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Evidence for periodic, Holocene loess deposition in kettles in a sandy, interlobate landscape, Michigan, USA

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ABSTRACT

Loess deposits are common in mid-continental North America, but are rare in Michigan, and most loess found in this region is of last-glacial age. We report on evidence for Holocene-age, silt-dominated deposits found in kettle bottoms, which we interpret as loess. These silty deposits contrast with the broader interlobate landscape, which is composed of glaciofluvial materials dominated by medium and fine sands (125–500 μm). The abrupt lateral edges of the silty deposits, and their unique textural properties relative to the surrounding landscape, suggest that the silts were not washed from kettle backslopes. Rather, we suggest that the silts originated as loess that was episodically deposited in kettle bottoms across the Upland. Later, loess that may have been deposited on backslopes was occasionally redeposited into the centers of vegetated kettles, along with some background sands, by wind and water. Evidence in support of our conclusions includes (1) the fine-silty textural characteristics of the sediments, set within an otherwise sand-dominated landscape, (2) depositional sequences of charcoal-rich paleosols, intercalated within the otherwise "clean" kettle bottom silts, pointing to episodes of loess deposition interspersed with periods of slope stability and pedogenesis, and (3) increased silt contents within the upper meter of sandy soils on nearby stable uplands. Radiocarbon ages on bulk charcoal from nine paleosols within the kettle-bottom silt deposits fall mainly within the early Holocene. These deposits and ^{14}C ages provide the first evidence of Holocene loess in the Great Lakes region, some of which probably originated from the nearby Muskegon River floodplain.

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1. Introduction

Kettles mark the former locations of detached masses of glacial ice (Rieck, 1979; Bennett and Glasser, 1996). Because most kettles are topographically closed and internally-draining, they have the potential to collect and retain sedimentological and biological materials, potentially preserving a record of their inputs (Walker and Ruhe, 1968). Infilled kettle sediments, therefore, can provide sedimentary records that may prove insightful as to local and/or regional paleoenvironmental change (Florin and Wright, 1969; Lagerback and Robertsson, 1988).

This study is in a densely kettled, interlobate upland in southern Michigan, which we named the Evart Upland, for its location near the city of Evart (Fig. 1). The Evart Upland formed between the Lake Michigan and Saginaw lobes of the Laurentide ice sheet (Rieck and Winters, 1993). Sandy, glaciofluvial sediment dominates this and similar landscapes nearby (Farrand and Bell, 1982; Rieck and Winters, 1993; Schaetzl and Weisenborn, 2004; Schaetzl and Forman, 2008). Initial field investigations in the Evart Upland revealed that many of the kettles there have silty sediment in the central, lowest portion of the depression. These sediments are anomalous because they are set within an otherwise sand-dominated landscape. The silty deposits occur within the exact bottom-centers of dry kettles, and are usually <2 m in thickness and <20 m in diameter; they abruptly overlie coarse textured, sandy outwash. Furthermore, buried soils commonly occur in the silty sediments of some kettle bottoms. The purpose of this research was to determine the likely geomorphic origin(s) for these silty deposits, and by dating the paleosols within them, to also constrain the timing of the silt deposition. We believe that, taken together, these data will provide important information about aeolian paleoenvironments in general, and loess in particular, for this region.

This study provides interesting and unique conclusions about what we believe is Holocene-aged loess in dry kettle bottoms in southern Michigan. Loess is rare in Michigan (Schaetzl, 2008; Schaetzl and Loope, 2008; Schaetzl and Hook, 2009) and Holocene-aged loess is especially uncommon; none has yet been reported in the upper Great Lakes region. Ultimately, this research provides insight into loess generation, deposition, and (re)distribution in a high relief, sandy landscape, one in which aeolian silt is commonly not observed.

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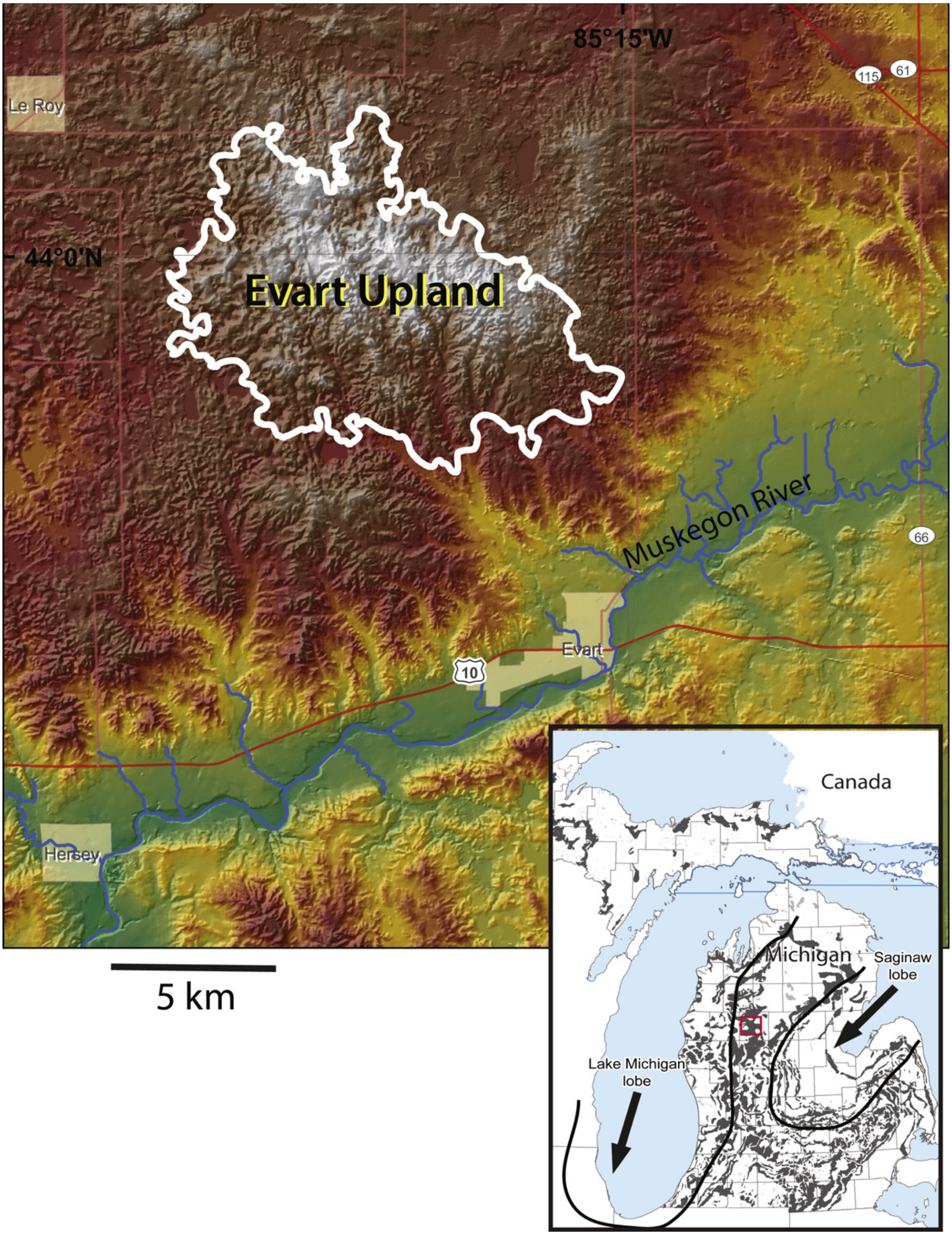

Fig. 1. Location and topography of the study area and surrounding landscape. The white line delineates the extent of the Evart Upland. Inset map: location of the study area relative to the major glacial lobes that formed it. The location of the Evart Upland in the inset map is shown as a red square. Elevations in this figure range from to 280 to 467 m asl. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2. Hypotheses

During fieldwork, we observed that many of the dry, upland kettles in the Evart Upland contain silty deposits, and that these deposits are almost always present in the non-forested kettles. The near ubiquity of silt deposits in kettle bottoms suggests that the kettle depressions have acted as accumulation basins, preserving a post-glacial sedimentary record (Walker and Ruhe, 1968; Schaetzl, 2008; Makeev, 2009). We then formulated two hypotheses to explain the origin of these silty deposits:

Hypothesis 1: the silt was winnowed from the surrounding upslope (within the kettle backslopes) sediments by water, as slopewash.

Hypothesis 2: the silt is loess that was blown into the region and has become spatially concentrated in the kettle bottoms.

