Loamy, Two-Storied Soils on the Outwash Plains of Southwestern Lower Michigan: Pedoturbation of Loess with the Underlying Sand

Michael D. Luehmann,* Brad G. Peter,† Christopher B. Connallon,† Randall J. Schaetzl,† Samuel J. Smidt,† Wei Liu,† Kevin A. Kincare,‡ Toni A. Walkowiak,† Elin Thorlund,† and Marie S. Holler§

*Atwell, LLC
†Department of Geography, Michigan State University
‡U.S. Geological Survey
§Department of Urban Planning, University of Sheffield

Soils on many of the outwash plains in southwestern Michigan have loamy upper profiles, despite being underlain by sand-textured outwash. The origin of this upper, loamy material has long been unknown. The purpose of this study is to analyze the spatio-textural characteristics of these loamy-textured sediments to ascertain their origin(s). The textural curves of this material have distinct bimodality, with clear silt and sand peaks. Because the sand peaks align with those in the outwash below, we conclude that the upper material is a mixture of an initially silty material with the sand from below, forming loamy textures. By applying a textural filtering operation to the data, we determined its original characteristics; nearly all of the soils originally had silt loam upper profiles, typical for loess. Field data showed that the loamy material is thickest east of a broad, north–south trending valley (the Niles-Thornapple Spillway) that once carried glacial meltwater. The material becomes thinner, generally better sorted, and finer in texture eastward, away from this channel. We conclude that the loamy mantle on many of the adjacent outwash plains is silt-rich loess, derived from the Niles-Thornapple Spillway and its tributary channels and transported on mainly westerly winds. The spillway was active between ca. 17.3 and 16.8 k cal. years ago. At this time, a large network of tunnel channels existed beneath the stagnant Saginaw lobe ice. Meltwater from the lobe funneled silt-rich sediment into the spillway, rendering it a prodigious silt source. *Key Words: eolian systems, loess, outwash plains, pedoturbation, spatial analysis.*

密西根西南方诸多冰川沉积平原的土壤, 儘管位于砂质冰川沉积平原下方, 但仍具有上层壤土剖面。此一上层壤土物质的来源, 长久以来不为人知。本研究的目的, 便在于分析这些壤土质地沉积物的空间—结构特徵, 以确认其来源。此一物质的结构曲线, 具有清晰的粉砂与砂两峰的特殊双模态。由于砂峰与位于下方冰川沉积平原之物一致, 我们因此断定, 上层物质是原本的粉砂物质和下方砂的混合物, 组成了壤土结构。我们对数据进行结构过滤, 确认其原本的特徵; 近乎所有的土壤原本皆具有粉砂壤土的上层剖面, 并以黄土为代表。田野数据显示, 壤土物质在曾经运送冰川融水的宽广南北向河谷 (耐士—曼陀罗溢洪道) 中的东边最为肥沃。该物质越往东远离此一渠道, 便愈益稀少、普遍更佳地区分, 且质地更为细緻。我们于结论中主张, 诸多邻近的冰川沉积平原的壤土覆盖物, 是粉砂丰富的黄土, 该物质起源于耐士—曼陀罗溢洪道及其支流水道, 并主要由西风带所运送。该溢洪道约在 17.3 和 16.8 千公暦年间活跃。于此期间, 大范围网络的地下河道, 存在于停滞的赛基诺冰舌之下。来自冰舌的冰川融水, 将富含粉砂的沉积物注入溢洪道中, 使其成为庞大的粉砂来源。 *关键词: 风积系统, 黄土, 冰川沉积平原, 扰动, 空间分析。*

Los suelos de muchas de las planicies de acarreo fluvioglacial [*outwash*] en el sudoeste de Michigan tienen perfiles superiores arcillosos, a pesar de estar superpuestos sobre depósitos de textura arenosa. El origen de este material arcilloso superior se desconoce. El propósito de este estudio es analizar las características espacio-texturales de estos sedimentos de textura arcillosa para determinar su(s) origen(es). Las curvas de textura de este material tienen marcada bimodalidad, con claros picos de limo y arena. Debido a que los picos de arena se alinean con los del material outwash subyacente, concluimos que el material superior es una mezcla de un material inicialmente limoso con la arena de abajo, formando texturas limosas. Aplicando una operación de tamizado textural a los datos, determinamos sus características originales; casi todos los suelos tuvieron originalmente perfiles superiores de limo arcilloso, lo cual es típico del loess. Los datos de campo mostraron que el material arcilloso es del máximo espesor al este de un vasto valle de orientación norte-sur (el Desagüe Niles-Thornapple), que alguna vez fue recorrido por agua de deshielo glacial. El material se hace más delgado, generalmente mejor clasificado y de estructura más fina, hacia el este, lejos de aquel canal. Concluimos que el manto arcilloso en muchas de las

Annals of the American Association of Geographers, 106(3) 2016, pp. 551–571 © 2016 by American Association of Geographers
Initial submission, February 2015; revised submission, June 2015; final acceptance, August 2015
Published by Taylor & Francis, LLC.

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planicies outwash adyacentes es de loess rico en limo, derivado del Desagüe Niles-Thornapple y sus canales tributarios, transportado hasta allí por los vientos oestes. El desagüe estuvo activo entre ca. 17.3 y 16.8 k cal. años atrás. En ese tiempo existió una gran red canales en forma de túneles por debajo del lóbulo de hielo estancado de Saginaw. El agua de deshielo del lóbulo hacía pasar sedimento rico en limo hasta el desagüe, convirtiendo así a este cauce en prodigiosa fuente de limo. *Palabras clave: sistemas eólicos, loess, planicies de acarreo fluvioglacial, pedoturbación, análisis espacial.*

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Due to their persistence through time, soil parent materials provide insights into past sedimentologic and depositional systems (Hunt 1972; Veseth and Montagne 1980; Hoover and Ciolkosz 1988; Muhs et al. 1990; Birkeland, Machette, and Haller 1991; Crownover, Collins, and Lietzke 1994; Oganesyan and Susekova 1995; Kleber 1997; Schaetzl et al. 2000). Maps of parent materials help determine the spatial variation in sedimentary systems, whereas stacked sequences of parent materials help assess this variation through time. Assessment and dating of parent materials, stacked or otherwise, can also help estimate the age of the surface or sediments within which the soils were formed (Mason, Mildred, and Nater 1994; Schaetzl and Forman 2008). For these reasons and many others, researchers have recently shown heightened interest in soil parent materials (Cremeens, Brown, and Huddleston 1994; Cremeens 2000; Schoeneberger and Wysocki 2005; Wysocki, Schoeneberger, and LaGarry 2005; Wald, Graham, and Schoeneberger 2013), in part fueling the rapid growth of investigations of the Earth's critical zone (Lin 2010; Brantley and Lebedeva 2011). Another extension of the interest in soil parent materials is manifested in the application of geographic information systems (GIS), wherein soil maps are used as surrogates for geologic maps (Rabenhorst and Foss 1981; Schaetzl and Weisenborn 2004; Miller, Burras, and Crumpton 2008; Scull and Schaetzl 2011; Schulze, Owens, and Van Scoyoc 2012; Schaetzl et al. 2013). As should be obvious, the correct identification of soil parent materials has great potential for improving our understanding of the near-surface ecosystem and past environments and for better managing the soil resource.

Establishing and applying the links between soil parent materials and past geologic processes seems simple; for example, soils formed in glacial till indicate a history of recent glaciation, and soils formed in dune sand indicate the presence of eolian activity. Two complications routinely arise, however: (1) identification of the genetic origin of the parent material is not always straightforward and (2) soils, commonly referred to as "two-storied" soils, could be composed of stacked parent materials with an intervening lithologic discontinuity.

In response to the first complication, we have previously categorized all of the soil series mapped in Wisconsin and Michigan to parent material, using the Official Series Descriptions (OSDs) on the Natural Resources Conservation Service's (NRCS) Web site (http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/soils/home/?cid=nrcs142p2_053587; see Scull and Schaetzl 2011). Genetic parent material names are periodically used in the OSDs, such as till, loess, or alluvium. Many soil series are described with more generic names, however, such as sandy materials, loamy materials, or drift. Indeed, of the 1,167 soil series mapped in these two states, 307 (26.3 percent) lack clear genetic descriptions of their parent material. Thus, considerable confusion and uncertainty exist when trying to link many of the "less well-defined" soil parent materials to a specific geologic or sedimentologic system.

Two-storied soils record an even more complex geologic history, and there are many such soils in existence, especially in glaciated regions. For example, Schaetzl (1998) observed that about a third of the soil series in the United States have a lithologic discontinuity within the upper 2 m; that is, they are two-storied soils consisting of two different parent materials. Nearly seven have two or more discontinuities. In two-storied soils, the uppermost parent material records the last depositional event or process for the soil. Knowing about this last depositional event could be very useful to our understanding of the recent paleoenvironmental history (Mason et al. 2003; Mandel 2008; Schaetzl and Loope 2008; Ahr, Nordt, and Driese 2012). That is, the uppermost parent material records the last depositional event, depicting the final depositional system. Identifying the uppermost parent material in two-storied soils is often complicated, however, by the fact that it is often either thin or variously mixed with the sediment below (Schaetzl and Luehmann 2013). Both factors combine to render interpretation of the soil's genetic history difficult.

