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Coarse-textured basal zones in thin loess deposits: Products of sediment mixing and/or paleoenvironmental change?

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ABSTRACT

The purpose of this research was to characterize and interpret the coarse basal zones that are common in thin loess deposits that overlie coarser-textured sediment. To that end, we sampled nine pedons in northeastern Wisconsin and the Upper Peninsula of Michigan, each of which had formed in thin (≤55 cm) loess over sandy glacial sediment. At most of these sites, the loess became noticeably coarser near the lithologic discontinuity. The loess has a primary particle size mode in the coarse silt or fine, very fine sand fraction (≈30–65 μm) and a secondary mode in the fine or medium sand fraction (≈200–400 μm). We attribute the secondary mode to mixing of underlying sands into the loess, either during loess deposition or by post-depositional pedoturbation. In thin loess, pedoturbation processes can penetrate into the underlying sediment, facilitating mixing upward as far as 50 cm into the loess. Silt from the loess has also been mixed into the underlying sandy sediment. Alternatively, in some pedons, the loess itself coarsens with depth; the particle size mode for the loess becomes increasingly coarser with depth. This coarsening suggests that, during loess deposition, one or more of the following was occurring: (1) wind velocities were decreasing over time, (2) the textural character of the loess source area(s) were changing/decreasing, or (3) additional source areas—with finer-textured sediment—became more dominant over time. Our research demonstrates the utility of detailed particle size data for detecting and interpreting the paleoenvironmental history of loess. We also document the extent to which pedoturbation can impact the original textural characteristics of loess (or any sediment) that occurs as a thin surficial mantle.

1. Introduction

Most loess deposits are dominantly silt-sized (Bettis et al., 2003; Fehrenbacher et al., 1965; Pye, 1984, 1995; Smalley, 1972, 1990; Wascher et al., 1947); indeed, the silty texture of loess often helps soil mappers, soil scientists and Quaternary geologists identify loess in the field. Loess often occurs in meters-thick accumulations, with silt loam textures dominating nearly the entire loess column (Basarina et al., 2009; Follmer, 1996; Pierce et al., 2011; Roberts et al., 2003; Rousseau and Kukla, 1994; Ruhe, 1984). However, where loess overlies coarser-textured sediment, e.g., till or glacial outwash, the loess is often slightly coarser-textured near its base, e.g., Follmer et al. (1979). That is, silt loam textures within the loess will grade into coarser (or less often, finer; see Frolking et al. (1983)) textures as the lithologic discontinuity between the loess deposit and underlying sediment is approached (Foss and Rust, 1968; Harlan and Franzmeier, 1977; Mason et al., 1994). At and near the discontinuity, textures change not only in the fine earth (<2 mm) fraction, but often in the coarse fraction (>2 mm) as well. This phenomenon is especially common in thin loess deposits (McSweeney et al., 1988; Stanley and Schaetzl, 2011). These "coarse basal zones" in loess deposits can obscure the lower boundary of the loess, making the lithologic discontinuity difficult to determine (Allan and Hole, 1968; Barnhisel et al., 1971; Borchardt et al., 1968; Caldwell and White, 1956). Likewise, these texture changes make it difficult to ascertain the original thickness of the loess unit, and/or the original texture of the earliest loess (Karathanasis and Macneal, 1994; Price et al., 1975).

Coarse textured basal zones in loess are poorly understood and seldom completely described. Loess may be deposited as well-sorted sediment, but mixing processes during the early phases of deposition may cause some of the underlying sediment to be mixed into the loess. If this lower sediment is sandy, these processes will result in a coarse-textured basal zone within the loess. Obviously, not only can the lower sediment be mixed into the overlying loess, but some loess can also be mixed into the underlying sediment, effectively blurring the lithologic discontinuity.

Little is known about the specific pedoturbative processes that mix loess with the underlying sediment, or vice versa. Strong winds may mix the two sediments during deposition, especially on bare ground where the sediment is not held in place by vegetation. Cryoturbation and bioturbation, both of which can mix soils to shallow depths, are the most likely types of mixing processes on cold, wind-blown landscapes (Anderson, 1988; Baker et al., 1991; Caldwell and White, 1956; Johnson et al., 1987; Leigh, 2001; Small et al., 1990). We suggest that

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the extent to which the underlying sediment has been mixed into the loess above, i.e., the thickness of the coarse basal zone, is largely a function of the types and intensities of the pedotubative processes vis-à-vis loess depositional processes. Detailed study of these basal zones may help tease out the significance and strength of each of these sets of processes.

Alternatively some coarse-textured basal zones, or loess particle size curves that are distinctly bimodal in character (Dinghuai et al., 2004), may be due to changing paleoenvironmental conditions, i.e., diminishing wind speeds or changes in source area characteristics, during deposition (Gillette et al., 1974; Muhs and Bettis, 2003; Xiao et al., 1995). For example, Stanley and Schaetzl (2011) believed that the coarser-textured basal zone in a thin loess sheet in Wisconsin formed because of a change in source area; the initial source area was supplying coarser sediment to the loess sheet, but then later, a second, silt-dominated source area, became dominant. Thus, some coarse-textured basal zones in loess may be due to changing paleoenvironmental conditions during deposition, and not to pedoturbation.