In the first hypothesis, the surrounding kettle backslope sediment is the presumed silt source, as has been documented elsewhere (although with distinct anthropogenic drivers – Frielinghaus and Vahrson (1998)). Textural differences between backslopes and bottomlands are common; on most steep, internally drained hillslopes, erosion and sorting processes result in gradual, downslope-fining texture sequences (Milne, 1936; Walker and Ruhe, 1968; Malo et al., 1974). In order to accept this hypothesis, therefore, two conditions must be met: (1) backslope sediments in the study area must contain significant amounts of silt (of comparable particle size distribution) to that in kettle bottoms, and (2) silty kettle bottom deposits must gradually "coarsen" from their centers to the distant edges, eventually merging into the "clean" sands of the backslopes.

If these conditions do not hold, we will argue for an (initial) aeolian origin for the kettle bottom silt (Hypothesis 2), because there exists no other reasonable mechanism by which such silty deposits could have been deposited in the kettle bottoms. We use the word "initial" because some loess could have been subsequently redistributed by wind and water (and likely was) into lowlands and kettle bottoms. The only other mechanisms that could explain the origin of these silty sediments involve increased weathering of near-surface, in situ sediments, or deposition of silts in previous, subaqueous, i.e., kettle lake, settings. Both of these scenarios are highly unlikely for the Evart Upland. The sediments here are all <17,000 years old (Blewett et al., 2009), minimally weathered, and heavily quartz-dominated. The soils are all relatively weakly developed Entisols and Spodosols, with deep water tables, and have formed under generally xeric conditions that are not conducive to weathering (Mettert, 1969; Soil Survey Staff, 1999; Mikesell et al., 2004). The long-term weathering necessary to produce large amounts of silt, especially from these quartz-dominated parent materials, seems unlikely. Additionally, the soils in the dry kettles, where silty deposits exist, are high on the interlobate landscape, where water tables are very deep, in most cases >10 m, and as such, have not likely ponded water, even in the Latest Pleistocene.

The two hypotheses we present imply significantly different paleoenvironmental interpretations for the Evart Upland. A slopewash origin for the kettle bottom silts suggests that precipitation and snowmelt can generate enough runoff on these sandy slopes to winnow silt from the sandy backslope sediment and transport it to the kettle bottoms. It implies that, despite the sandy textures, surface runoff frequently occurs here, and thus, slope instability, erosion, and downslope deposition are parts of the ongoing geomorphic evolution of this landscape. In contrast, an aeolian origin for the kettle bottom silts suggests that a nearby silt (loess) *source* exists, and that, at some time in the past, there existed ample winds to deflate and transport this silt into the study area. Slope instability is not necessary to accept this hypothesis, because small amounts of aeolian silt could have been episodically deposited in, and transported downslope into, kettle bottoms. Downslope transport can occur on top of otherwise stable and vegetated (grassed and treeless) slopes. Indeed, considerable amounts of slope stability are actually implied in the "aeolian" Hypothesis 2.

3. Study area

We defined the Evart Upland (Fig. 1) topographically and hydrologically. This ~68 km^2 upland is characterized by highly undulating and hummocky terrain, and contains numerous dry kettles; the upland has little or no external drainage. In contrast, the surrounding lowlands have lower relief and exhibit wetter, less hummocky terrain. Many of the kettles outside of the upland proper are ponds, bogs, and/or wetlands (Fig. 2). Hills in the Evart Upland rise >150 m above the surrounding landscapes (Figs. 1 and 2). Local relief on the upland (between kettle bottoms and adjacent summits) can be up to 24 m, but is typically ~6–7 m. The abundance of dry kettles, and the ubiquity of well-sorted, sandy sediments, across the study area, confirm that the upland is an interlobate landscape derived mainly from glaciofluvial deposition (Folsom, 1971; Rieck, 1979; Fig. 1 inset).

Sediments in the upland are dominantly medium sands, with typical particle size distribution modes between 290 and 340 μm. Most soils are well- or excessively-drained, with deep water tables. In general, the climate in the study area is typical of humid continental, mild summer locations. The climate station nearest the Evart Upland, the City of Evart, is ~5.0 km southeast of the upland and 150 m lower in elevation (NOAA, 2008) (Fig. 1). At Evart, the warmest month (July) averages 20.2 °C, and the coldest month (January) averages −8.0°. Mean annual precipitation is approximately 843 mm, with typically ~139 cm of snowfall.

The combination of a cool climate with ubiquitously sandy parent materials and reasonably large amounts of snowmelt infiltration has led these soils to develop many characteristics of Entic and Lamellic Spodosols, and Typic Udipsamments (Schaetzl, 1996). Pedologic diversity across the Evart Upland is, therefore, low; five soil series with the taxonomic classifications mentioned above comprise >97% of the study area (Mettert, 1969). This observation underscores the uniform sandy characteristics of the sediments across the study area. Soils here rarely freeze, due to a combination of their location (just south of the mesic-frigid soil temperature boundary (Schaetzl et al., 2005), and the insulating effect of thick snowpacks (Isard and Schaetzl, 1998). Consequently, as in other sandy areas in southern Michigan, runoff, even during spring snowmelt, is almost nonexistent (Schaetzl, 2008).

As in the recent past, the vegetation of the Evart Upland is currently dominated by pine- mixed hardwood forest types (Albert, 1995; Comer et al., 1998; Hupy and Yansa, 2009). At the time of European settlement, the sandy ridges in the area were covered with oak-pine forest. Various species of ferns and grasses dominate the understory vegetation in the study area. Rice grass (*Oryzopsis asperifolia*) dominates the understory of some of the flatter landscape positions.

Many of the kettle bottoms in the Evart Upland are not forested, retaining instead a thick cover of grasses, forbs and ferns (Fig. 3). As such, they are readily identifiable on topographic maps and aerial photographs (Fig. 2). This appears to have been the stable type of ground cover for kettles here, as evidence of past forest cover in kettle bottoms, e.g., stumps or wood, is almost always lacking. The vegetation across most kettles changes from a forest on the upper shoulders, to backslopes and toeslopes of grasses and ferns. Although 1840's-era GLO (General Land Office) survey reports did not make reference to an absence of trees in kettle depressions, in counties further northeast, GLO surveyors did note "large frost pockets" in depressions on outwash plains and described these areas as dry prairie openings (Albert, 1995).

4. Methods

4.1. Field methods

Digital spatial data, i.e., topography, soils, hydrography, were obtained from the Michigan Geographic Data Library (Michigan Department of Information Technology, 2007) and loaded onto a field laptop equipped with ArcMap software (ESRI, Redlands, CA), to be used for site selection, field navigation, and data recording. Non-forested kettles were selected for study because initial field