Numerous examples from the upper Midwest can be used to illustrate these situations, all of which highlight what can be learned by careful study of the uppermost parent material in two-storied soils. Feldhauser soils

Figure 1. Flat outwash plains in southwestern Michigan, where Kalamazoo and similar soils dominate the soil landscape. (Color figure available online.)

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(coarse-loamy, mixed, active, frigid Oxyaquic Glossudalfs) in northern Lower Michigan, whose upper sola (upper 50 cm) are loamy but become sandier with depth, were not thought to be two-storied. Neither did OSD data suggest that the upper material in these soils was a separate and unique parent material. Recent work, however, concluded that this upper loamy material is a thin mantle of (originally) silty loess, which became loamy in texture after mixing with the sandier sediment below (Schaetzl 2008; Luehmann et al. 2013; Schaetzl and Luehmann 2013). Schaetzl (2008) used this information to not only invoke a brief loess depositional episode for northern Lower Michigan during the late Pleistocene, but the loess cap also pointed to a period of periglacial activity and widespread permafrost for this landscape. Neither of these two geologic events would have been known had this mantle of loess not been identified and interpreted. Similarly, a thin loess mantle on sandy glacial sediments in Michigan's Upper Peninsula helped link a dune-building event on the floor of former glacial Lake Algonquin to loess deposition on the crests of its islands (Schaetzl and Loope 2008). Again, much of this loess was loamy, having been mixed with sand from below.

In this study, we present data on a suite of soils found extensively across southwestern Michigan, where broad, sandy and gravelly outwash plains are common (Figure 1). Although the soils on some of these outwash surfaces are sandy throughout, most get increasingly loamy in the upper profile. Some even attain silt loam textures within the A horizon. The purpose of this study is to analyze the spatiotextural characteristics and distribution of these types of loamy-textured soils and sediments in southwestern Michigan. We hypothesize that these soils have had additions of loess, and if shown to be correct, we intend to use the spatial characteristics of the loess to better understand the paleoenvironmental conditions that led to its deposition and preservation across this region.

Study Area

Glacial Geomorphology

The study area generally spans ten counties in southwestern Michigan (Figure 2). Landforms here have direct glacial origins related to retreat of the Laurentide ice sheet (LIS) between about 19,000 and 16,000 cal. years ago (Larson and Kincare 2009). The terrain within the study area is a mix of moraines, till plains, and outwash plains. Much of the study area is composed of broad, flat uplands, commonly associated with outwash plains, and hummocky uplands with collapse topography associated with end moraines. A prominent drumlin field, the Union Streamlined Plain, occupies the eastern part of the study area (Folsom 1971; Fisher, Jol, and Boudreau 2005; Schaetzl et al. 2013).

Although the sediments that comprise the study area were emplaced by three different lobes of the LIS, deposits of the Saginaw lobe dominate. This lobe advanced southwesterly, out of the present Saginaw Bay area, and eventually covered much of southwestern Michigan. Its western and eastern edges merged with those of the Lake Michigan lobe in the Lake Michigan basin and the Huron-Erie lobe in the Lake Erie basin, respectively (Farrand and Eschman 1974; Kehew, Nicks, and Straw 1999; Blewett, Lusch, and Schaetzl 2009). After reaching its maximum extent south of the present-day Indiana border, the Saginaw lobe is thought to have retreated rapidly and experienced widespread stagnation, possibly due to loss of ice flow to the Huron-Erie lobe (S. Brown, personal communication, 2012; Kehew et al. 2005).

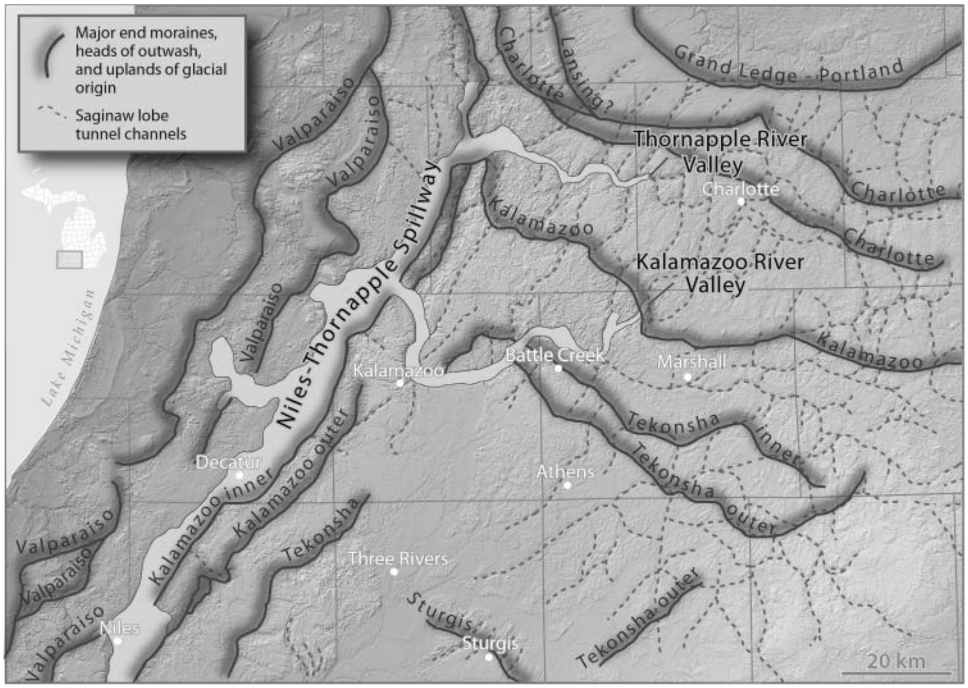

Figure 2. Topography of the study area, showing general locations and names of possible ice margins as thick gray lines. Also shown are the various tunnel channels formed during deglaciation and the place names used in the text.

The traditional view of deglaciation here is one of stepwise and synchronous retreat of the Saginaw, Lake Michigan, and Huron-Erie lobes (Leverett and Taylor 1915; Figure 2). Episodes of readvance, however, in addition to periods of ice stagnation, have added complexity to the story. For example, the early retreat of the Saginaw lobe exposed large parts of southwestern Michigan (Kehew, Nicks, and Straw 1999; Kehew et al. 2005; Kehew et al. 2012), allowing the Lake Michigan and Huron–Erie lobes to override some of the landscapes uncovered by the retreating Saginaw lobe (Kehew et al. 2005). Although most meltwater at this time generally drained to the south, this complex sequence of deglaciation also dramatically influenced the pathways of meltwater flow, proglacial ponding, and sediment deposition. Nonetheless, the general picture of deglaciation involves fairly rapid retreat of the ice margin, exposing new glacial deposits to various subaerial and subaqueous processes.

Moraines associated with the retreating Saginaw lobe are, from oldest to youngest, the Sturgis, Tekonsha, Kalamazoo, and Valparaiso-Charlotte (Kehew et al. 2005; Figure 2). Most of what is visible today of the Sturgis moraine is associated with the Saginaw lobe. This feature was likely overridden on its western side by the Lake Michigan lobe (Kehew, Nicks, and Straw 1999; Kehew et al. 2005). Ice might have then retreated to form several small ice-contact margins known locally as the Tekonsha moraine, although there is often no till associated with it, and the existence of a Tekonsha moraine is unlikely (Dodson 1993); it might be a remnant of an older landform (Fisher, Jol, and Boudreau 2005). During the Tekonsha stillstand and at other times, meltwater flowed southwesterly, between the drumlins, partially burying them and forming the large outwash surface known as the Three Rivers Lowlands (Schaetzl et al. 2013; Figure 3). Ice then retreated and stabilized at the Kalamazoo moraine, which represents a prominent ice marginal position in the region (Kehew et al. 2005). The double-ridged Kalamazoo moraine (Leverett and Taylor 1915) is interspersed with some areas of till and marks the former margins of both the Lake Michigan and Saginaw lobes (Kehew et al. 2005; Figure 2). While the ice of the Lake Michigan and Saginaw lobes was at the Kalamazoo moraine, meltwater continued to flow across the Three Rivers Lowlands, south into present-day Indiana. Outwash from the retreating ice cut through and buried parts of the preexisting Sturgis moraine, expanding the Three Rivers Lowlands into a broad, flat plain that bisects the present-day Sturgis moraine in St. Joseph County (Figure 3).