Ascertaining the cause(s) and implications of some coarse-textured loess basal zones is a focus of this paper. We report detailed textural data from soils on stable, upland sites in northern Wisconsin and the western Upper Peninsula (UP) of Michigan, where thin loess deposits are widespread, and where they commonly overlie coarse-textured glacial sediment. Particle size data, examined with depth and at nine different sites, are used to infer the processes that produced these coarse-textured basal zones. Although the main purpose of this study is to determine the characteristics and origins of these coarse-textured zones, we also explore the possibility that loess thickness *per se* also impacts the thickness of this mixed zone. For example, in thick loess areas, rapid loess deposition rates may have provided little time for mixing of the two sediments during deposition, thereby minimizing the mixed zone in the basal loess.

The purpose of our research is to determine the extent to which coarse-textured basal zones in thin loess deposits in the study area were formed by (1) pedoturbation of the underlying, coarse-textured glacial sediment into the silty loess column, and/or (2) the initial deposition of coarser-textured loess. Determination of the process(es) by which these coarse-textured zones formed has significant paleoenvironmental implications.

2. Study area

The study area covers much of the western UP of Michigan, with one site in northeastern Wisconsin (Fig. 1). The landscapes were most recently glaciated by the Laurentide ice sheet, with sandy ground moraines, end moraines, and outwash plains being common (Peterson, 1985, 1986). Although incompletely dated because of the general lack of organic material in the glacial sediments (Clayton and Moran, 1982; Clayton et al., 2001), most of these landscapes were likely deglaciated shortly after ≈13.5 ka yr BP, and all were ice-free by ≈ 11.4 ka yr BP (Lowell et al., 1999). Many swampy areas exist interspersed between uplands, and bedrock knobs are especially common in the NE part of the study area. The soils mapped by the Natural Resources Conservation Service (NRCS), in conjunction with county soil survey reports, almost all have sandy C horizons. Most of the

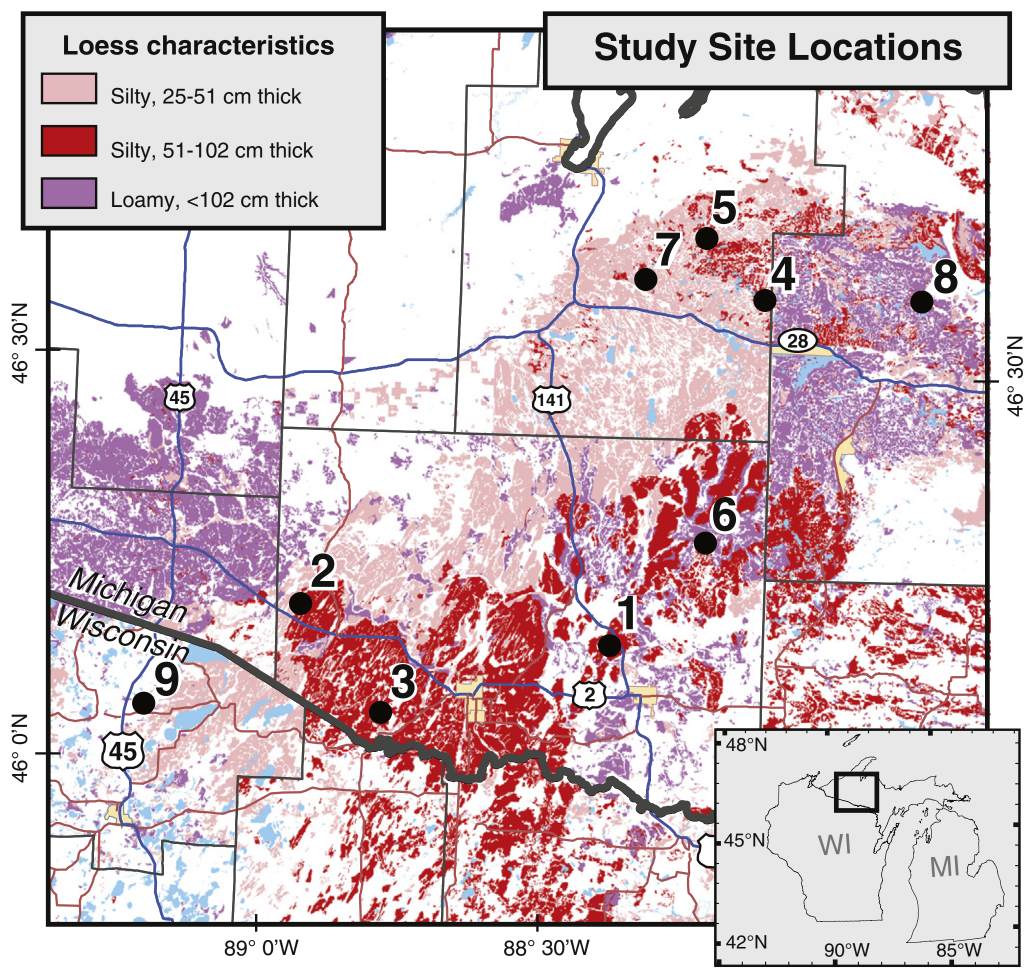

Fig. 1. Extent and thickness of loess across the study area and nearby locations, as determined from NCRS county soil survey maps. Sample site locations and numbers are shown in black.

upland soils classify as coarse-loamy Oxyaquic Fragiorthods, although widespread areas of coarse-loamy or sandy, Typic, Alfic or Entic Haplorthods also exist (Berndt, 1988; Boelter and Elg, 2004; Linsemier, 1997).