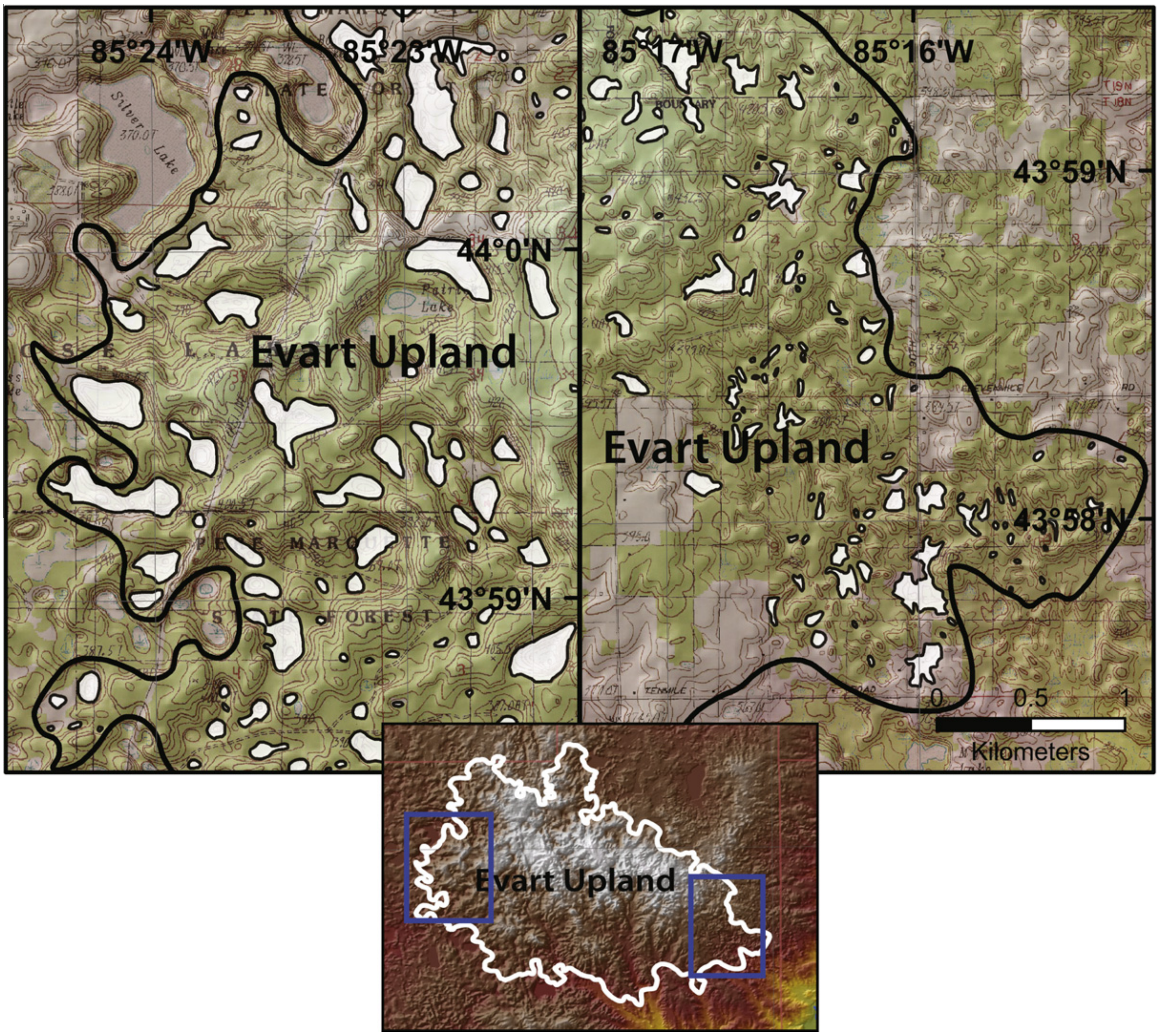

Fig. 2. Topographic maps of two different parts of the Evart Upland, one on the western end and one on the eastern end. Each area shows distinct differences in kettle morphology. On each, the boundary of the upland is indicated. Gray/white areas indicate kettles, drawn from the highest, closed contour line.

investigations suggested that such sites often contained silty deposits. At each site, one sample was obtained by hand auger from the silty kettle bottom deposit and the surrounding kettle backslope. The former sample was acquired from the bottom–center portion of the depression, where silts are dominant, usually at a depth of 40–70 cm. The latter sample was obtained from a soil on the closest, steepest, convergent backslope position (often about halfway up the slope); at this position, slopewash processes, if present, would be most pronounced (Pennock and De Jong, 1987). Kettle backslopes were consistently sampled at 15–30 cm depth in order to capture a representative sample that would not have been stripped of its silt content (on the assumption that backslope soils may have been a source of kettle bottom silt). In total, 60 kettles were sampled (Fig. 4).

Additionally, we sampled soils on geomorphically stable, uplands. We sampled the upper 20–30 cm from soils at 75 such sites, throughout the Upland, taking care to sample only sandy soils on flat sites. At 10 other sites, we sampled sandy soils at 50, 100 and 150 cm depths, to determine if subtle textural trends existed, with depth.

Finally, nine kettles, each containing one or more buried soils (paleosols), were depth-sampled, at 10–20 cm intervals, into and including the underlying, sandy outwash (110–220 cm). Many of the kettle bottom paleosols contained charcoal fragments, especially in their A horizons. After bulk samples from these paleosols were collected, the charcoal within was isolated and dated using AMS-^{14}C techniques. The ^{14}C ages were not calibrated to calendar years because they represent pooled ages from among a suite of charcoal fragments of potentially different ages.

In order to better understand the sedimentology and spatial extent of the silt deposits in comparison to the "background" outwash sands within these kettles, we performed detailed sampling along a transect in a typical, unforested kettle (kettle #18, see Fig. 4). Twelve sites were sampled along this transect, starting at the upland next to the kettle, continuing downslope, into the kettle, and ending at the center of the silt deposit. Samples were taken at each site with a bucket auger, at 10, 20, 40 and 80 cm depths, for particle size analysis.

4.2. Lab methods

All samples were air-dried, lightly ground with a mortar and pestle, and passed through a 2-mm sieve to remove coarse fragments. The remaining fine-earth fraction was then homogenized by passing it through a sample splitter three times, ensuring a representative sub-sample for particle size analysis (psa), which was performed on a Malvern Mastersizer 2000 laser particle size analyzer. Prior to psa, samples were shaken for 2 h in a water-based solution with $[NaPO_3]_{13}{\cdot}Na_2O$ as the dispersant. In recent years, laser diffractometry has generally replaced the traditional sieve-

Fig. 3. Photographs of representative kettles from the Evart Upland. Site numbers are shown in Fig. 4. The transect study was performed at kettle #18.

pipette method for particle size analysis (Sperazza et al., 2004; Arriaga et al., 2006). Although the data produced by the two methods are comparable and highly correlated (Arriaga et al., 2006), some differences do exist, mainly in the estimation of the clay fraction (Buurman et al., 1997); laser diffractometry commonly underestimates the amount of <2 μm clay, when compared to the pipette method (Loizeau et al., 1994; Beuselinck et al., 1998). For this reason, Konert and Vandenberghe (1997) suggested that a clay–silt break of 8 μm be utilized in laser diffractometry, in order to facilitate comparisons with traditional particle size analysis data. In-house data suggested that correlations between clay contents determined by pipette vs. laser diffractometry are highest when the clay–silt break for the latter is set at 6 μm, which is the procedure followed here.

Soil with charcoal fragments from the buried paleosols was rinsed through a 250 μm sieve to isolate the charcoal fragments, which were then dried at 25 °C overnight. The larger fragments were isolated with tweezers and further dried at 65 °C. This process was repeated until at least 0.2 g of charcoal was obtained. The charcoal samples were analyzed by accelerator mass spectrometry at the Center for Applied Isotope Studies (CAIS) at the University of Georgia, for ^{14}C age determination.

To better characterize the silty kettle bottom deposits, the 20–53 μm size fraction (coarse silt) from four kettle bottom and adjacent backslope sample pairs was analyzed using X-ray diffraction. These four sample pairs were chosen because they each exhibited a large textural contrast, and therefore, the silts within would most likely have been from different source populations. The silts were first separated mechanically, and then pulverized with a Fritsch Analysette 3 Spartan Pulverisette for ~180 s, until most of the grains were <5 μm in diameter. A dry, random, powder mount technique was used for X-ray diffraction analysis of the silts. We carefully tapped the powder into a dedicated container, using the straight edge to randomly orient the crushed silt (Zhang et al., 2003). The silt was X-rayed in a MiniFlex+ X-ray diffractometer (Rigaku Corporation, The Woodlands, TX) using Cu Kα radiation, from 25° to 29° 2θ, using a 2-s count time and a 0.02° step size. We identified quartz, K-feldspar, and plagioclase mineral peaks in the samples, at 26.5°, 27.4°, and 27.8° 2θ, respectively. The diffraction patterns of the eight samples were plotted and qualitatively compared, to ascertain if notable differences in silt mineralogy exist among silts in the kettle bottom and kettle backslope sediments.

5. Results and discussion

5.1. Characteristics of backslope and kettle bottom sediments

Fieldwork confirmed that 55 of 60 sampled kettles contain silty deposits, which occur as essentially lenticular bodies set within the very bottom–centers of the kettles. In many of the smaller kettles, these bodies may be less than 2 m across and 1 m thick, while in larger kettles thicknesses of 2–3 m are achieved, and widths (at the surface) can reach 8–10 m. The silty bodies have an abrupt textural discontinuity at their bases, indicating that they likely are not autochthonous sediment. The silt bodies transition fairly rapidly from silty sediment to the "background" outwash sands of the Upland proper that laterally surround them, usually over a transition distance of 1.0–1.5 m.

Soil analyses along a typical kettle transect (66 m across, 12 m deep, 45% slope gradient at backslope; kettle #18) show that the silty deposits there are ~5 m in diameter and less than 90 cm thick. The soils along the slope are all uniformly sandy, with sands peaking in the 250–300 μ (medium sand) range, and typically have less than 8% silt. There is almost no variation in texture along the slope catena, except for sites immediately adjacent to the kettle-bottom silts, which are finer-textured. As expected, the silty deposits within the kettle bottom have bimodal particle size distributions, with a silt peak at 10–25 μ and with a fine-medium sand (secondary) peak. There is no indication that the silts within the kettle bottom extend upslope beyond the kettle toeslope; they are confined to the very bottom–center of the kettle.