Eventually, the ice margin withdrew from the Kalamazoo margin, likely stabilizing at the Valparaiso

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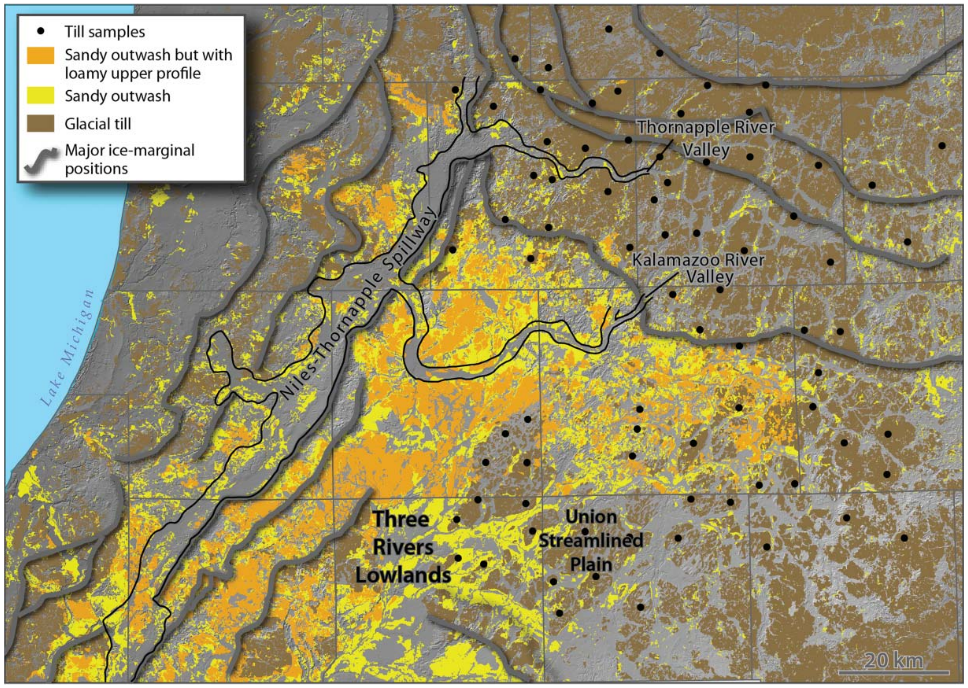

Figure 3. Ice margins, landforms, and surficial sediments of the study area, interpreted from Natural Resources Conservation Service soil survey (SSURGO) data. Till sample sites are shown as black dots. (Color figure available online.)

(Lake Michigan lobe)–Charlotte (Saginaw lobe) position (Figure 2), although evidence for a clear ice-marginal position is equivocal. At this time, a meltwater channel formed between the retreating ice margin and the west-facing, ice-contact slope of the Kalamazoo moraine; Schaetzl et al. (2013) named this meltwater channel the Niles-Thornapple Spillway (Figures 2 and 3). The spillway is a north–south trending channel, roughly 3 to 4 km wide, with between 25 and 45 m of local relief. It drained southward into present-day Indiana (Schaetzl et al. 2013; Figure 4). In the north, across Saginaw lobe terrain, meltwater was not confined by a large moraine but instead flowed chaotically to the west and south, through a system of tunnel channels and into what would become the Kalamazoo and Thornapple River valleys, which then flowed into the Niles-Thornapple Spillway (Figure 2). With the Kalamazoo moraine acting as a topographic barrier to the east, the Niles-Thornapple Spillway became a preferred drainage way for meltwater from both the Saginaw and Lake Michigan lobes.

The Saginaw lobe tunnel channels are etched into the loamy, till plain sediments and are suggestive of widespread stagnation (Fisher, Jol, and Boudreau 2005; Kozlowski, Kehew, and Bird 2005) and possibly subglacial outburst flooding (Fisher and Taylor 2002; Kozlowski, Kehew, and Bird 2005). The channels are linear-to-anastomosing valleys about 30 m deep and usually about 0.5 to 1.5 km wide (Figure 2). Many contain eskers, elongated kettle lakes, and kamic features (Rieck and Winters 1980; Fisher, Jol, and Boudreau 2005). Formation

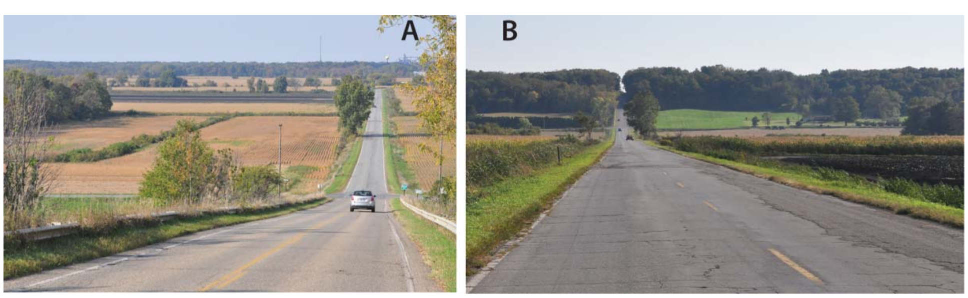

Figure 4. Images of the Niles-Thornapple Spillway, about 2 km southwest of the city of Decatur, as viewed from (A) above and (B) within. (Color figure available online.)

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Table 1. Major soils found on outwash plains in the study area

Soil series	USDA taxonomic family	Upper solum texture	C horizon texture	NRCS-derived productivity rankings (out of 15 total)	Mean overall NRCS rank (out of 15 total)
Kalamazoo	Fine-loamy, mixed, semiactive, mesic Typic Hapludalfs	Loam	Gravelly sand	Corn: 7 Corn silage: 4 Soybeans: 7 Wheat: 6 Oats: 6 Hay: 4	7
Schoolcraft	Fine-loamy, mixed, superactive, mesic Typic Argiudolls	Loam	Sand	Corn: 1 Corn silage: 3 Soybeans: 5 Wheat: 1 Oats: 1 Hay: 2	1
Dowagiac	Fine-loamy, mixed, semiactive, mesic Mollic Hapludalfs	Loam	Sand	Corn: 4 Corn silage: 2 Soybeans: 6 Wheat: 8 Oats: 3 Hay: 5	4
Ockley	Fine-loamy, mixed, active, mesic Typic Hapludalfs	Silt loam	Stratified coarse sand and very gravelly coarse sand	Corn: 5 Corn silage: 8 Soybeans: 3 Wheat: 4 Oats: 4 Hay: 6	5
Oshtemo	Coarse-loamy, mixed, active, mesic Typic Hapludalfs	Sandy loam	Sand and gravelly sand	(Not calculated)	

Note: USDA = U.S. Department of Agriculture; NRCS = Natural Resources Conservation Service.

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of these tunnel channels would have mobilized considerable amounts of sediment from the till plain, much of which would have flowed into the Kalamazoo and Thornapple River valleys, ultimately merging in the Niles-Thornapple Spillway with meltwater from the Kalamazoo margin. Continued retreat of the ice allowed meltwater from the Lake Michigan lobe to flow to the south via other channels, farther west than the spillway. Likewise, Saginaw lobe meltwater found alternate pathways to the north, following a regional topographic gradient, eventually flowing down the Glacial Grand River valley and into ancestral Lake Michigan.

Soils

Soils in the study area are geologically young and, thus, strongly reflect their parent materials, almost all of which are glacial sediments. We focused on soils that occur on broad, flat uplands formed in sandy outwash deposits, mainly within the Kalamazoo, Schoolcraft, Dowagiac, Ockley, and Oshtemo series (Table 1; see also Figures 1 and 5). Most of these soils are well drained and have loamy upper profiles; even Oshtemo soils, the sandiest of the group, often have loamier textures near their surfaces than in their deeper horizons. These types of textural depth trends suggest a secondary addition of allochthonous fine sediment after the outwash surfaces stabilized. Most of the soils in Table 1 are alfisols, with a pronounced Bt horizon, having formed under deciduous forest vegetation. Schoolcraft soils are, however, associated with tallgrass prairie, and are mollisols. Sand and gravel—often quite coarse—underlie all of the soils on these outwash plains.

Vegetation and Land Use

Landscapes in the study area were mainly forest, mixed savanna, or prairie at the time of European settlement (Schaetzl et al. 2013). To gain insight into the association between these soils and their native

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vegetation, we performed a spatial intersect operation in ArcGIS. The four soil series mentioned earlier (Table 1) were extracted as a new layer from the NRCS's SSURGO data files and analyzed for vegetation cover using a zonal analysis function and the Tabulate Area tool in ArcMap (ESRI 2014d). Presettlement vegetation data were used to determine the spatial association among vegetation and soils. With regard to the soils in Table 1, nearly 40 percent of the area was covered by mixed oak savanna at the time of European settlement, 23 percent by beech and sugar maple forest, 22 percent by oak and hickory forest, and 9 percent by grassland. Schoolcraft soils, the only mollisol, were mainly covered by the grassland (67 percent). Ockley soils were covered by the most hardwood forest, at nearly 76 percent of its area. Kalamazoo and Dowagiac soils were primarily covered by mixed oak savanna at 40 percent and 50 percent, respectively.

The same methods were used for evaluating current land use. A 2006 land use–land cover data set (National Oceanic and Atmospheric Administration Coastal Services Center 2008) was clipped to the boundaries of the study area, and the various land use categories associated with each soil were determined. Across the entire study area, as of 2006, 50 percent of the total land area was farmed to row crop agriculture. The soils account for 69 percent of the total row crop acreage here and support some of the region's most productive agriculture. Based on NRCS crop yield data from county soil surveys, the high productivity of the four soils under study was confirmed. Schoolcraft soils had the highest projected crop yields for all of the well-drained soils analyzed. Kalamazoo soils are the second largest bulk producer of all commodities within the study area, despite yields for many crops that are not exceptional, due in large part to their expansive acreage. Because the loamy-textured soils on broad outwash plains in this region are clear agricultural assets, identifying the source of the loamy material and its spatial variation could have wide economic implications.

