial period. As they were being incised into the outwash column, sandy sediment would have been



**Fig. 10.** Maps of (A) primary particle size mode, (B) fine and medium sand content, (C) silt/sand ratios, and (D) mean weighted particle size for the loamy mantle sediments on the Buckley Flats, using raw (unfiltered) data.

exposed to wind. Most of the gullies here are shallow and broad, with gently sloping side slopes, allowing for enhanced wind turbulence and facilitating the entrainment of sands. Similarly, deep gullies can act as traps (temporary or permanent) to saltating sand (Mason et al., 1999).

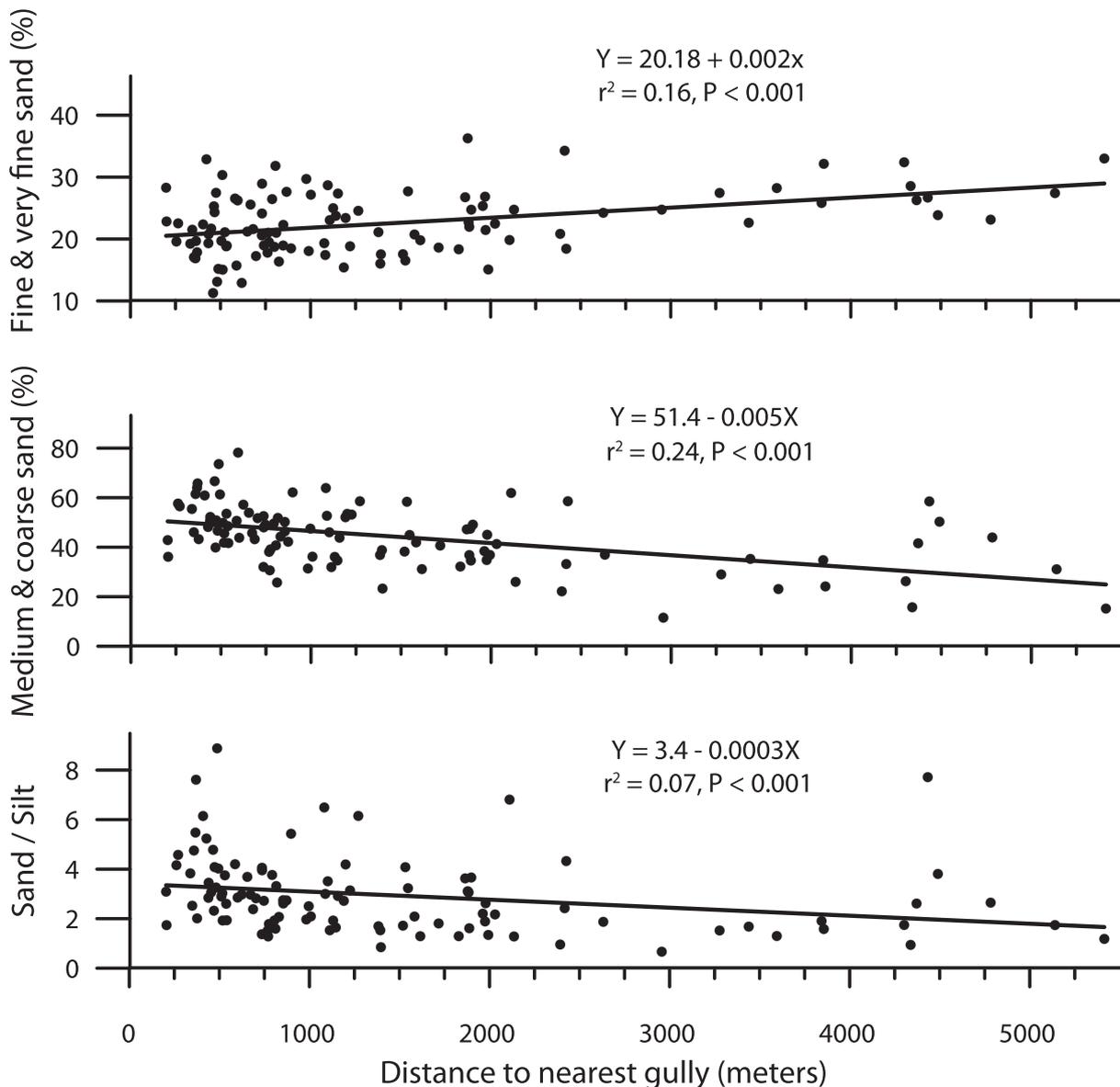
These data, when taken together, argue for the importance of the gullies on the west side of the Flats to the development of the loamy mantle. Two possibilities emerge. Sand in the loamy mantle on the Buckley Flats was largely derived from these actively eroding gullies such as in the Fletcher Creek system (Fig. 13). Our data suggest that such systems were important to the sourcing of sands onto the Flats. Additionally, although of lesser importance, as sand was migrating across the flat upland to the west of the Flats (west of the Fletcher Creek valley), it facilitated the entrainment of loess. Much of this sand got trapped in deep gullies, allowing mainly loess/silt to be transported to the east, onto the Flats proper. Data on mantle textures (sandiest near the gullies and silty at sites farther away) support these scenarios, but suggest that the gullies as sand sources was key to the development of the loamy mantle. Indeed, the only site with a silt loam mantle (raw data) is in the northern part of the Flats, far from the gullies and sheltered from saltating sand by a dense network of kettles to its immediate south.