Summary data for the 55 kettle bottom samples indicate that they contain, on average, nearly four times the amount of clay-free silt than do backslope samples (58.1% vs. 14.8%) (Table 1). A paired *t*-test, on the 55 sample pairs, revealed significant differences ($\rho < 0.001$) between each sample type for all the textural components listed in Table 1. The additional detail provided in Fig. 5, which shows continuous particle size distribution curves of all 55 kettle backslopes and kettle bottom sediment samples, is particularly useful for interpretation. Fig. 5a shows that most backslope

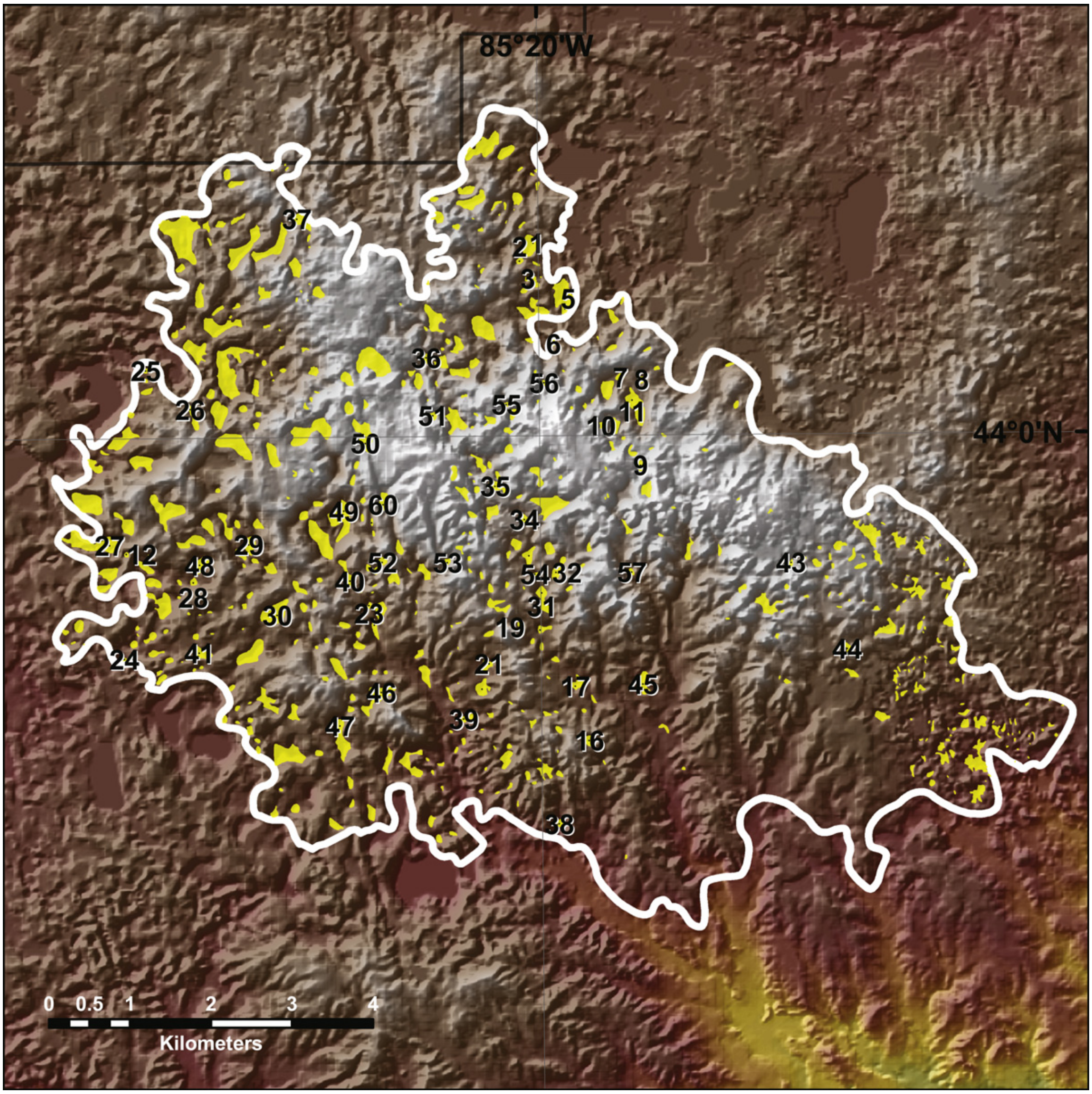

Fig. 4. Detailed elevation model of the Evart Upland, showing the locations and site numbers of the 55 kettle sample sites containing site deposits.

Table 1
Summary textural characteristics for kettle bottom and backslope sediments.[a]

Textural characteristic	Mean (St. Dev.) for kettle bottom sediment ($n = 55$) (% of fine earth fraction)	Mean (St. Dev.) for kettle backslope sediment ($n = 55$) (% of fine earth fraction)
Clay (<2 μm)[b]	15.3 (5.3)	3.1 (2.0)
Very fine silt (2–12 μm)	15.1 (4.3)	3.0 (1.7)
Fine silt (12–25 μm)	19.2 (4.5)	4.8 (2.2)
Medium silt (25–35 μm)	7.8 (1.7)	3.0 (1.2)
Fine and medium silt (12–35 μm)	26.9 (5.9)	7.8 (3.4)
Coarse silt (35–50 μm)	6.7 (1.6)	3.5 (1.4)
Silt (2–50 μm)	48.8 (10.5)	14.3 (6.1)
Clay-free silt	58.3 (14.7)	14.8 (6.7)
Very fine sand (50–125 μm)	12.0 (4.0)	10.1 (4.1)
Fine sand (125–250 μm)	9.8 (4.9)	24.2 (5.2)
Medium sand (250–500 μm)	10.0 (7.5)	35.2 (6.4)
Sand (50–2000 μm)	36.1 (14.5)	82.6 (7.8)
Clay-free sand	41.9 (14.5)	86.2 (6.7)

[a] All of the variable means were significantly different at $p < 0.001$, based on a paired t-test.
[b] Actual delimiter for clay/silt boundary used in this study is 6 μm, see *Lab Methods* section.

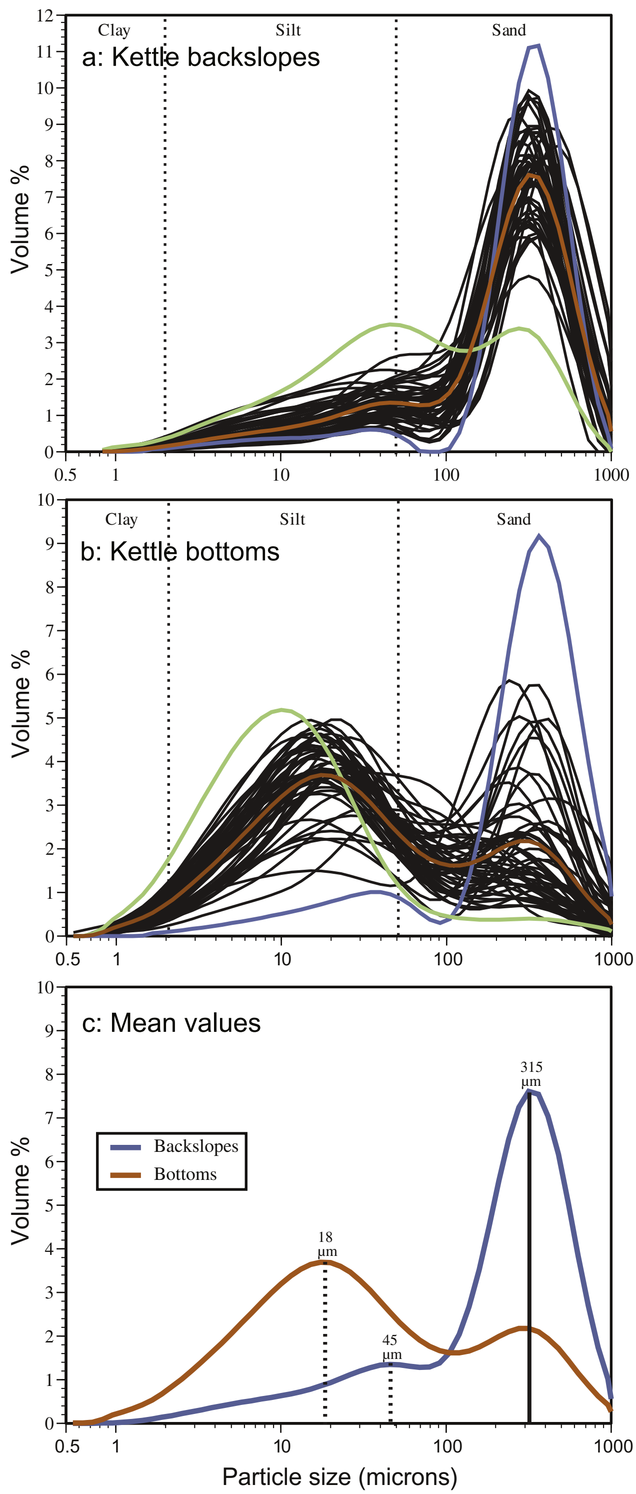

Fig. 5. Continuous particle size distribution curves for samples from the Evart Upland. Red lines in A and B indicate the mean values. Blue and green lines in A and B indicate the coarsest and finest textured samples, respectively. (a) Kettle backslope samples; (b) Kettle bottom samples and (c) mean values for the data shown in A and B.

samples contain much less silt than do kettle bottom sediments. Backslope sediment is dominated by 250–500 μm, medium sands, whereas kettle bottom sediment exhibits modal particle size peaks in the 10–25 μm (fine silt) range (Fig. 5, Table 1). Both sediment types are relatively impoverished in coarse silts and very fine sands (~40–110 μm) (Fig. 5).