Methods

Field Methods

Using a GIS, digital NRCS soil survey data were examined to find potential sampling areas. Soils data were overlain onto a hill-shaded digital elevation model (DEM) to better visualize broad, flat uplands with Kalamazoo, Schoolcraft, Dowagiac, and Ockley soils. Areas with Oshtemo soils near any of the other four soil types were also considered for sampling. Although sampling priority was given to woodlands, which are less disturbed than agricultural fields, most of our samples were in agricultural fields, as the soil types under study are agriculturally productive (Table 1, Figure 1). At each potential sample area, we identified a specific target point for sampling, usually near a road but usually also on the flattest, most centrally located section of the target area. Navigation to the target points was done using a laptop equipped

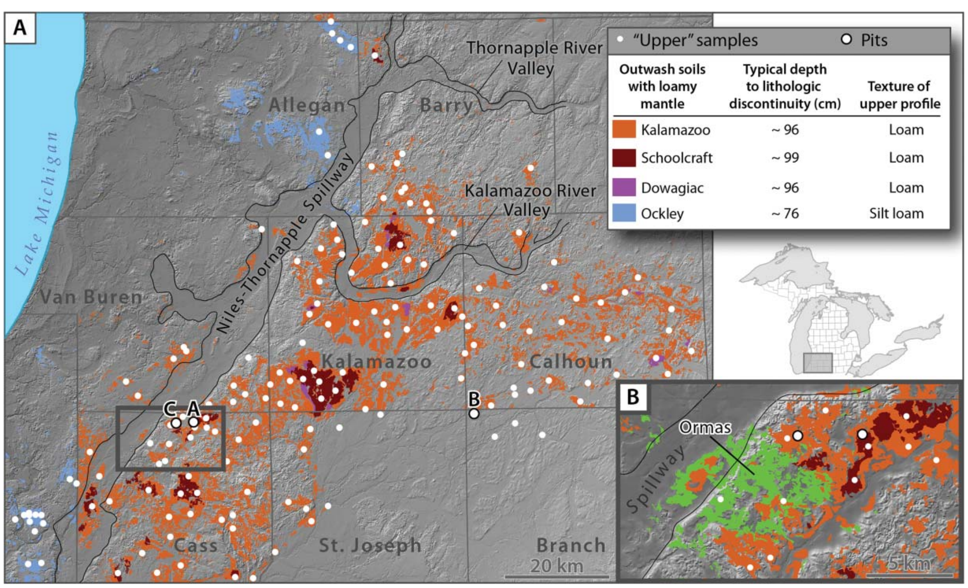

Figure 5. The major soil series of outwash plains in the study area, set on a hillshade base. The inset map (A) is shown enlarged in (B), which also illustrates the extent of Ormas soils. (Color figure available online.)

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with a built-in Global Positioning System (GPS) unit. At each point, we inspected the soil gathered with a bucket auger to determine whether it met the criteria for one of the four soil series. If the criteria were met in the hand-sample, the approximate thickness of the loamy mantle was determined and ≈500 g of soil was collected for further analysis. Our goal was to collect sediment that was representative of the entire column of upper loamy material but no closer than 15 to 20 cm from the underlying lithologic discontinuity. We did this by taking subsamples throughout the upper sediment, as we were augering through it, and combining them into one sample for the site. In all, loamy upper profile material was sampled at 167 sites (Figure 5). In addition, at forty-nine of those sites, distributed uniformly across the study area, a deep sample of the underlying outwash was taken to allow for textural comparisons between the upper loamy material and outwash. Material within 15 to 20 cm of the overlying lithologic discontinuity was avoided during sampling of the outwash, due to potential mixing. We termed the samples of the upper, loamy material *uppers* and the outwash samples *lowers*.

Three pits, each approximately 2 m deep, were also excavated by backhoe in representative Kalamazoo map units and described according to Schoeneberger et al. (2012). Samples were taken from a cleaned pit face every 10 cm for the first 100 cm depth and every 20 cm thereafter to the base of the pit.

We also sampled sites composed of till, as these could have been eroded during deglaciation and thus served as a silt source for local meltwater valleys (Figure 3). The general extent of the area sampled for till was initially delineated using the Watershed tool in ArcMap's Hydrology tool set, based on a statewide, 10-m-resolution DEM (Gesch et al. 2002; Gesch 2007). To start, we digitized two lines, one within the Kalamazoo River valley and the other in the Thornapple River valley. These lines functioned as pour points and were the reference for the Watershed tool to calculate areas that presently drain to them. Most of the sample sites were selected from within the watersheds, as outlined in ArcMap (ESRI 2014e). We sampled till at seventy-eight sites by augering until reaching calcareous material, from which the sample was taken (Figure 3).

Lab and Data Analysis

All samples (upper loamy sediment, outwash, and till) were air dried and lightly ground before being passed through a 2-mm sieve. To achieve complete homogenization before laser diffractometry, ground and sieved samples were run through a sample splitter three times. Diffractometry pretreatment involved shaking subsamples for two hours in a water-based solution of $(NaPO_3)_{13}{\cdot}Na_2O$. Dispersed samples were then analyzed on a Malvern Mastersizer 2000E laser particle-size analyzer. Particle-size data (105 bins, or particle-size subsets) were exported into Microsoft Excel and graphed as continuous, particle-size distribution plots, which we call textural curves (Luehmann et al. 2013; Schaetzl and Luehmann 2013). Bin data were then grouped into more traditional particle-size classes—for example, very fine sand, silt, very coarse silt, and so on—in Excel.

Because of the textural variation that occurs within the sample bags and because laser diffractometry uses such small samples for analysis, we ran the till and upper samples twice and then used a mean value in subsequent analyses. First, however, a quality control (QC) method was applied. This method compares each pair of sample data with precision standards initially established by Miller and Schaetzl (2012) and recently updated. QC analyses indicated which samples required further particle-size analysis; that is, until the sample mean value was statistically sufficient to represent the entire sample.

Using the mean data, a filtering method developed by Luehmann et al. (2013) was used to adjust or filter the data for the upper samples. These data consistently had a primary silt mode and a secondary, sand-dominated mode. The algorithm of Luehmann et al. (2013) runs in Excel. It filters textural data with two clear textural peaks by removing the sand data, thereby recovering the data for the original silty sediment from the previously mixed sediment. The remaining data, termed *filtered data*, were adjusted using an algorithm in Excel, to ensure a sum of 100 percent. Theoretically, filtered data are representative of the original characteristics of the silt-rich sample.

Samples from the upper material did not contain any very coarse sand (VCS), but outwash and till samples often did, and the laser diffractometer used in this study does not measure this particle-size fraction. Therefore, after diffractometry analyses, the remaining outwash and till samples were passed through a 1-mm sieve to determine the VCS content. The data for the remaining particle-size fractions, initially output from the laser diffractometer, were then adjusted accordingly, to sum to 100 percent.

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GIS Methods: Cluster and Outlier Analysis

Soils, especially if they have been affected by slope or mixing processes, often display considerable variability over relatively short distances, potentially causing data from irregular sample points to interrupt any overarching spatial trend(s). To identify such outliers, we used ESRI's Cluster and Outlier Analysis (Anselin local Moran's *I*); this method can identify statistically significant high-value clusters, low-value clusters, and spatial outliers, compared to surrounding sample points (ESRI 2014a). We used inverse distance conceptualization of spatial relationships, ensuring that the neighboring features would have the greatest influence on the generated statistics (ESRI 2014a). The analysis was performed across a comprehensive suite of soil particle-size derivatives and soil characteristics. From our initial 167 sample data set, only three points, which were statistical outliers more than half of the time, were discarded from subsequent analyses, resulting in a final sample data set of 164.

GIS Methods: Kriging

We used simple kriging on the 164 upper samples to examine patterns across the study area (ESRI 2014b). This method allows for a set of sample points to be interpolated into a continuous field of data, suitable for visual interpretation; it has been used successfully for examining the distributions of loess (Scull and Schaetzl 2011; Stanley and Schaetzl 2011; Schaetzl and Attig 2013). Variables selected for analysis, from among a list that included loess thickness, sorting, mode, and a number of standard textural classes and ratios, were chosen by evaluating a Pearson correlation matrix, particle-size distributions, and spatial clustering of points. Inverse distance weighting (IDW) was also used as a preliminary data exploration method for visualizing spatial distributions. The resulting interpolated data were overlain and masked using the NRCS soil grid to depict data where the soils under study are mapped.

GIS Methods: Grouping Analysis

To this same set of upper samples, we applied ESRI's (2014c) Grouping Analysis Tool, using ArcMap 10.2. This tool uses the SKATER algorithm (Assuncao et al. 2006) to classify sample points into a specified number of groups based on attributes, input parameters, and spatial constraints. We chose this autoclassification tool because it can identify natural clusters within the sample data, some of which might lend insight into the eolian systems possibly responsible for deposition of the silty material. Because spatial heterogeneity can be observed among sample points for a large number of variables, and their patterns also vary, this tool allowed us to examine multiple variables at the same time and helped identify discriminators (ESRI 2014c).

As introduced earlier, we grouped the 105 bins of particle-size data into several traditional particle-size classes, and we also calculated some ratios of values for different particle-size classes. In this grouping analysis, we called each of the particle-size classes and ratios a variable. Important variables were selected and formed a variable group; we called each group of this kind a combination of variables. We used three different combinations for grouping analysis. Variables and ratios were chosen that, when examined spatially, helped identify sediment as loess. Iteratively, the optimal number of groups was determined by maximizing grouping effectiveness, as measured with the Calinski–Harabasz pseudo F-statistic (ESRI 2014c). Groups of two points or less were not allowed. We used eight nearest neighbors as spatial constraints for all three grouping analyses. ArcMap generates a report for each grouping process, which provided box plots that further facilitated our interpretations.