In order to better characterize the landscape, we derived estimates of the extent and thickness of loess (Fig. 1) using digital soil maps obtained from NRCS county-level soil survey reports (Berndt, 1988; Boelter and Elg, 2004; Linsemier, 1997) and the NRCS's Soil Data Mart (http://soildatamart.nrcs.usda.gov/). Each soil series in the study area was coded to parent material, based on text taken verbatim from the NRCS Official Soil Series Descriptions. For soils in which loess is indicated as a parent material, its thickness was also entered into the database. Loess exists across many uplands in NE Wisconsin and the western UP of Michigan (Scull and Schaetzl, 2011; Fig. 1). In parts of the study area the loess is typically 40–90 cm thick, thinning progressively in all directions (Bigsby, 2010; Fig. 1). Thick loess here typically contains 45–75% clayfree silt.

3. Methods

Our approach was to examine several pedons that had clear evidence of silt-rich, but thin (<1 m), loess overlying generally sandy glacial sediment. Coarse-textured sediment below loess is not only quite common in this area, but the contrasts in grain size facilitate the observation and interpretation of any mixing processes that may have occurred. Several areas in the study area, known for having thin loess cover, were chosen for sampling (Flint, 1971; Hole, 1976; Scull and Schaetzl, 2011). The glacial sediments here are generally sandy (Barrett et al., 1995; Kabrick et al., 1997; Peterson, 1985, 1986; Simpkins et al., 1987). Using a GIS running on a laptop computer and linked to a GPS, we navigated to nine predetermined sites that met the following criteria: (1) mapped by the NRCS as having formed in <≈75 cm loess over sandy glacial sediment, (2) located on a broad, flat upland, i.e., where post-glacial erosion would have been minimal, and (3) currently forested and, based on surface microtopography (Schaetzl et al., 1990), showing no signs of ever having been cultivated (Fig. 1).

At each site, we excavated a soil pit to a depth several cm below any field-estimated lithologic discontinuity, i.e., into the underlying sediment. Approximately 150 g of sediment were sampled from the pedon face, every 5 cm, beginning at the surface, until the lower parent material was reached. At least two samples were taken, also at 5-cm (or larger) intervals, from within the sandy sediment below. At the nine sampled sites, loess thicknesses ranged from ≈15 to 55 cm (Table 1).

Each sample was ground with a mortar and wooden pestle, after being air-dried. The ground sample was then passed through a 2 mm sieve. The remaining fine earth was sent through a sample splitter three times in order to thoroughly homogenize the sample. All of our samples were leached of carbonate, and low in organic matter, and therefore, we did not pre-treat the samples for these components. Soil samples were then prepared for particle size analysis by adding ~1 g of soil to a vial containing a water-based solution, using $(NaPO_3)_{13}$ with Na_2O as the dispersant (Scull and Schaetzl, 2011). The vials were agitated slowly for 2 h on an oscillating shaker to disperse the sample. The dispersed soil was analyzed on a Malvern Mastersizer 2000 laser particle size diffractometer (Malvern Instruments Ltd., Worcestershire, UK). Hobbs et al. (2011) provided a brief discussion of the advantages and shortcomings of laser particle size data, vis-a-vis traditional pipette methods. Particle size data from the Malvern unit were exported and formatted for Microsoft Excel software, in which a continuous textural curve was graphed for each sample, showing the sand, silt and clay textural breaks.

Table 1
Loess thicknesses at each of the nine study sites.

Site number	Loess thickness (cm)[a]
1	55
2	50
3	40
4	40
5	35
6	35
7	30
8	20
9	≤15

[a] Loess thickness is based on analysis of textural data, with depth, as well as field observations and notes.

4. Results and discussion

We provide detailed textural data for the loess and the sediments immediately below, by showing both (1) continuous particle size curves and (2) depth plots of various particle size fractions and ratios thereof. Depth plot data are reported on a clayfree basis to minimize the effects of clay translocation within the soils, on the data.

4.1. Sites with a mixed zone within the basal loess

Loess that overlies coarser materials often has a coarser-textured basal zone. Depth plots of mean weighted particle size data for our sites show that the loess at most of our nine sampled sites becomes increasingly coarser with depth (Fig. 2). Only rarely, e.g., at Site 2, does the loess coarsen abruptly at the lithologic discontinuity. One explanation for the increasing coarseness with depth is that sandy sediment from below has been mixed upward, into the lower parts of the loess. Because most of the underlying sediment is coarser than the loess, the lower parts of the loess mantle acquire coarser textures. In this circumstance, the uppermost parts of the loess, if the loess is thick enough, should lack evidence of such mixing, i.e., it will be nearly "pure," silty loess. Although none of our sites have soils with "thick" loess mantles, the loess at Site 3 is 40 cm thicker than at most of the other sites (Fig. 3). The soil at Site 3 is silt loam textured in the upper 30 cm, but below, it transitions into a coarser, loam-textured zone. In many of the soils developed in thinner loess, the loess texture is also often coarse at the base, but the effects of mixing extend up and through the entire loess column. As a result, the loess does not get appreciably finer nearer the surface, and the entire loess column, except for perhaps the lowermost loess sample, often has the same texture class. In soils such as these, the texture of the loess could be mistakenly interpreted as being coarser than what it was originally, if the effects of mixing are not accounted for.