Fig. 5c shows the mean particle size distribution curves for each sediment population; both curves are distinctly bimodal. The most prominent (modal) peak for kettle bottom deposits is at 18 μm (fine silt), with a secondary peak in the medium sand range (315 μm). The prominent peak in the kettle backslope samples is also at 315 μm, with a very minor, secondary peak in the coarse silt (45 μm) range. Thus, although the sand peak is similar for both sampled populations, the silt peak is much finer for kettle bottom deposits. The similar sand peak for both curves suggests that the sand component of kettle bottoms and backslopes is likely from the same population; we suggest that it is from sand washed (and eventually, mixed) into pre-existing kettle bottom sediment, from the surrounding backslopes, or perhaps blown off of bare areas on nearby uplands. In contrast, the difference in silt peak location for both curves suggests that the silty component of kettle bottoms and backslopes was deposited by different processes and/or from different sources.

5.2. Origin of the kettle bottom silts

The distinct textural signatures of the two sediment types (Fig. 5) strongly suggest that kettle bottoms have been infilled with silt-rich sediment, but the silt has not been derived from the backslopes. Backslope sediments do not contain enough silt, and most importantly, silt of a comparable size fraction, to have been the primary source for the kettle bottom silt deposits. We also believe that most kettles are not large enough to have produced enough silt via winnowing of backslope sediments alone, given the low amount of silt in the native sediments, relative to the actual volumes of the silty sediment bodies. Sandy lenses and stringers in the kettle bottom silt deposits, indicated as secondary sand peaks in the kettle bottom silt deposits, attest to some amount of sand input into the silty sedment, possibly by isolated slopewash or aeolian events. Indeed, the sand in the kettle bottom silt deposits likely did come from backslopes, as it is of the same (modal) size fraction in each of the two deposits (315 μm). However, slopewash is not likely to have been the main pathway by which the silts were transported into the kettle bottoms, as indicated by the particle size curves in Fig. 5. Thus, we reject hypothesis 1 as not supported by the data. Infrequently, slopewash or aeolian events may have transported small amounts of sand into the kettle bottoms (Fig. 5b), but could not have been responsible for the large amounts of fine silt that dominate there.

To examine whether aeolian silt is present across the region, we studied the textural data from 75 sites, all on broad, sandy uplands. The data, recovered from the uppermost (20–30 cm) soil horizons, were mapped in ArcGIS (ESRI) using standard kriging techniques, with a smoothing factor of 0.6, to provide information about the spatial patterns of silt and other possible aeolian fractions in the upland soils. The kriged maps (Fig. 6) indicate that soils in the SE, and secondarily in the NW, parts of Upland have the highest concentrations of fine fractions, capable of being moved by aeolian processes. The southeast corner of the region shows the highest amount of enrichment by fines, with the high, central region exhibiting the "cleanest" sands. On the assumption that these patterns reflect post-glacial aeolian processes and not the original glacial depositional systems, we looked beyond the Evart Upland for possible sources of aeolian silt. One possible source of silt, to the southeast of the study area, is the Muskegon River floodplain (Fig. 6, inset). The floodplain is particularly wide in the area immediately east of the Evart Upland. Areas to the northwest of the Upland are primarily till plains composed of sandy loam sediment; these areas also could have supplied fine-textured aeolian material to the northwestern parts of the Evart Upland.

Building on these data, and knowing that silty sediment in the kettle bottoms was not sourced from slopewash, we therefore

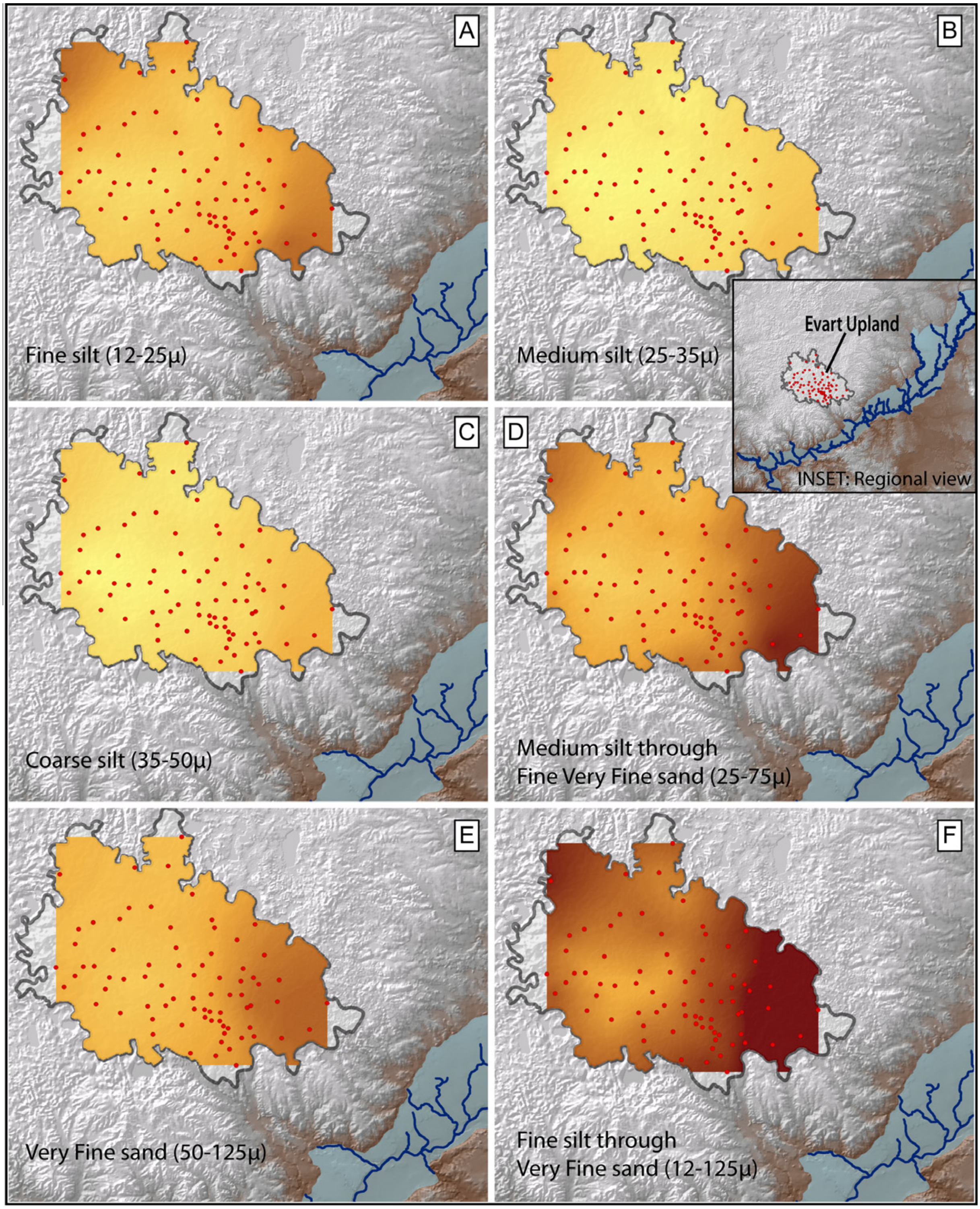

Fig. 6. Maps of various fine fractions in 75 upland, otherwise sandy, upland pedons in the Evart Upland. The maps were created in ArcGIS, using a smoothing factor of 0.6, and clipped to the combined extents of the Evart Upland and the sample grid. The Muskegon River and its floodplain and terraces are also shown. Red dots represent sample locations. For the color palettes listed below, darker colors always represent higher contents. (A) Fine silt (12–25 μ). Color palette ranges from 2% to 12%; (B) medium silt (25–35 μ). Color palette ranges from 2% to 12%; (C) coarse silt (35–50 μ). Color palette ranges from 2% to 12%; (D) medium silt through fine very fine sand (25–75 μ). Color palette ranges from 2% to 20%; (E) very fine sand (50–125 μ). Color palette ranges from 2% to 20% and (F) fine silt through very fine sand (12–25 μ). Color palette ranges from 2% to 30%.Inset map: the Evart Upland in relation to the Muskegon River, showing regional relationships between the two. Perennial streams that are tributary to the Muskegon River are shown, based on USGS 7.5 minute topographic maps.

accept Hypothesis 2: the silt was brought into the kettles by aeolian processes. That is, the silt in the kettles is loess, with the Muskegon River floodplain as at least one of its sources.