Although sand transport was probably mainly by saltation, previous work has shown that sands can also be transported consider-

able distances in suspension, if assisted by steep, upwardly sloping surfaces that can act as transport ramps (Anderson and Walker, 2006; DeVries-Zimmerman et al. 2014). Such long-distance transport of sand grains in temporary suspension, analogous to a “cloud” of suspended sand, is further assisted by turbulence at height. Such turbulence would have been greatest at the margins of the Flats, where gullies intersect the low relief outwash plain.

Textural data from the four pits closest to the large gully system on the southwestern margin of the Flats illustrate the silty nature of the loamy mantle, and how textures change markedly across its lower boundary (Fig. 12). At all of these sites, the mantle is sandiest in its lowest part and becomes most silty in the uppermost 20–40 cm. This implies that loess deposition may have continued after gully incision and its concomitant sand production had slowed or stopped. And it also suggests that the cessation of sand deposition may have actually gone hand-in-hand with loess deposition, i.e., as more and more of the uplands get a loess cap, fewer locations existed that could have acted as sand sources. By necessity then, silt transport and deposition would have outpaced sand transport and deposition, leading to surface mantles that became increasingly silty toward the surface.

The loamy mantle is sandiest at the pit nearest the large gully system and becomes increasingly silty with distance (Fig. 12), which supports our model of sand sources associated with gully



**Fig. 11.** Scatterplots showing statistical relationships between the contents of various textural components in the loamy mantle and distance to the nearest large gully, as calculated in ArcGIS. Gullies digitized for this analysis are shown on the map in Fig. 9. Note that finer sand fractions increase with distance from gullies and larger sand particles decrease. This trend is also highlighted by sand/silt ratios.

systems. In this model, sands are saltated up and onto the Flats from eroding gullies (Fig. 13). We cannot discount that saltating sand on the flat upland to the west of Fletcher Creek may have helped entrain silt, some of which eventually was deposited on the Buckley Flats as much of the saltating sand fell into the deep gullies of the Fletcher Creek system. Regardless, the period of sand mobility and deposition likely was contemporaneous with loess deposition and gully formation. Support for this conclusion comes from the lack of stratification in the loamy mantle sediment. Based on augering and data from the soil pits, the loamy mantle usually gets progressively siltier toward the surface, implying that loess deposition may have continued after gully incision and its concomitant sand production had slowed or stopped.

##### 5. Conclusions: Buckley Flats paleoenvironmental conditions during the post-Port Huron interval

The Buckley Flats are a perched, gently sloping outwash plain associated with the Outer Port Huron advance, having formed ca.

15,100 to 16,470 cal yrs ago. The outwash sediments here are covered with a  $\approx 70$  cm thick “loamy mantle”, which is the focus of this study. Our data show that the loamy mantle is a mix of discrete silt and sand components, with little or no stratification, and often with an abrupt lower boundary to undisturbed glacial outwash. The loamy mantle typically gets siltier toward the surface. Many of the outwash plains in southwestern Lower Michigan have similar near-surface stratigraphy and soils, which Luehmann et al. (2016) attributed in part to pedoturbation of loess with the outwash sands below. That scenario seems unlikely, or at least far less important, on the Buckley Flats, because of the abrupt lithologic contacts between the outwash and the loamy mantle sediments. Here, we suggest a new model for the genesis of the loamy mantle, one which has extensibility to other areas of similar soils.