The particle size mode of a sample, which we determined from our continuous particle size curves, provides excellent information about its sedimentologic origins (Tate et al., 2007). For example, in situations where a sample contains a mixed assemblage of sediment, each with different sedimentologic origins, the sample will often have two distinct particle size modes, each reflective of one sediment type (Hobbs et al., 2011; Sun et al., 2004). Loess samples from Site 3 have clear, dominant silt modes that fall between 27 and 35 μm—medium silt (Fig. 3). Conversely, the sandy sediment below has particle size modes that range between 367 and 407 μm—medium sand. These data illustrate the vastly different depositional environments of the loess (aeolian deposition) and the underlying sediment (glacial deposition).

Important additional information can be gleaned by examining the secondary (second largest) modes of the particle size curves; this is especially true for the samples from the coarse-textured zone in the basal loess. Correct interpretation of these modes can ascertain if mixing from below has occurred. The weak secondary mode in the uppermost loess sample from Site 3 indicates that the sample contains almost entirely "primary" loess, with almost no sands or coarser materials mixed in. With depth, however, each loess sample contains increasing amounts of sand, as shown by increasingly larger secondary modes, coupled

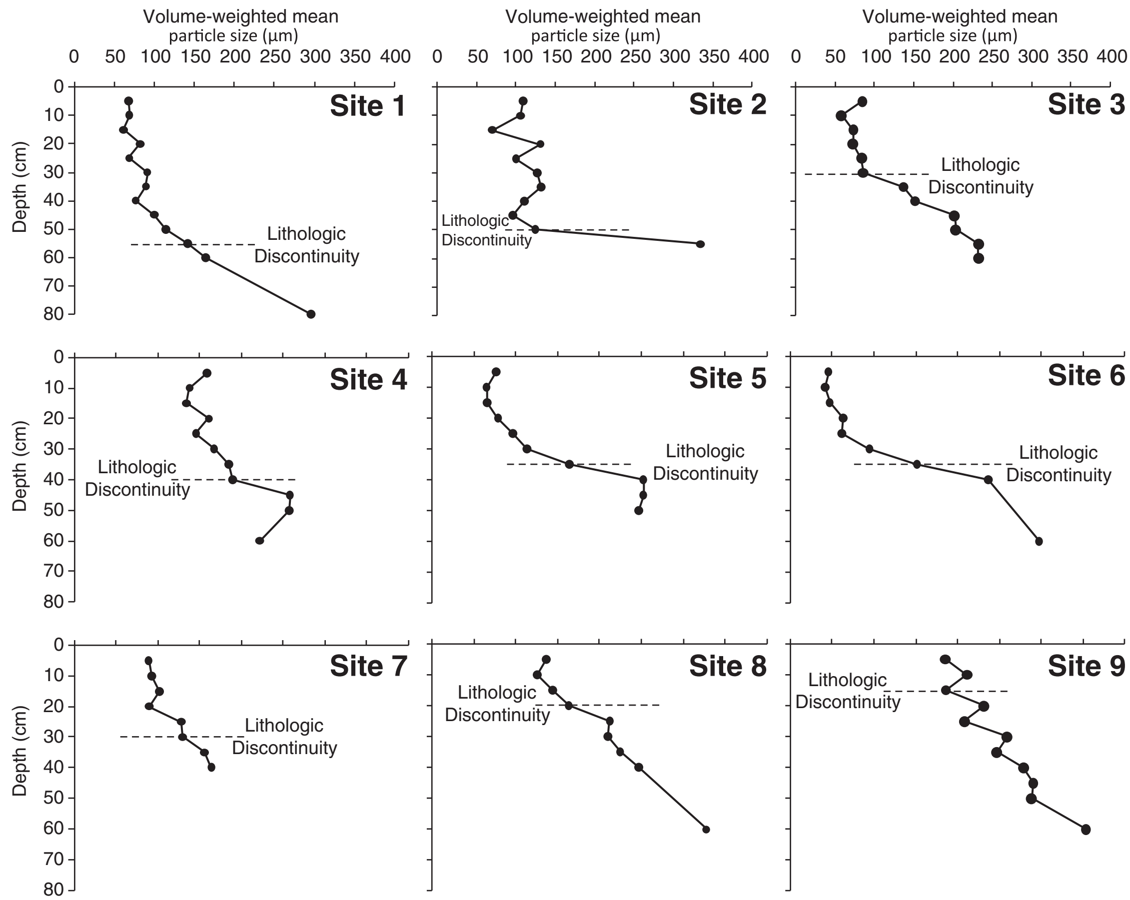

Fig. 2. Depth plots of mean weighted particle size data, as exported from the Malvern Mastersizer laser particle size analyzer. Locations of the field-identified lithologic discontinuities are shown as horizontal, dashed lines.

with smaller primary (silt) modes (Fig. 3). Evidence in support of a pedoturbation origin for the "secondary mode" sand in the loess is unmistakable; the secondary modes peak at locations along the X-axis that are comparable to those in the sediment below, ranging from 379 to 534 μm. Note that the modes in the loess samples at these same depths change little, illustrating that the loess itself does not get coarser with depth. Rather, the increasing sample coarseness (Fig. 2) is caused almost entirely by the added, i.e., mixed, medium sands. Site 3 is an example of thin loess with coarse (mostly medium sand) materials mixed into the lower parts of the loess column. Site 4 has many similarities to Site 3. Site 7 is also similar to Site 3, but with a 10-cm thinner loess mantle (Figs. 2, 3).