This conclusion seems intuitive; kettles provide natural "settling basins" or dust traps for loess (Goossens, 2006). Wind speeds should diminish within deep, grassy kettles (especially because they are surrounded by tall forest), facilitating aeolian deposition. Primary or near-primary loess falling onto the bottom centers of deep kettles in the Evart Upland would have been likely to stay there permanently, especially given the occasional wetness and deep snow that occurs there. Alternatively, some of the loess deposited onto steep kettle backslopes was probably later reworked and redistributed by water and wind, eventually getting deposited in the bottom centers of deep kettles. This loess could also have been washed downslope, on top of the dense, grassy sod, without disturbing the sandy sediment below. The lack of forest in many of these kettles could have facilitated transport of silty loess downslope, because (1) runoff would likely occur more readily across open, grassed surfaces than beneath a dense forest canopy, and (2) loess landing on a forest has two opportunities to be trapped – by the trees and within the forest floor. Loess falling on a grassed slope would be retained in/on the sod until water washed it further downslope. Envisioning reworking of loess by runoff within grassed kettles enables deposits of relatively pure silt to accumulate in the bottom centers, while at the same time reducing, but not entirely eliminating, the transport of sand from backslopes into the kettle centers. This scenario explains how the bottom centers of kettles become enriched in silt-rich sediment (reworked loess) that has small amounts of medium sand within, and why that sand matches the sands in the backslopes (Fig. 5). Aeolian processes could also occasionally re-entrain loess from backslopes; much of this loess could end up in kettle bottoms. Lastly, we cannot rule out the possibility that transport of loess to the kettle bottoms can occur during snowmelt, for any loess falling onto a snowpack would easily wash to the bottom center of the kettle. The most likely time of year for loess generation in this landscape is spring, when meltwater floods might have been occurring on the Muskegon River, while snowpacks persist in kettles on the Evart Upland.

5.3. Further evidence for loess in the Evart Upland

We provide evidence that the Evart Upland was receiving inputs of loess in the post-glacial past. We further tested this conclusion by depth-sampling sediments at ten flat, geomorphically stable sites; these areas are most likely to have preserved some of this primary loess (Schaetzl, 2008; Schaetzl and Hook, 2009; Fig. 7). (Kettles preserve primary AND secondary, or reworked, loess.) Fig. 7 shows that mean silt contents are clearly higher at 50 cm (7.1%) than at the depths below (3.0% at 100 cm, 2.0% at 150 cm). Likewise, the deeper samples have higher mean sand contents. Fine silt (8–20 μ), more readily transported by wind and also the

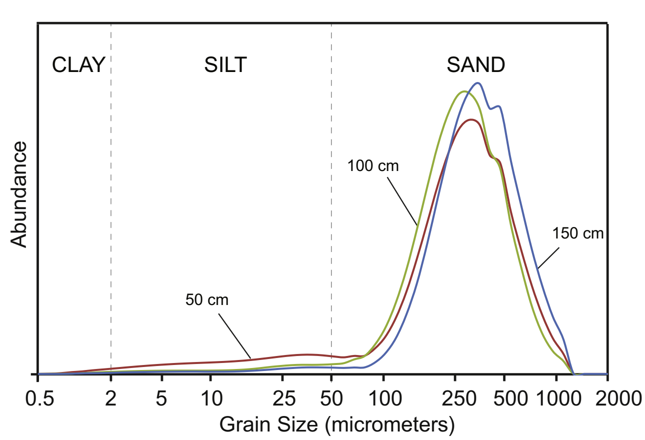

Fig. 7. Continuous particle size curves for stable, sandy, upland sites in the Evart Upland. Each curve represents the mean value of 10 samples (one from each of 10 sites) at the stated depth.

dominant particle size fraction in the kettle bottom deposits, increases up-profile even more than do medium and coarse silt (0,6% at 150 cm, 1.0% at 100 cm, and 2.9% at 50 cm). The ratios of 11 different silt fractions at 50 cm, when compared to those at 150 cm, range from 2.82 (very coarse silt) to 4.99 (very fine silt). These data support the conclusion that aeolian silt has impacted the Evart Upland in the past, and has been preserved in kettle bottoms as relatively pure deposits; on stable surfaces the thin loess deposits have since been thoroughly incorporated into the otherwise sandy, upper soil profile.

In some sandy landscapes, an up-profile increase in silt content has commonly been explained by increased physical weathering. Mikesell et al. (2004) studied the degree of hornblende etching (a mineral indicator of weathering) with depth in four sandy soils ~100–150 km north of the Evart Upland. Their data show that the up-profile increases in hornblende etching are usually accompanied by concomitant increases in silt content. As a result, they suggested that the silt increases may be due to increased weathering in the upper profile, while also acknowledging that it may be due to aeolian silt influx. Silt increases in the upper profiles of dry, sandy soils in northern Michigan were also attributed to aeolian influxes by Barrett (2001). Given that soils in the Evart Upland are so dry and relatively young, we believe that physical weathering is not likely to have been a significant contributing factor to the large up-profile silt increases in soils of the Evart Upland.

Up-profile silt increases in the stable, upland soils of the Evart Upland are expressed within a background dominated by sand (Fig. 7). Pedogenic processes, especially bioturbation, have likely mixed the silty loess into the profile and blurred any depositional characteristics or lithologic contacts. Therefore, these data cannot be used to determine whether the loess additions were episodic, or occurred during a single depositional event. Nor can they constrain the timing of the loess deposition. To answer these questions, we turn to the stratigraphy within the kettle bottom silt deposits.

5.4. Sediments in the kettle bottom deposits

Fieldwork confirmed that several of the sampled kettles contain buried paleosols within the kettle bottom silt deposits; nine were eventually excavated, described, and sampled, to better understand their depositional histories (Fig. 8). The paleosols clearly indicate that the Evart Upland has experienced periods of stability and instability (Valentine and Dalrymple, 1976; Busacca, 1989).

We display the textural data from these buried soil profiles using a method developed by Beierle et al. (2002), which enhances subtle, down-profile changes in particle size distribution. Essentially, the resultant graphs (Fig. 9) display the particle size distribution *curve* at each depth-sampled interval, and interpolate *z*-axis values (volume percent) between the sampled intervals. The result is a continuous grid surface of particle size distribution characteristics throughout the entire sampled depth. Potentially, such plots can depict sedimentary transitions that indicate changes in depositional processes; such insight may be more difficult to deduce from standard depth-plots of simple particle size splits or statistical summary data.

Some of the kettle bottom deposits contain intervals of sandy sediment that abruptly alternate with silty strata (Fig. 9). In other kettle bottoms, the sediments are better mixed, and no one mode of deposition is dominant (Fig. 9). These depth-profile differences indicate that silty and sandy sediment may be entering the kettle bottoms independently, e.g., inputs of loess may be temporally out of sync with slopewash sand additions. Also, many of the kettles show depth profile signatures that are site-specific. The one commonality is that all eight of the excavated kettles show alternating periods of stability (soil-formation) and instability (deposition of additional sediment, and burial of any pre-existing