Results and Discussion

Origin of the Upper, Loamy Material

Large, sandy outwash plains and broad meltwater channels occur across much of southwestern Michigan (Figures 1 and 5). On many of these surfaces, the soils are sandy throughout the profile, and especially at depth. Spinks (sandy, mixed, mesic Lamellic Hapludalfs) is but one example of a soil series common to the region, which has formed entirely in sandy sediment, usually outwash. Spinks's textures range from loamy sand at the surface to fine sand at depth. Other prominent soils on Michigan's outwash plain surfaces, like Oshtemo (coarse-loamy, mixed, active, mesic Typic Hapludalfs) and Rubicon (sandy, mixed, frigid Entic Haplorthods), remain sandy but become noticeably finer in the upper profile (Barrett and Schaetzl 1992; Schaetzl, Mikesell, and Velbel 2006). Some "outwash soils" like these even have a pronounced argillic (Bt) horizon, suggestive of parent materials containing considerable amounts of silt and clay. In southwestern Michigan, soils within the Kalamazoo and Schoolcraft (and related) series become progressively finer in their upper profiles. Typical textures for these soils are loam, silt loam, and clay loam in the A and upper B horizons, with sandy loam, loamy sand, and coarse sand textures in the C horizon.

Soils developing in uniform, outwash parent materials should also be sandy throughout. The loamy textures of the upper profiles of so many soils on the outwash plains of southwestern Michigan suggest that these landscapes are not formed entirely in outwash. Indeed, the genetic origin of the upper material in many of these soils has been enigmatic for decades. The OSD for Schoolcraft soils lists them as having formed in "loamy material over sand or gravelly sand on outwash plains, terraces, and valley trains," whereas the description for Kalamazoo soils invokes "loamy outwash overlying sand, loamy sand, or sand and gravel outwash on outwash plains, terraces, valley trains, and low lying moraines." The generic description of "loamy material" or "loamy outwash" implies that NRCS personnel who first described these soils did not know the specific origin of this upper material, prompting this research. We hypothesized that the loamy material in the upper profiles of many of the major outwash soils of southwestern Michigan is loess, mixed with sand from below.

Where found in thick deposits, loess is normally well-sorted and silt-dominated (Ruhe 1984; Leigh and Knox 1994; Bettis et al. 2003; Luehmann et al. 2013). The often well-sorted nature of loess leads to textures that, when plotted as a continuous curve or distribution from 0 to 2 mm, display a strong, unimodal distribution of particle sizes, with a peak in the silt fraction. Loess very near the source area (i.e., proximal loess) can peak in the very fine sand fraction, but it still is unimodal (Schaetzl and Attig 2013). Where loess is thin, however, it can be mixed with the underlying sediment, forming a bimodal distribution of particle sizes (Schaetzl and Luehmann 2013) and an overall texture that reflects the mixed sediment.

Textural and morphologic data from three soil pits were first used to evaluate our hypothesis of loessial additions to many of the sandy outwash soils of southwestern Michigan. Figure 6 and Table 2 provide data for two of our three soil pits, A and B, both on broad outwash plain landscapes and mapped within the Kalamazoo series. (Data for pit C are similar but are not shown to save space.) In Pit A, the sandy outwash at depth has a mean mode of 502 μm (coarse sand), whereas in Pit B, the mode for the outwash is 396 μm (medium sand). These particle-size peaks continue up-profile, into the loamy material. Here, they remain relatively unchanged in modal value for several tens of centimeters (Figure 6), although their intensity declines toward the surface. In Pit A, the sand peak declines so rapidly that it is barely visible in the upper 20 cm; the upper horizons here have silt loam textures (Table 1). In the upper profile of Pit B, the sand peak in the upper loamy material remains strong, even at the surface, where the texture is loam. The sand peaks in the upper profile of Pit A have an average modal value of 393 μm, whereas in Pit B, these

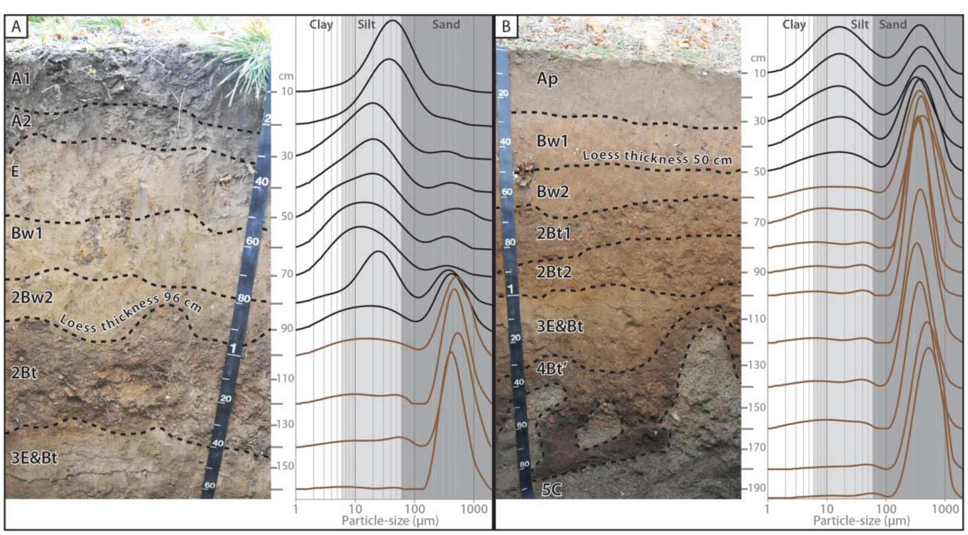

Figure 6. Photos, with horizon boundaries marked, and textural curves for two of the three soil profiles (A and B; see Figure 4) excavated in Kalamazoo soils. (Color figure available online.)

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Table 2. Profile descriptions for two Kalamazoo pedons

Horizon	Depth (cm)	Color (moist)	Texture (est. percentage gravel)	Structure[a]	Consistency (moist)	Boundary[b]
Pit A — 7.0 km SE of Decatur (42° 2′ 57″ N. Lat, 85° 56′ 40″ W. Long.)						
A1	0–23	10YR 2/1	Silt loam (0)	Mod, fine & med, gr	Friable	Gr, sm
A2	23–32	10YR 3/2	Silt loam (0)	Wk, fine & med, sbk	Friable	Gr, sm
E	32–54	10YR 4/3	Silt loam (0)	Mod, med, sbk, parting to mod, med, platy	Friable	Cl, sm
Bw1	54–79	10YR 4/6	Silt loam (0)	Str, med, sbk	Firm	Gr, sm
2Bw2	79–96	10YR 4/4	Sandy loam (4)	Str, med & crs, sbk	Friable	Cl, sm
2Bt	96–142	7.5YR 3/4	Loamy coarse sand (15)	Wk, crs, sbk	V friable	Cl, sm
3E&Bt	142–195+	10YR 5/4	Sand (2)	Single grained	Loose	
Pit B — 4.3 km SW of Athens (42° 3′ 44″ N. Lat, 85° 16′ 30″ W. Long.)						
Ap	0–33	10YR 3/2	Loam (2)	Mod, med & crs, sbk	Friable	Ab, sm
Bw1	33–55	7.5YR 4/3	Sandy loam (2)	Mod, med & crs, sbk	Friable	Gr, sm
Bw2	55–72	7.5YR 4/4	Loamy sand (4)	Mod, med & crs, sbk	Friable	Cl, sm
2Bt1	72–85	5YR 3/3	Sand (6)	Mod-wk, fine & med, sbk	V friable	Gr, sm
2Bt2	85–100	7.5YR 3/4	Sand (10)	Wk, fine & med, sbk	V friable	Cl, sm
3E&Bt	100–135	10YR 4/4 (E) 5YR 3/3 (Bt)	Sand (6)	Wk, fine & med, sbk	V friable	Gr, irr
4Bt'	135–188	7.5YR 4/3 (matrix) 5YR 3/2 (gravelly areas)	Sand (12)	Wk, fine & med, sbk	V friable	Cl, brok
5C	188–215+	10YR 5/3	Coarse sand (18)	Single grained	Loose	—

[a]Structure abbreviations: wk = weak; mod = moderate; str = strong; med = medium; crs = coarse; gr = granular; sbk = subangular blocky.
[b]Boundary abbreviations: gr = gradual; cl = clear; ab = abrupt; sm = smooth; irr = irregular; brok = broken.

peaks average 379 μm (Figure 6). Together, these data suggest that sand from the outwash has been mixed into the upper profile but that (1) finer sands are preferentially mixed upward, because the sand modes are slightly smaller in the upper profile and (2) the amount of mixed sand diminishes up-profile, such that the surface horizons almost always have the least sand.

Textural, primarily silt, data from the upper profile of the two soil pits support our hypothesis of loess additions to the outwash surface, which were then subsequently modified by pedoturbation (Figure 6). At Pit A, the primary particle-size peaks in the upper profile are in the silt fraction, averaging 23 μm. Equivalent data for Pit B modes average 16 μm—fine silt. In both pits, these peaks continue down-profile as weak, broad plateaus into the upper parts of the outwash below. This pattern suggests that mixing across the lithologic discontinuity has occurred in these soils, but that (perhaps) pedoturbation has been more effective at mixing sand up and into the upper material than in mixing silt downward into the outwash. Some sand, of similar textural characteristics as that in the outwash, could also have been deposited by wind, with the loess, especially earlier in the loess depositional interval. Two different types of textural data support these hypotheses: (1) sand contributions continue well upward, above the lithologic discontinuity, into the upper profile, which is mainly silty and (2) only small amounts of silt occur in the sandy outwash and, even then, they quickly dissipate with depth (Figure 6). The data show the blurred contact between the two parent materials in these two-storied soils (Schaetzl 1998). Sand mixed with thin loess has clouded the historical interpretations of such materials (Schaetzl 2008; Schaetzl and Hook 2008).