Site 8, too, has a coarse-textured mixed zone at the base of the loess (Fig. 3). Unlike the previous examples, however, the loess at Site 8 is much thinner (≈20 cm) and slightly coarser (modes range from 42 to 51 μm). This site illustrates that, in situations where the loess is less than 25 cm thick, all of it eventually gets texturally compromised by pedoturbation. We stress that, although the loess at Site 8 actually has fine sandy loam textures, these textures are caused by sands that were mixed into the overlying loess. The part of the sample that is aeolian, i.e., the part with the coarse silt or very fine sand mode, is only slightly coarser than the loess at Sites 2 and 3. Note that the loess samples at Sites 2 and 3 have mean modes of 32.0 and 38.7 μm, whereas at Site 8 the loess has a mean mode of 48.2 μm. At Site 8, however, in some of the deeper loess samples, so much sandy sediment has been mixed in from below, i.e., the mixing zone is so pronounced, that the mode for the aeolian (loess) component is secondary to the mode within the medium sand fraction (Fig. 3). Even the uppermost loess sample has a prominent secondary mode within the sand fraction (fine sand, in this case).

Lastly, we examine the data for Site 9, located on a small drumlin. The soil here is mapped by the NRCS as a sandy, mixed, frigid Alfic Haplorthod; this series is described as having formed in "sandy deposits." Nonetheless, many drumlins nearby are mapped in soil series that are described as having a mantle of "modified loamy eolian material," leading us to believe that thin loess also exists at Site 9, on top of sandy deposits. In the field, this site did not exhibit a clear, distinct, silty loess mantle, although it does get slightly finer, texturally, toward the surface. At depth, the soil at Site 9 is dominated by gravelly sandy loam and loamy sand glacial outwash. Particle size data for Site 9 confirmed our field observations; this site has silty material mixed into the otherwise sandy sediment below (Fig. 3). At all depths, the sand mode, typically between 320 and 400 μm, is larger than the silt mode. This site illustrates the complete mixing of a very thin loess deposit into the underlying sediment. In the pedons discussed above, all of which have formed in thicker loess, this process was also present, but the focus was on the mixing of the underlying coarse-textured materials into the overlying loess. Here, at Site 9, the loess deposit is so thin that it has been thoroughly mixed into the sandy sediment below, as is shown on the particle size curves by a small, secondary mode within the silt fraction.

4.2. Sites with a minimal mixed zone—or no mixed zone—within the basal loess

The loam textured loess at Site 2 is slightly coarser than at many other sites—top to bottom. Likewise, the underlying sediment is very coarse (loamy coarse sand). Site 2 is a good example—and the only one of the nine studied pedons—of a soil with a fairly abrupt lithologic discontinuity between the loess and the underlying, loamy coarse