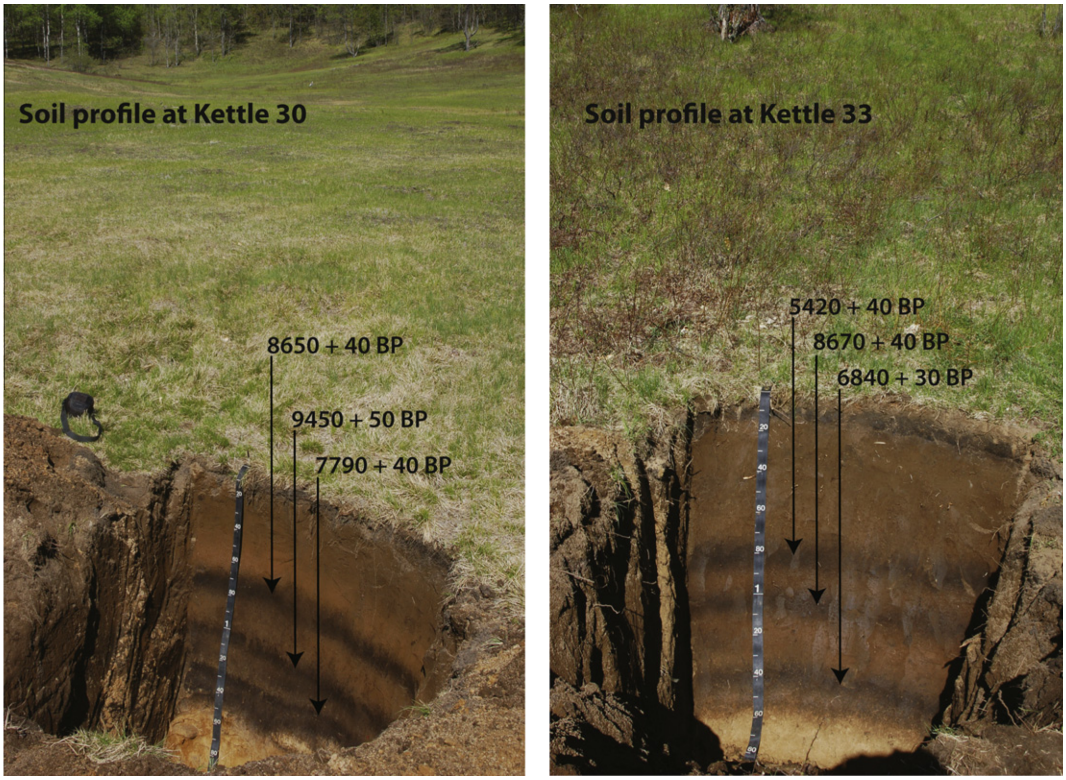

Fig. 8. Photos of profile faces at sites 30 and 33, showing buried paleosols in the kettle bottom silts and underlying outwash sand. ^{14}C ages for the pooled charcoal fragments taken from these soils is also shown.

soil), suggesting that, although this landscape may be sensitive to disturbance, it does exhibit periods of stability and soil formation, even within depositional settings like kettle bottoms.

As would be expected in depositional systems where loess and sandy slopewash are the main sediment inputs, the kettle bottom sediments fluctuate between silty end members, typical of pure "kettle bottom deposits" as shown in Fig. 5b, and sandy end members, similar to backslope materials (Figs. 5a, 9). Strata in the kettle bottom sediments that are intermediate in textural character point to post-depositional mixing of the two, end-member sediment types.

5.5. Ages of charcoal in buried soils, and the timing of loess deposition

Usually imprinted onto the kettle bottom sediments is a sequence of buried soils. The varying numbers and depths of buried soils in each kettle, coupled with the different textural depth trends (Figs. 8 and 9), implies that sediment deposition was strongly influenced by local conditions. Because these sequences typically alternate between paleosols rich in charcoal and organic matter, and relatively "clean" and silty sediment, we conclude that periods of stability (soil formation) have alternated with loess deposition episodes. We did not encounter any evidence of pre-burial erosion of the paleosols; they appeared to have been buried intact.

In this dry, sandy, and geomorphically sensitive landscape, fire is a common disturbance mechanism (Albert, 1995). Charcoal fragments, found in all of the buried soils, support this contention and provide an opportunity to constrain the general periods of stability, fire-related disturbance, and loess deposition in the Evart Upland (Fig. 7; Table 2; Huang et al., 2006). Because the charcoal is associated more with the paleosols than with the intervening loess, we assumed that the kettle bottom soils gradually accumulate charcoal as fires intermittently sweep through the landscape, and wind and water later redistribute some of it into the kettle bottoms. Subsequently, a loess depositional event occurs, burying the soil in relatively clean loess (Fig. 8). Charcoal deposited on the surface of any of the kettle bottom soils has the potential to be mixed into the underlying sediment (loess), accounting for some flecks of charcoal in the sediments below each paleosol (and the surface soil).

AMS dating was used on consolidated assemblages of charcoal fragments from within each of several buried soils, because the typical size of the fragments was very small. We interpret the data in Table 2 as pooled ^{14}C ages on charcoal fragments derived from potentially many populations, each produced by an individual fire. These radiocarbon dates span 10,010 years – the entire Holocene (Table 2). Although one date is latest Pleistocene (10,930 years ago) and another is from the last 1000 years (920 years ago), the remaining seven dates span from 9500 to 400 years ago. The age-depth reversals at Sites 30 and 33 (Fig. 8) suggest that the ^{14}C ages cannot be correlated to individual fires. Rather, they represent pools of largely Holocene-aged charcoal that were variously accessed during periods of erosion and aeolian deposition.

These data clearly demonstrate that fire disturbances are common on this landscape, and that the main period of such disturbance was the early Holocene, coinciding with the warm, dry climatic optimum (Kutzbach et al., 1998), when xeric, oak- and pine-dominated forests dominated this region (Hupy and Yansa, 2009). Similarly, in the early Holocene, levels of the Great Lakes were much lower than at present (Hough, 1955; Bader and Pranschke, 1987; Rae et al., 1994; Lewis et al., 2007), possibly facilitating lowered regional water tables and periodically ultra-xeric edaphic conditions. Indeed, several studies have documented and modeled increased aridity for southern Michigan in the early Holocene (Webb et al., 1983; Bartlein et al., 1998), and our observations on fire-related disturbance in the Evart Upland appear to agree with those studies.

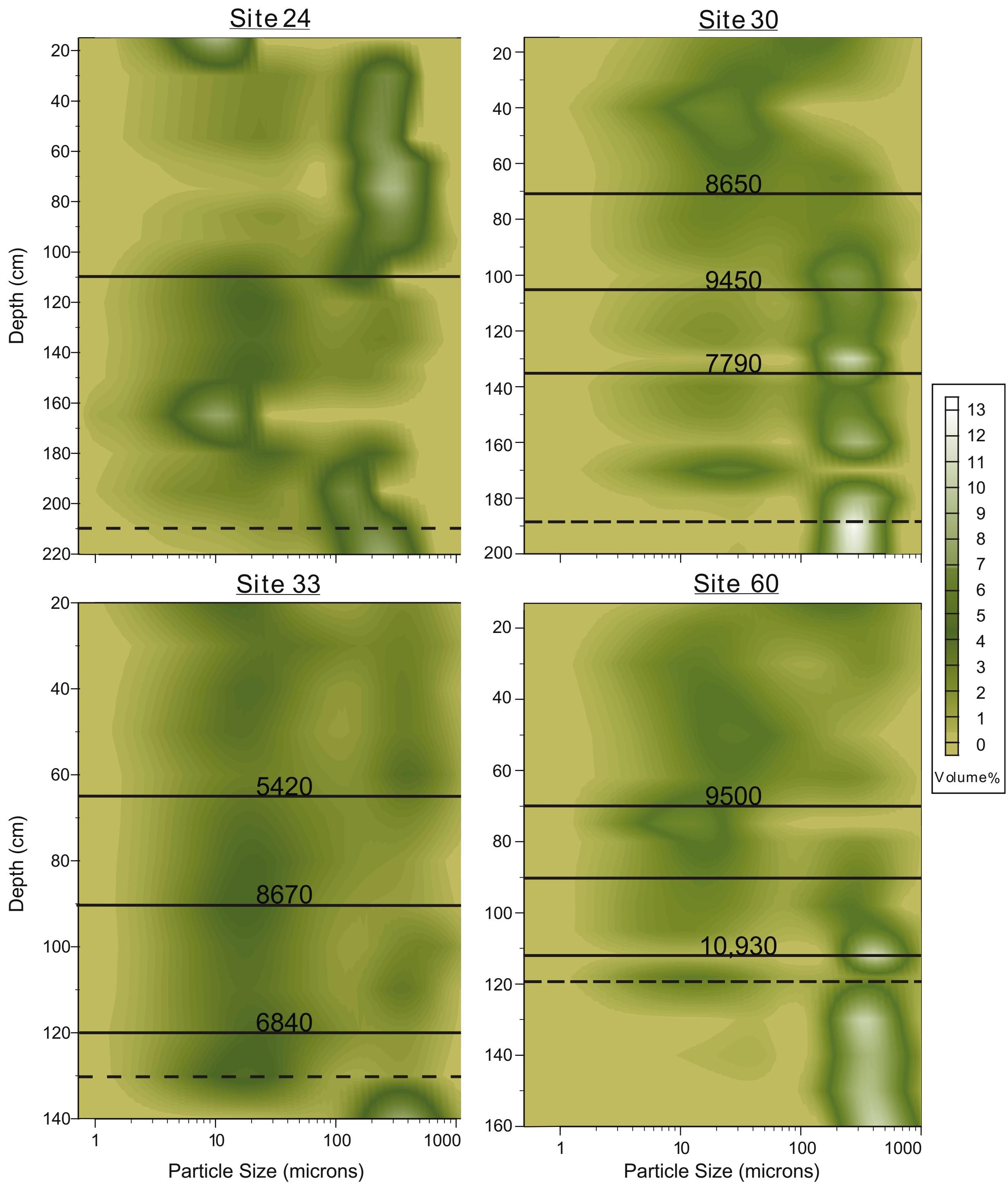

Fig. 9. Depth diagrams showing continuous particle size distributions with depth, for four sites in the Evart Upland. Locations of the tops of the buried paleosols (with ^{14}C dates on bulk charcoal samples indicated) and the lithologic discontinuities at the bottom of the silts are also shown. Note the varying depth scales for each soil. The tape has markings every 10 cm.