Bioturbation, especially by soil infauna, is the most likely form of pedoturbation that was and is operative here. Insects such as ants and beetles and arthropods (e.g., centipedes and millipedes) are all likely to have been vectors for this type of mixing. Although a recent invader to the area, earthworms would have also been an important bioturbator. In the deep, rich, loamy soils of these outwash plain landscapes, soil faunal populations would have been high, and the deep water tables would have allowed for deep burrowing.

The most likely origin of a silty mantle in a glaciated landscape such as this one is eolian that is, as loess. Similar data for sand mixed into a thin loess

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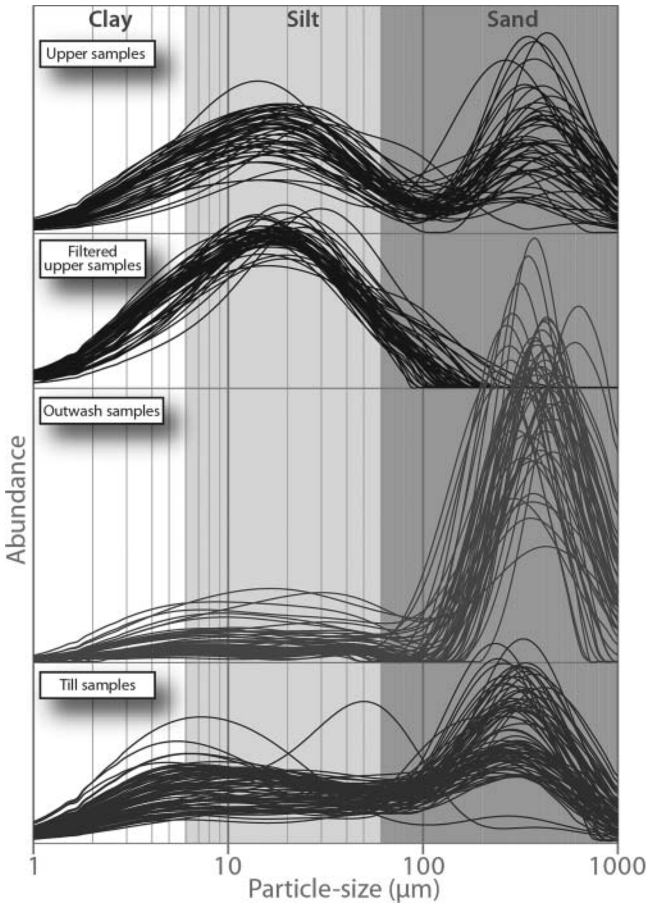

Figure 7. Particle-size curves for the various samples taken in this study. Shown are the 164 upper loamy material samples, before and after the filtering process; the forty-nine outwash samples; and the seventy-eight till samples.

mantle were provided by Schaetzl and Luehmann (2013) for soils in Michigan's Upper Peninsula. Indeed, after outwash plains have lost their meltwater source and dried up, they are optimal locations for preservation of silty eolian sediment. The flat, permeable substrate minimizes runoff and erosion, facilitating the retention of eolian sediment (Schaetzl and Hook 2008).

As expected, data for the outwash, compiled from samples taken at 49 of the 164 sites, confirm that the lower material at these sites is coarse-textured glaciofluvial sediment (Figures 7 and 8). Textural curves for these samples show strong sand peaks. Almost 51 percent of the samples had coarse sand or loamy coarse sand textures, whereas 24 percent were sand textured. Most of the outwash samples exhibited only a small silt peak (Figure 7), probably due to (1) mixing of silt from the overlying sediment or (2) incomplete sorting by the glacial meltwater. Silt contents ranged from 1.9 to 59.4 percent, although the median silt content (6.8 percent) value is a better reflection of the sandy character of the outwash. Unquestionably, the outwash textures would be even more sand-rich, had we been able to auger more deeply; many of our deep sampling attempts were stopped by large clasts. In these instances, our sample might have been taken too close to the lithologic discontinuity, and silt from the upper material might have been mixed into it.

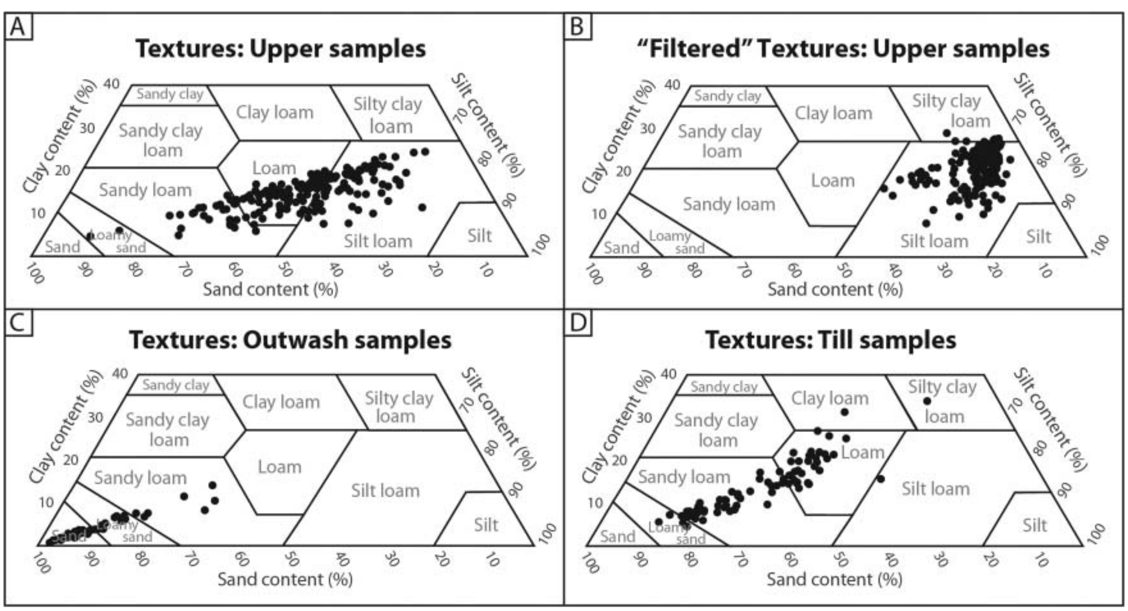

Figure 8. Textural data, set within a standard U.S. Department of Agriculture textural triangle, for the upper, lower (outwash), and till samples, including filtered data for the upper, loamy sediment.

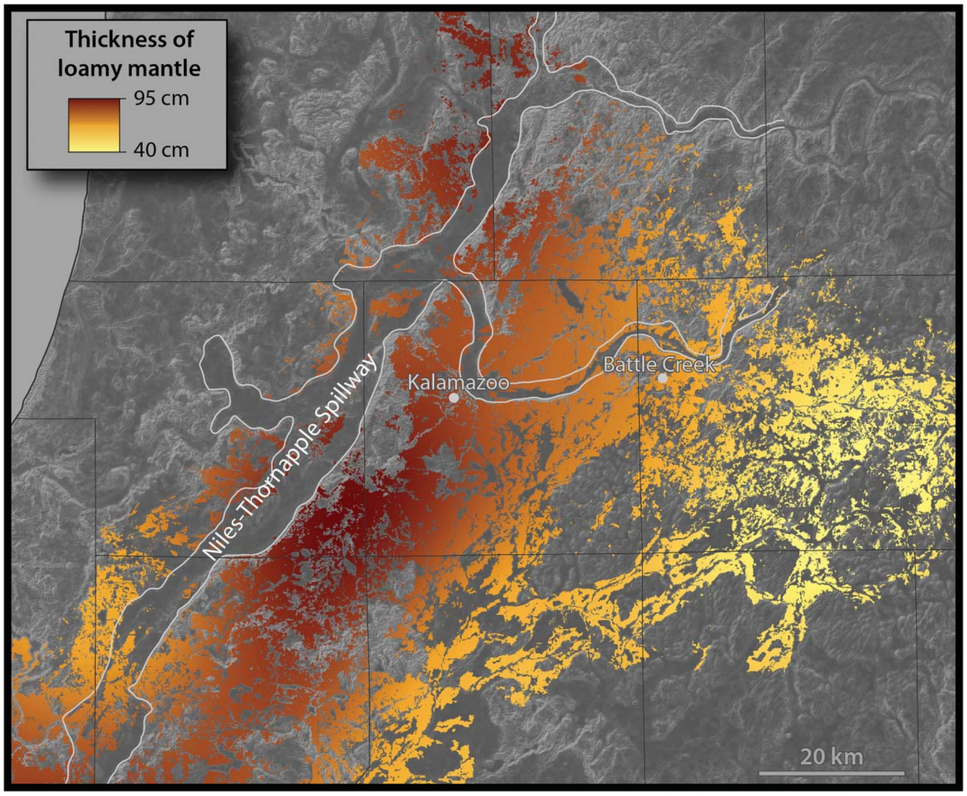

Figure 9. Interpolated, kriged map of the thickness of the upper sediment, which we interpret as loess, across southwestern Michigan. Interpolated data are shown only in areas where one of the four target soils are mapped or where two additional outwash soils (Fox and Oshtemo) are mapped. (Color figure available online.)