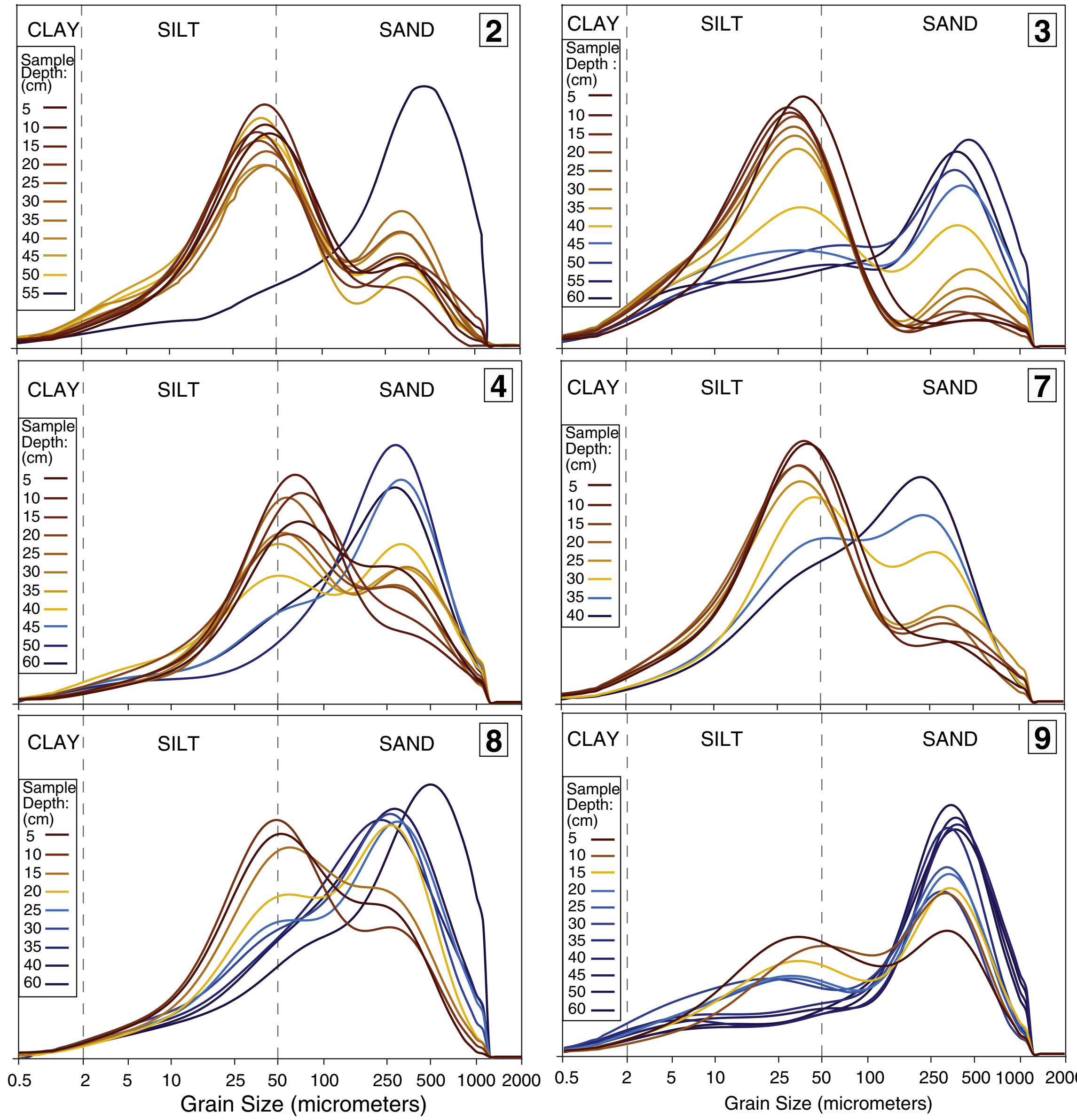

Fig. 3. Continuous particle size curves for the Sites 2, 3, 4, 7, 8 and 9. Data for samples taken from loess are shown in brown-to-yellow hues, from the surface downward. Data for samples taken from the underlying glacial sediment are shown in blue hues, with the deepest samples in the darkest blue colors. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sand sediment. This soil lacks a distinct coarse-textured "transitional" zone within the basal loess (Figs. 2, 3). The continuous particle size data suggest that almost complete mixing has occurred here, all the way to the soil surface, although evidence for slightly more fine and medium sand occurs in the lower half of the loess column (Fig. 3). Additionally, as in the loess at Site 3, less "mixed sand" is present in the uppermost two samples than in samples below. We cannot explain why the loess at Site 2 has been so uniformly mixed, but the fact that this type of thin loess sedimentology exists articulates the rate and efficacy of pedoturbation in this region, at least to 50-cm depth.

4.3. Loess thickness vis-à-vis mixed zone depth

Our study may provide data to address the question: Does loess thickness *per se* impact the depth of the mixed zone? Examination of Fig. 3 suggests that no correlation exists between these two variables. Soils with thick loess, e.g., Sites 3 and 4, have mixed zones that easily exceed 20–30 cm in thickness, while soils with intermediate loess thicknesses, e.g., Sites 5 and 6 (Fig. 4), exhibit minimal evidence of mixing. Site 2, with 50 cm of loess, shows evidence of mixing that continues to the surface. And in soils with thin loess mantles, e.g., Sites 8 and 9, mixing processes have been so pronounced that it would be difficult to sample any loess that has not been completely texturally compromised. These data suggest that the thickness of the mixed zone is affected most by local site conditions, rather than loess thickness *per se*. Nonetheless, we caution that any loess within 50 cm of an underlying lithologic discontinuity be considered texturally compromised, and not useful for OSL sampling/dating.

Mixed zones are discernable in loess based on their bimodal particle size distributions, with the amount of mixing correlated with the relative mode heights in the continuous particle size curves. We stress that, even where loess is perceived simply to be coarse, the coarseness may be due to mixing of sands from the underlying sediment, i.e., it may not reflect the initial depositional characteristics of the loess. Certainly, in areas where the loess is thinner than 25 cm, mixing of sediment from below can easily extend to the surface. We caution that the thickness of these types of mixing zones may be different (usually thinner) in situations where the loess is thick, i.e., where the lower units of loess are farther removed from mixing processes associated with the surface, e.g., bioturbation, frost heave, etc.

4.4. Sites with coarser basal loess, but with minimal mixed zones

As discussed above, Sites 3, 7, 8 and 9 have clear mixed zones within the basal zones of the loess, and where the loess is thin, the entire loess column shows evidence of sand mixing (Fig. 3). Three other sites—5, 6 and 1—have only small mixed zones in their basal loess, but importantly, also exhibit loess that coarsens with depth (Fig. 4). Site 5 is an excellent example of this situation.

At Site 5, the lithologic discontinuity between the loess and the underlying sediment is extremely abrupt. There is little evidence at Site 5 for a mixed zone within the 35 cm of loess, as all samples—whether they are loess or the sandy sediment below—are unimodal. The modes for the loess samples, however, get progressively finer toward the surface; the coarsest loess exists immediately above the lithologic discontinuity (Fig. 4). Modes within the loess are (from the bottom-most sample upward) 77, 74, 70, 58, 44, 41 and 42 µm. This degree of coarsening may go unnoticed in the field, but is very apparent from data in the textural curves (Fig. 3) and the mean weighted particle size depth plots (Fig. 2). Note that the sandy sediment below the loess is also unimodal, peaking at 276, 293 and 289 µm (medium sand); it has virtually no "mixed" silt. This site, even though it has a clear coarse-textured basal zone within the loess, may have the most abrupt lithologic discontinuity of all nine sites sampled.