As has been shown for other parts of Michigan (Schaeztl, 2008; Lusch et al., 2009), the Flats likely experienced a period of permafrost. This event likely occurred during and shortly after the Port Huron advance, while the ice margin was nearby. Because the Buckley Flats are a high, perched outwash plain, they may have

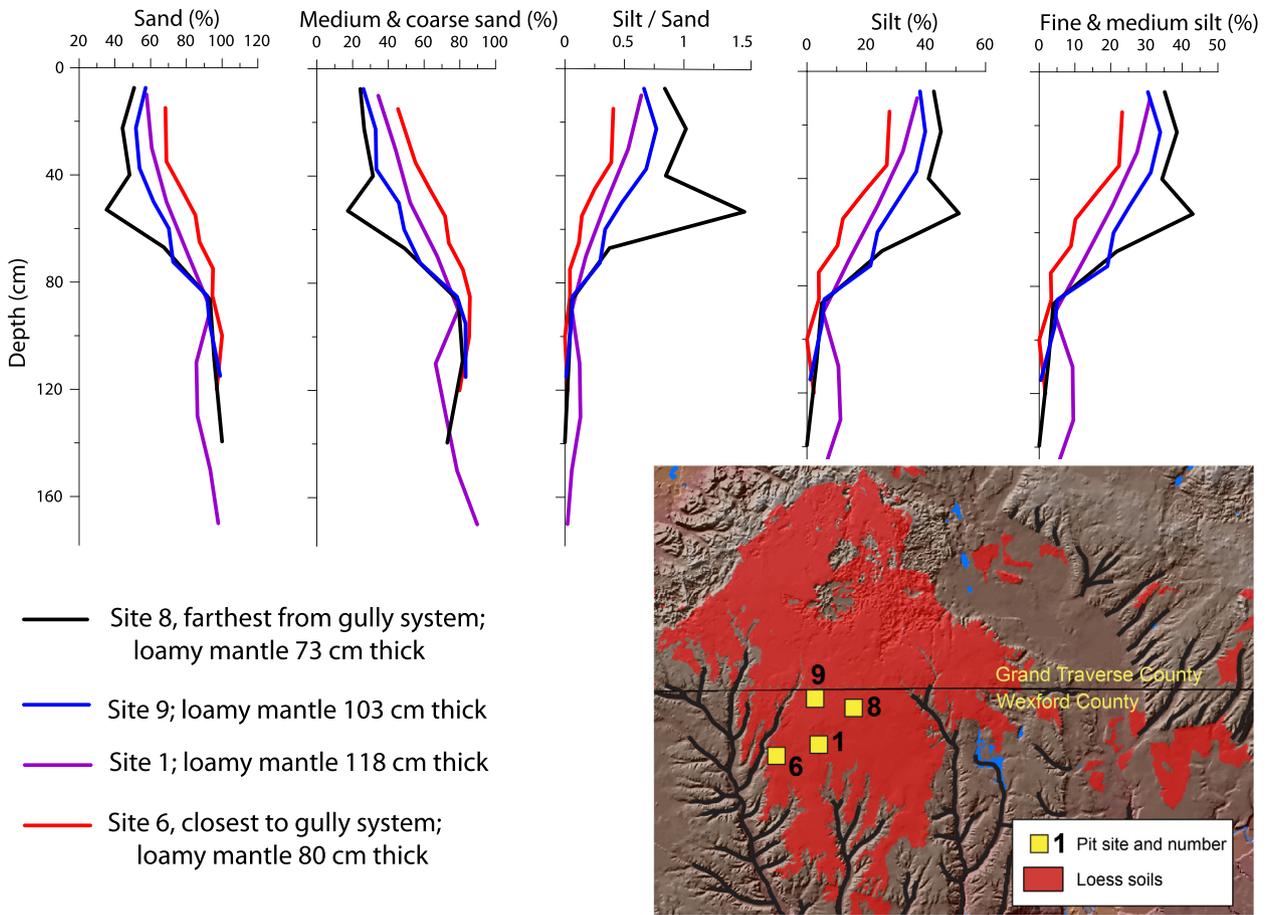


Fig. 12. Depth plots of various textural parameters for the four pits closest to the large gully system on the SW side of the Buckley Flats.