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Loess within the Study Area: Textural Characteristics

Operating on the assumption that the upper, loamy material on southwestern Michigan's outwash plains is loess, we examined data from the 164 upper samples to ascertain its spatiotextural characteristics. Downcatena versions of these soils were not sampled; in the field we often could not rule out alluvial or slopewash additions in their typical slope positions; that is, on footslopes and in lowlands.

The texture of most of the upper, loamy material in the 164 upper samples is usually silt loam (43 percent) or loam (41 percent; Figure 8). Other samples were sandy loam, loamy sand, or fine sandy loam in texture. Without exception, the upper samples had clear, bimodal particle-size distributions, just as in the soil pits (Figures 6 and 7). Thus, we felt confident in concluding that loess mantles most of the flat outwash surfaces of the study area, at least where our four target soils are mapped (Figure 5). On sloping sites, such as on slightly pitted or incised outwash plains, the upper loamy material was often quite thin or nonexistent, leading to sandier textures near the surface. We attribute this situation to a thinner initial loess mantle, perhaps due to frozen, permafrost conditions during the depositional period, which likely facilitated runoff (Schaetzl 2008). In addition, sloping sites would have been more susceptible to geologic erosion. We have also noted that many soils mapped as Oshtemo (a sandier version of Kalamazoo) on outwash plains in the far southeast part of the study area are sandy loam at the surface; we interpret these textures also to thinner initial loess mantles. Postdepositional mixing has diluted the silty sediment, such that textures of the upper profile are not as loamy as in Kalamazoo or Schoolcraft soils.

Loess within the Study Area: Spatial Characteristics

Loess (actually, the loamy mantle) is thickest along the western side of the study area, near the eastern margin of the Niles-Thornapple Spillway, a prominent outwash channel previously studied by Kehew et al. (2005). This sluiceway carried glacial meltwater derived from the Saginaw lobe and probably also the Huron–Erie lobe. The spillway was likely active for approximately 500 years, starting just prior to when the ice margin was at the Valparaiso–Charlotte

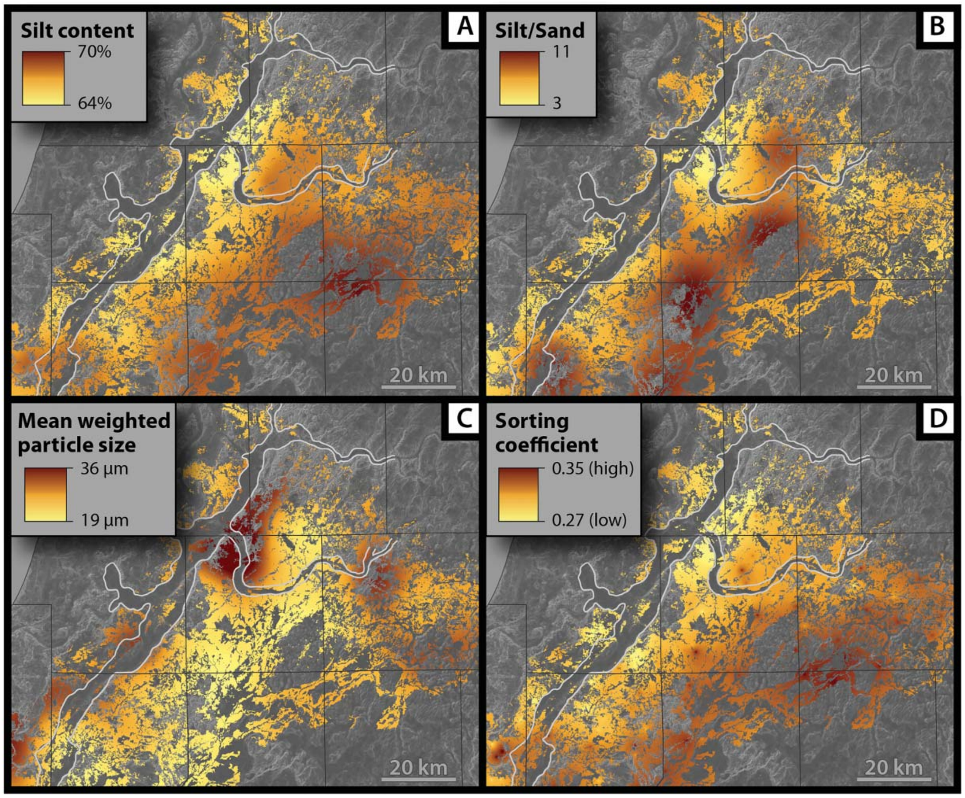

Figure 10. Interpolated, kriged map of various kinds of textural data (filtered) for the upper sediment, which we interpret as loess, across southwestern Michigan. Mapping follows that in Figure 9. (Color figure available online.)

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moraine, about 17.1 ka ago. Loess, thickest just east of the central reach of the spillway, thins to the east and is particularly thin along the far eastern margins of the study area. Our kriged interpolation of thickness data for the upper material (Figure 9) should be interpreted as maximal loess thickness, because the data are derived from sites where erosion would have been minimal. Very little loess appears to be present west of the spillway, even though flat, sandy landscapes also occur here (Figure 3). These data suggest that this spillway was a likely source for the loess and that loess transport was via predominantly westerly winds.

Filtered, textural data (Figure 7) add additional support for the Niles-Thornapple Spillway as the source for this loess (Figures 2 and 4). Recall that the upper samples are composed of a mix of two different types of sediment, necessitating the application of Luehmann et al.' s (2013) filtering algorithm to the textural data, to more accurately estimate the original textural attributes of the loess (Figure 7). This method has been shown to work effectively for mixed samples of this type (Schaetzl and Attig 2013; Schaetzl, Forman, and Attig 2014).

Loess normally exhibits very predictable spatial patterns with respect to thickness and texture, mainly due to the strong sorting capabilities of the eolian system (Fehrenbacher et al. 1965; Rutledge et al. 1975; Mason, Nater, and Hobbs 1994; Mason 2001; Roberts et al. 2003; Wang, Mason, and Balsam 2006; Schaetzl and Attig 2013). Loess normally gets thinner and finer in texture with distance from the source, largely due to diminishing amounts of fine and very fine sand, leading to correspondingly increasing amounts of silt. Near the spillway, the loess is sandier and has lower silt/sand ratios (Figure 10). Mean weighted particle size (MWPS) data also show local highs near the spillway (Figure 10C). The MWPS of the loess also becomes progressively smaller to the east, although in the far eastern margins on the study area, values again rise. We attribute this slight increase to loess generated (at least partially) from local sources, perhaps off the southeast Michigan interlobate region, which would have been rich in buried ice and, hence, unstable ground at this time. Finally, we note that the loess closest to the spillway is less sorted, as indicated by the Trask sorting coefficient (So; Trask 1932; Figure 10D). Well-sorted sediments have So values < 2.5, whereas poorly sorted deposits have So values > 4.0 (Krumbein and Sloss 1963). The data for the loess indicate its highly sorted

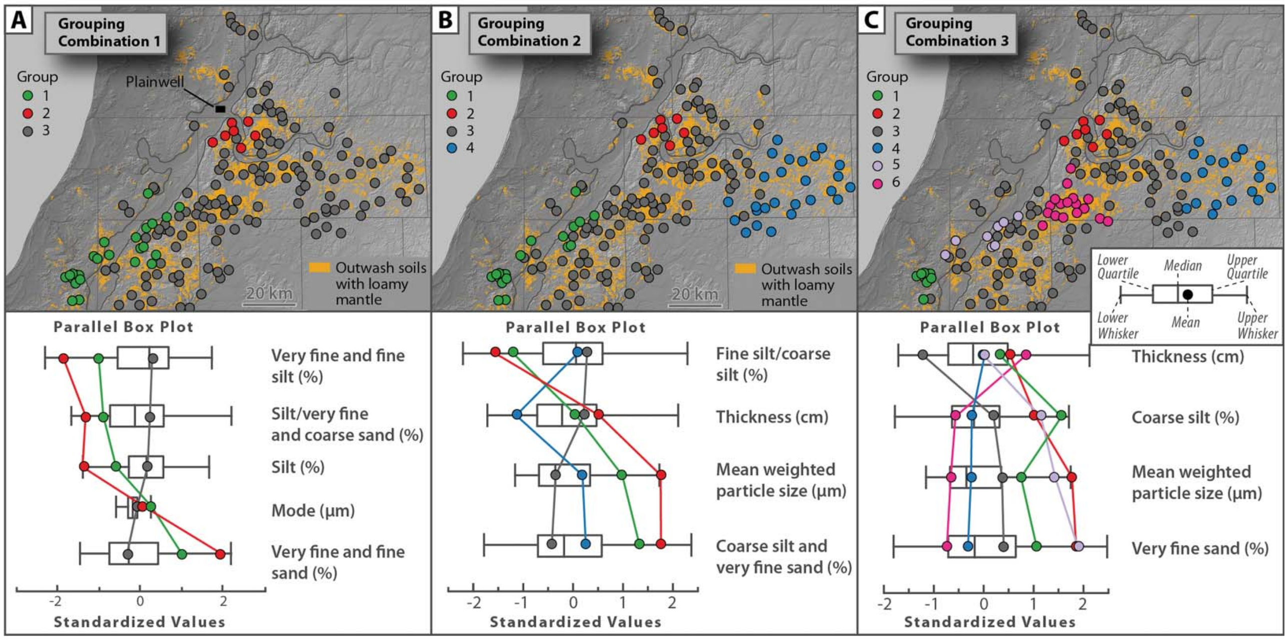

Figure 11. Maps and box plots for three different grouping combinations, applied to data for the upper samples, which we interpret as loess. (Color figure available online.)