Site 6 is similar to Site 5—the loess is equally thick and is underlain by sandy loam sediment (Fig. 4). Site 6 also exhibits a clear trend of coarsening loess textures with depth. However, Site 6 has considerable amounts of sand mixed into the lowermost loess sample, and small amounts of sand are also evident in loess samples nearer the surface. Fine sediment from the loess has also been mixed into the upper 10 cm of the sediment, as evidenced by modes within the very fine sand fraction (Fig. 4). Site 1 exhibits similar textural patterns.

We interpret the coarsening of the loess with depth, i.e., its fining nearer the surface, as evidence that paleoenvironmental conditions were changing during loess deposition; initial loess deposits were coarser, and over time, the loess became finer. Several possible interpretations exist for the changes in loess particle size with depth:

1. Coarser loess at depth may imply stronger winds, capable of transporting larger sediment (Sun et al., 2004). This scenario suggests that winds may have been slowly diminishing in strength during the loess deposition period. As the ice margin retreated northward during the Late Pleistocene, it seems likely that wind speeds would have diminished slowly over time, at least in some locations.
2. The loess at these sites may have been multi-sourced. That is, loess source regions may have been changing over time, as suggested by Stanley and Schaetzl (2011) for a dual-sourced loess deposit farther south, in central Wisconsin. At our sites, where the loess gets finer nearer the surface, the implication is that a source area with coarse sediment was dominant early in the loess deposition event. Then, a second source area, with finer sediment, or perhaps a more distant one, became dominant. Across the region, several potential loess source areas exist, e.g., outwash plains, lake plains and large end moraines (Scull and Schaetzl, 2011). These features surround the study area and could have been loess sources at various times during the Late Pleistocene, as paleoenvironmental conditions changed.
3. The textural characteristics of the source area(s) changed over time. For example, there may have been more areas of exposed very fine sand on the landscape during the earliest parts of loess deposition, and later, as loess deposits became more widespread on the landscape, silt-sized sediments were more readily entrained (or re-entrained) and transported to sites of loess deposition. This trend may again point to the importance of local loess sources early in the loess depositional period, because many of these finer sands may have only been transportable for short distances across the irregular, recently deglaciated landscapes of the study area. Then, later, finer-textured, siltier deposits, were deflated from more distant sources. Any or all of these interpretations have direct paleoenvironmental implications for the period of loess deposition.

5. Implications of the research

Loess is transported in suspension, giving it ample opportunities for solar "resetting." Therefore, loess is amenable to dating by optically stimulated luminescence (OSL) (Forman and Pierson, 2002; Lang et

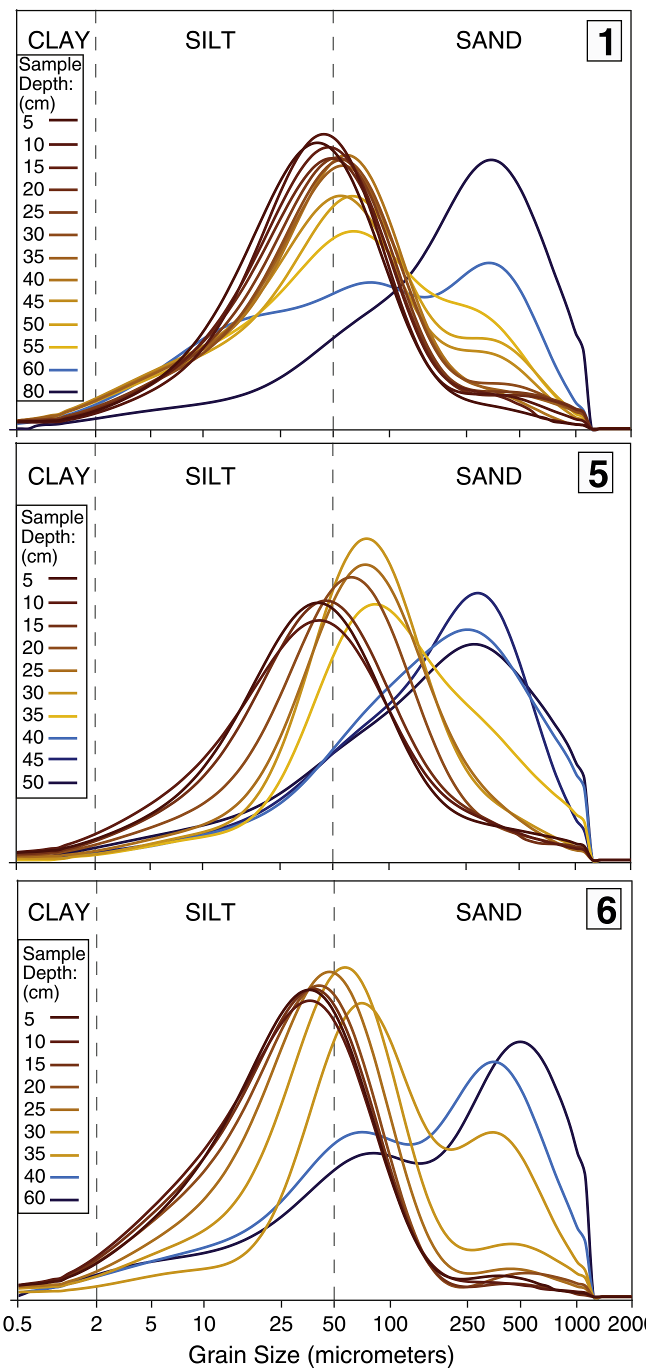

Fig. 4. Continuous particle size curves for the Sites 1, 5, and 6. The symbology used is the same as that used in Fig. 3.