Perhaps more importantly, the data suggest that both fire disturbances and aeolian silt deposition in/on the Evart Upland have occurred episodically throughout the early and mid Holocene. The lack of reports of Holocene loess in the Great Lakes region gives this study regional significance. Deposition of Holocene-aged aeolian silt was both temporally and spatially variable, i.e. not all kettles were collecting silt at the same time (Fig. 6).

5.6. Silt in the Evart Upland

Silt in the Evart Upland, presumably aeolian in origin, is found mainly in kettle bottoms and intermixed into the soils on stable landscape positions. The data suggest that primary loess on the Upland is likely from the Muskegon River floodplain or sources NW of the Upland, but that localized reworking/re-deposition throughout the Holocene is responsible for the spatial and tempo-

Table 2
Radiocarbon dates on charcoal from buried soils in kettle bottoms, in the Evart Upland.

Site number	Location and depth (cm) of top of paleosol[a]	^{14}C age of charcoal[b]
17	1, 120	920 ± 20
30	1, 72	8650 ± 40
30	2, 105	9450 ± 50
30	3, 135	7790 ± 40
33	1, 65	5420 ± 40
33	2, 90	8670 ± 40
33	3, 120	6840 ± 30
60	1, 69	9500 ± 40
60	3, 115	10,930 ± 40

[a] First paleosol from top = 1, second paleosol from top = 2, etc. Depth in cm from surface.
[b] In radiocarbon years BP, with one-sigma error term included.

ral variation that exist today, in the kettles there. An alternative interpretation involves long-distance loess, brought in from outside the study area.

To resolve this question, coarse silt (20–53 μm) from two paired samples were evaluated using X-ray diffraction (XRD) techniques: (1) silty kettle bottom deposits, and (2) sandy backslopes. The XRD data were examined for peak matches between the two sediment types (Kufmann, 2003). We assumed that significant mineralogical differences between backslope silt and kettle bottom deposits would indicate that the kettle bottom silt is from outside the region (allochthonous dust). On the other hand, if minimal mineralogical differences are apparent between the two sample types, it is reasonable to assume that (1) the silt in kettle bottoms is mainly local in origin, and/or (2) the source region is outside the Evart Upland, but the mineralogical composition of the sediment there is similar to the local sediment.

The diffraction patterns of silt in the two selected kettle bottom/backslope pairs (Fig. 10) are almost identical; they are mineralogically equivalent. Quartz is by far the most abundant mineral in the eight samples analyzed, and indeed probably the most abundant mineral found within soils of the surrounding regions, which, in this part of northern Lower Michigan, are dominantly comprised of outwash sands (Schaetzl and Forman, 2008). Although the intensity of quartz in the diffraction patterns may have overwhelmed the other, less significant, mineral peaks, the diffraction patterns do illustrate that there are no significant mineral peaks present in one sample that are not present in another. Therefore, it is likely that the silt in kettle bottoms is locally redistributed loess that was winnowed out of nearby exposed surfaces and deposited across the Evart Upland, rather than being derived from an extra-regional source area.

5.7. Paleoenvironmental significance

Fire was probably frequent on dry, sandy uplands in Michigan, throughout the Holocene; abundant charcoal in the buried soils we examined confirm this. Dry, sandy landscapes like the Evart Upland promote fire-prone species, e.g., pine and oak, and their subsequent bio-physical feedbacks (Brubaker, 1975; Whitney, 1986; Comer et al., 1998; Leahy and Pregitzer, 2003). Indeed, GLO reports on nearby, sandy regions noted that expansive areas of recently burned forest were common at the time of the surveys (~1850s) (Simard and Blank, 1982; Whitney, 1986; Albert, 1995). Recently burned surfaces are somewhat hydrophobic because of the addition of water repellent organic compounds released from plant materials during fire (Savage, 1974; DeBano et al., 1979). This trait may have facilitated the downslope translocation of fresh loess on kettle backslopes.

6. Conclusions

Small bodies of silty sediment frequently occur in the bottom centers of kettles in the otherwise dry and sandy Evart Upland of southern Michigan. The deposits are dominated by fine silt, and often have one or more charcoal-rich paleosols within their sedimentary sequence. Secondary particle size peaks of medium sand in these deposits coincide in size with the sands found on the kettle backslopes, attesting to occasional, small additions of slopewash. Backslope sediments contain little silt, however, and what silt they have is typically coarse silt; we interpret this as evidence that the silt in the kettle bottoms was not sourced from the backslopes or even from the interlobate landscape at large. Rather, we believe that the silt is loess, intermittently blown onto the landscape form the nearby Muskegon River floodplain and/or from other, silt-rich surfaces recently disturbed by fire. This silt settled into the kettle bottoms and/or was washed into them on top of stable, grassed, backslope surfaces. Buried paleosols attest to the intermittency of the loess additions, punctuated by periods of soil formation. Silt increases in the upper profiles of sandy soils on uplands also point to small additions of loess to the landscape as a whole.

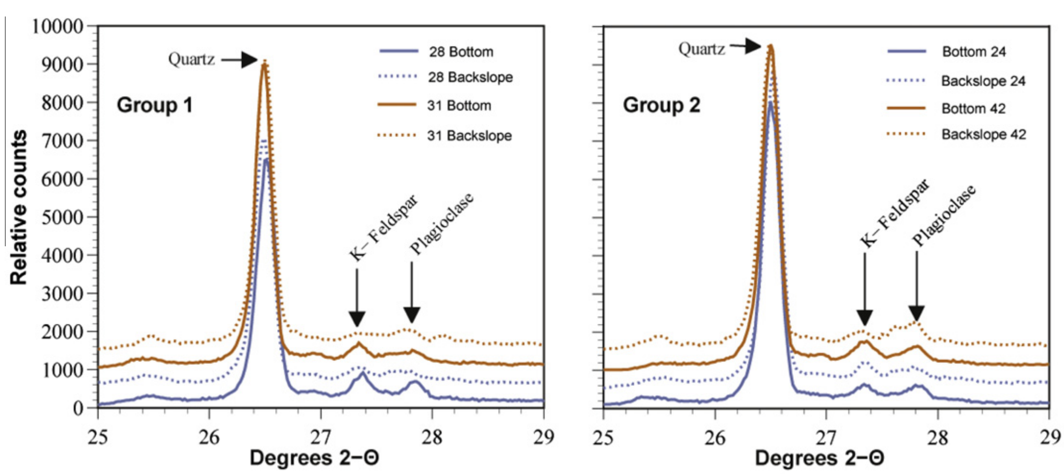

Fig. 10. X-ray diffractograms for silts from four kettle bottom/backslope pairs. Solid lines represent kettle bottom samples; dashed lines represent adjacent backslope samples. The diffractograms are offset by 500 counts, and split into two groups to clarify comparison.

Although dune-forming, aeolian activity during the Holocene has been documented for sites in the Great Lakes region (Arbogast et al., 2002; Arbogast and Packman, 2004), ours is the first study to document loess that dates to this period in Michigan, or even in the Great Lakes region. Thus, even small loess depositional events in the Holocene have left discernable sedimentary signals in the dry kettle bottoms of the Evart Upland.

Lastly, we summarize by noting that this research offers three important, broad contributions. First, we document the existence of loess in a sandy interlobate landscape in southern Michigan, where, until now, loess had not been reported. This work shows that loess can be present in a landscape, but be so intimately mixed into the native sediments that it can go unnoticed; it need not be present as a thick, discrete silt ‘‘cap’’. Second, because the Evart Upland loess is mainly Holocene-aged, this work demonstrates that small amounts of loess can be generated by large rivers, even in postglacial climates. Lastly, this work confirms that dry kettles are excellent depositional settings for sediment – both local sediment and loess – and as such, offer research opportunities as repositories of paleoenvironmental conditions.

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