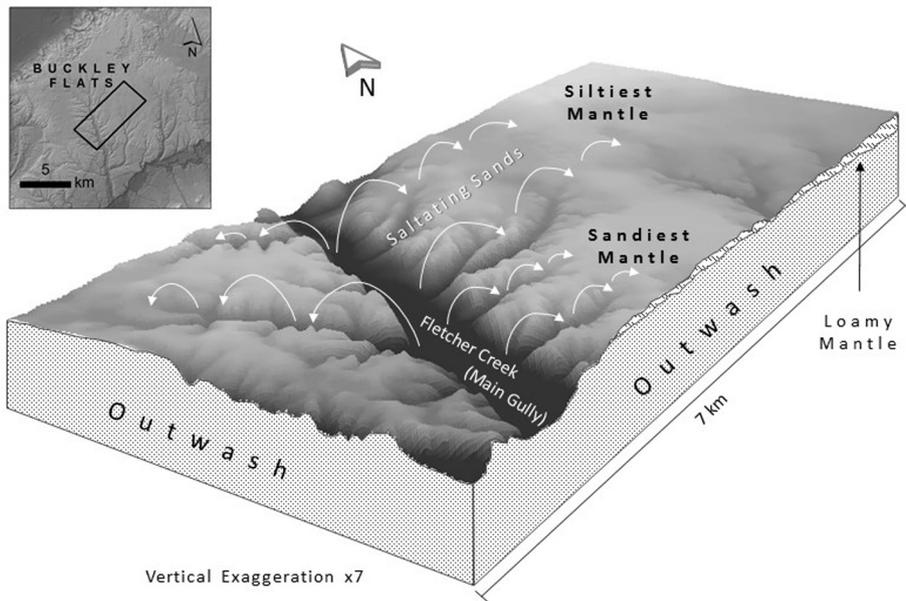


Fig. 13. Block diagram of the western part of the Buckley Flats, showing the contemporaneous deposition of sands (by saltation up from eroding gullies) and silts (settling out of regional atmospheric suspension) onto the uplands. Together, these two suites of processes formed the loamy mantle that exists there today.

become periodically free of meltwater, and geomorphically stable earlier than other Port Huron landscapes. Once meltwater-free, permafrost could have developed quickly. As occurred on the Grayling Fingers upland roughly 90 km to the northeast, where side-slope gullies in sandy sediments are deep and numerous (Schaeztl, 2008), permafrost likely fostered runoff and gully incision. Sand contents in the loamy mantle are considerably higher at sites near these gullies, and decrease predictably with distance from them, indicating that the sand component in the loamy mantle was derived from (or passed through) these actively eroding gullies, as sand saltated up and onto the outwash surface, just as likely occurred in the Grayling Fingers. Very fine sands increase slightly away from the gullies, becoming maximal in the central parts of the Flats. These finer sands may have been more easily transported across the outwash surface, possibly becoming trapped in what may have been seasonal ponds in the central Flats.

Silts in the loamy mantle sediments originally were deposited as loess. When examined without the sand component, they show little variation across the Flats, and are dominated by fine silts. The lack of clear spatial variation in silt contents across the Flats suggests that there was no single dominant loess source nearby. Based on the new data presented here, the loess on the Flats appears to have been regionally derived, likely from a variety of local sources, much like loess in parts of Michigan's western Upper Peninsula (Luehmann et al., 2013). Outwash plains and other glacial surfaces abound in northern Lower Michigan, and were active both during and after the Outer Port Huron advance (Blewett and Winters, 1995; Schaeztl et al., 2006). Any of these surfaces could have contributed silt to the regional winds. Northern Lower Michigan was a dusty place immediately after the Port Huron advance. And at this time, the Flats, especially the central Flats where relief is minimal, may have been underlain by permafrost but with some vegetation and (locally) ephemeral ponding, resulting in conditions that would have led to the efficient retention of silts that settled out of suspension.

In summary, these new data suggest that saltating sands and loess comprise the loamy mantle on the Buckley Flats, and for at least some of the depositional interval both systems were simultaneously operative. Because the soils here often get siltier near the surface, we argue that loess deposition may have continued after permafrost had thawed and gully incision had ceased. Nonetheless, it is important to also note that, as the stable uplands on the Flats variously accumulated loess and eolian sands, they (and nearby areas) became increasingly loess-covered and silty, facilitating colonization and further stabilization by plants. Fewer locations then may have remained open as sources of eolian sand, necessitating that the eolian sand part of the system slow or even shut down. The controls on loess generation, transport and deposition may have continued unabated, because they would have been unaffected by the thickening mantle on the uplands. Thus, over time, the stable, aggradational sites on the landscape necessarily became siltier nearer the surface; such situations have been observed at numerous sites across the upper Midwest (Schaeztl, 2008; Luehmann et al., 2013, 2016).

Our work helps elucidate how loess soils can have distinct sand modes. They may form by post-deposition pedoturbation and/or loess and aeolian sand deposition onto a stable substrate.

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