al., 2003; Packman et al., 2007; Roberts, 2008; Roberts et al., 2003; Wintle, 2008). However, mixing of other types of "unzeroed" or insufficiently bleached sediment from below, e.g., glacial till or outwash, into a loess unit can dramatically affect the dates obtained by luminescence dating (Bateman et al., 2007; Bush and Feathers, 2003; Fuchs and Owen, 2008). For this reason, it is important that loess sampled for OSL dating not only be completely solar-reset, but also not mixed or contaminated with other types of sediment with different solar-resetting histories (Forrest et al., 2003). Findings from our study provide important information for researchers who need to determine if loess near a lithologic contact has been "compromised" by mixing of unzeroed sediment (Tate et al., 2007) from below. If, for example, a coarse-textured basal layer represents a mixed zone, then it can be avoided for OSL sampling. Alternatively, if the coarser-textured loess is simply that—coarse loess—then sampling it for optical dating would be less problematic, and could provide important information about an early period of coarser loess deposition. Many soils are covered with a thin loess mantle (Borchardt et al., 1968; Hobbs et al., 2011; Mason and Jacobs, 1998; Schaetzl and Hook, 2008; Scull and Schaetzl, 2011). In some cases, the loess is almost undetectably thin; all of it has been mixed into the underlying sediment. Because of its fine texture and (often) carbonate-rich mineralogy, additions of loess to soils or sediment can dramatically affect pedogenesis and soil evolution pathways (Allan and Hole, 1968; Almond and Tonkin, 1999; Beavers et al., 1963; Chadwick and Davis, 1990; Danin et al., 1983; Dixon, 1991; Harlan et al., 1977; Jacobs and Mason, 2005; Jenkins and Bower, 1974; Kleiss, 1973; Lindbo et al., 1997; Litaor, 1987; Muhs et al., 2004; Saif et al., 1997; Wilson et al., 2010; Yaalon, 1987). Additionally, the presence of a lithologic discontinuity between the loess and the underlying sediment impacts water movement and, hence, many pedogenic processes associated with percolating water (Foss and Rust, 1968; Schaetzl, 1998; Tremocoldi et al., 1994). Thus, our findings will enrich pedogenic and sedimentologic research by providing a method for assessing the (1) thickness of an eolian cap, i.e., the location of the lithologic discontinuity, in soils with a loess mantle, as well as (2) abruptness of the lithologic discontinuity at the base of overlying loess.

In many discussions of loess and loess stratigraphy, information about the textural character of the loess near the lithologic contacts is often ignored, with the emphasis (understandably) placed on the loess in the middle of the column, where it is "purest." In this paper, we place a new emphasis on loess textural changes that occur incrementally with depth, and especially near (both above and below) its contact to the sediment that underlies it.

6. Conclusions

This study examined nine pedons that have formed in thin (≤55 cm) loess over coarser-textured glacial sediment. In most of the pedons, the silt loam or loam textured loess often has a slightly coarser-textured basal zone, as is typical of loess in these types of sedimentary settings. The purpose of this research was to characterize these coarser-textured basal zones in the loess, and ascertain their possible origins.

Thin loess in the study area has primary particle size modes within the coarse silt or fine, very fine sand fractions (≈30–65 μm). However, the loess mantle often also has a secondary particle size mode within the medium or fine sand fraction (≈200–400 μm). The magnitude of the secondary sand mode, and hence, the coarseness of the loess, increases with depth, down to the lithologic contact with the sandy sediment below. We attribute this secondary sand mode to mixing of underlying sands into the loess, either during loess deposition or by pedoturbation processes that occurred subsequently. Because the loess is thin, pedoturbation processes have been able to penetrate into the underlying sediment and mix some of it into the loess. In thicker loess sections, only the mixing that occurred during deposition would have been operational, as pedoturbation within the modern soils could not penetrate down to the lithologic discontinuity. Sands from the underlying sediment usually get mixed up to 50 cm into the overlying loess, compromising this lower part of the loess column for luminescence dating. Textural analyses of loess near an underlying lithologic contact, i.e., within 50–70 cm, should be done with these post-depositional processes in mind.

In addition, some pedons with a coarser-textured basal zone also exhibit loess that itself coarsens with depth, i.e., the particle size mode for the loess gets increasingly coarser. The loess in these pedons becomes increasingly finer in texture during the depositional event, pointing to either decreased wind velocities or changing source area conditions. This type of basal coarse zone has distinct paleoenvironmental implications.

As other work has done, e.g., Dinghuai et al. (2004), Prins et al. (2007), Tate et al., (2007), Menendez et al. (2009), Hobbs et al. (2011), our research again demonstrates the importance of detailed particle size data for detecting and interpreting the pedologic and paleoenvironmental history of loess and related sediments. It also provides important baseline information about the extent to which pedoturbation processes can impact the original sedimentary characteristics of eolian sediment.

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