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nature, but it becomes less well sorted nearer the spillway. Additional data, not shown here for brevity, show similar textural patterns—a coarser, sandier sediment near the spillway that gets progressively siltier and finer in texture to the east.

Field work uncovered another soil—Ormas (loamy, mixed, active, mesic Arenic Hapludalfs)—that dominates the uplands just east of the central reach of the spillway; it is rarely found in other parts of the study area. Ormas soils have loamy sand textures in their upper profile and are underlain by gravelly, sandy sediment. We interpret this soil as a thick, coarse, poorly sorted end member to the loess deposit. Ormas soils start at the spillway and continue to the east, merging into Kalamazoo map units as the loamy sand sediment grades into siltier and less sandy sediment, while also becoming better sorted. These data also suggest that some of the sand in the loamy mantle, farther from the spillway, may have been deposited there on strong winds, along with the loess. Sediment that comprises the parent material for Ormas soils resembles the cover sands of Europe (Vanmaercke-Gottigny 1981; Kasse 2002), which also grade into siltier deposits of loess in the presumed downwind direction.

We applied the grouping algorithm in ArcMap to the filtered upper data (Figure 7) to further interpret its spatiotextural attributes and to determine if any natural loess groups exist (Figure 11). To our knowledge, our study represents the first such application of this geographic tool to loess data. We chose variables for this analysis that, based on our understanding of eolian systems, should vary spatially and predictably across the study area, as across any loess deposit of this size.

The first combination of variables produced two small groups amidst a large "background" of upper samples (Figure 11A). These two groups were located (1) at the junction of the Kalamazoo River valley with the Niles-Thornapple Spillway and (2) along the spillway, nearer its southern reaches. Box plot data show that both of these groups have low values for very fine sand content, silt/sand ratio, and silt content, while also having high values for very fine and fine sand. Together, they suggest that these two areas of the spillway were particularly prodigious sites for the generation of coarse eolian sediment. Loess at the former site (the Kalamazoo–Niles–Thornapple junction, or K–N–T) is particularly noteworthy for its large mean particle size (Figure 11A). We are unable to explain why these two areas have unique loess characteristics, but it seems reasonable that the loess derived from them is sufficiently different as to justify singling it out. The K–N–T junction, being an area where two large spillways merge, provides more "source area" per unit area than any other location within the study area.

The second grouping combination used different variables but nonetheless still identified two groups in the same two areas, plus an additional group focused

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on the eastern margin of the study area (Figure 11B). Once again, the first two groups sort out on variables that are typically and predictably high (coarse silt and very fine sand content, and MWPS) or low (fine/coarse silt ratio) near loess source areas. The new third group has low values for loess thickness; loess is thin near the eastern margins of the study area (Figure 11B). This threefold grouping is a logical way to separate the upper data—two groups associated with coarse loess near the source area and a third group that is far from the source, where the loess is thin and better sorted. Loess in this eastern region falls near the median values for most of the textural variables (Figure 11B). Some of this loess might be associated with flow-through meltwater channels coming off the Huron-Erie lobe, which surged into the southeastern part of this region late, supplying meltwater to a number of small channels that flowed across it.

Finally, our third grouping effort roughly identified these same three groups but split one of them up and added another, yielding five total groups (Figure 11C). The group of sites near the southern end of the spillway was split by the grouping algorithm into two smaller groups. The more southerly group is entirely west of the spillway, on a landform that might be a delta on a proglacial lake that once existed in the southern end of the spillway. If so, this loess might have been deposited slightly later, and on a topographically higher surface. Loess here is very high in coarse silt, whereas sites farther up the valley that were previously in the same group have more very fine sand. The new group identified by using this set of variables is located east of the spillway and east of the Ormas soils discussed earlier, in an area dominated by the Schoolcraft series. Schoolcraft soils are mollisols, and in this area are normally associated with prairies at the time of European settlement. Michigan's largest prairie, the Schoolcraft Prairie, is located in the heart of this group (Figures 5 and 11C). This area has some of the thickest loess in the region, and because it is also associated with mollisols, it also supports some of the most intensive, productive, large-scale cash grain operations in the state. Loess here is also texturally quite fine, further enhancing its utility for crop production because of its excellent water-holding capacities. Loess might be more fine-textured here simply because of location; it is equidistant from the two main generators of coarse-textured eolian sediment to its north and south, along the spillway, but far from the local sources of loess that likely have affected sites farther east. The Schoolcraft Prairie is also an exceptionally flat area, which perhaps might have facilitated the retention of the finer loess particles.

Paleoenvironments of Loess Deposition

Across the Midwestern United States, glacial sluiceways and outwash valleys have long been known as prodigious loess sources (Fehrenbacher et al. 1965; Rutledge et al. 1975; Ruhe 1984; Bettis et al. 2003; Jacobs, Mason, and Hanson 2011; Schaetzl, Forman, and Attig 2014). Worldwide, similar conclusions can be drawn: Meltwater rivers and valleys are often excellent sources of silt-rich alluvium that is a potential loess source (Smalley 1972; Buggle et al. 2008; Antoine et al. 2009; Marković et al. 2009; Lefort, Danukalova, and Monnier 2011). Despite the fact that many of these meltwater valleys are, today, greatly changed in character and flow regime, if they carried meltwater during glacial times they were likely to have been loess sources (Badura, Jary, and Smalley 2013).

The Niles-Thornapple Spillway is unlike most of these other Midwestern outwash spillways, such as the Mississippi, Missouri, and Wabash Rivers, because it no longer contains a large, through-flowing river. Instead, the spillway today is a broad, sandy lowland with wet soils; no river flows along its entire length (Figure 4). Nonetheless, as the Lake Michigan lobe withdrew from the Kalamazoo moraine, its meltwater flowed down the spillway. Although less certain, the spillway also likely drained much of the Saginaw lobe terrain during the Kalamazoo–Charlotte transition (Figure 2). Much of the meltwater that flowed south through the spillway was trapped between the Lake Michigan lobe ice margin and the ice-contact face of the Inner Kalamazoo moraine to the east. The moraine here is largely a head of outwash, with a steep, high proximal slope associated with the former ice-contact face. Sandy sediment in this area would have enabled easy erosion of the valley walls, facilitating valley widening. The spillway ranges in width from 2.5 km to as wide as 9 km (Figures 3 and 4).

The spillway could have carried meltwater for approximately 500 years, from ca. 17,300 cal. years ago, when the ice first began to retreat from the Inner Kalamazoo margin, to ca. 16,800 cal. years ago, when the ice margin was at the Inner Valparaiso margin. Stone et al. (2003) and Kehew et al. (2005) provided clear evidence for a deep proglacial lake in the southern end of the spillway, perhaps preceding the free flow of meltwater. Interestingly, Group 4 samples (Figure 11, green) from the third grouping combination are all associated with loess that mantles a possible delta, likely formed in a proglacial lake. Loess could only have been deposited here after the lake had drained,

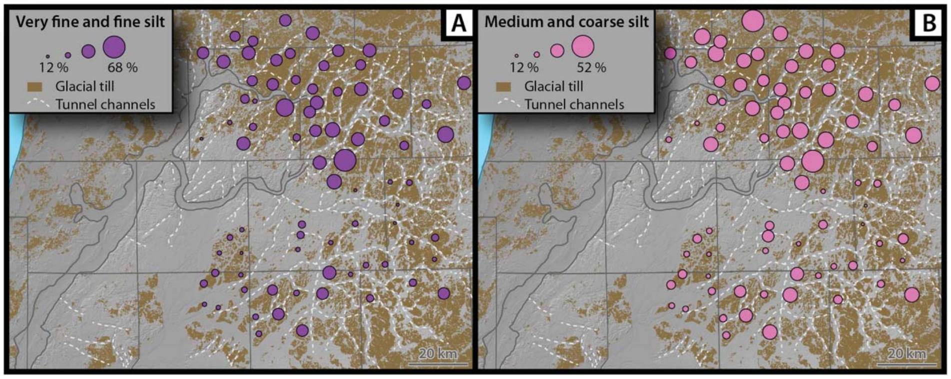

Figure 12. Graduated circle maps of the silt contents of the till samples acquired across the study area. (Color figure available online.)

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which presumably coincides with the opening up of the channel to free-flowing meltwater. Retreat from the Inner Valparaiso margin would have allowed meltwater to follow other routes, leaving the spillway dry. Kozlowski, Kehew, and Bird (2005) provided evidence that the spillway (at least downstream from Plainwell) was eventually opened and then scoured by one or more outburst floods from the Saginaw lobe. These floods would presumably have been connected upstream to the Kalamazoo and (possibly) Thornapple valleys.

The two main meltwater tributaries at the upper end of the spillway, the Kalamazoo and Thornapple rivers, both have overwidened valleys and flow today in them as underfit streams. These valleys, in turn, variously connect upstream to an impressive network of tunnel channel valleys, all within Saginaw lobe terrain (Fisher, Jol, and Boudreau 2005; Kehew et al. 2005; Kozlowski, Kehew, and Bird 2005; Figure 2). Most of these valleys are flat-floored and wide and display evidence of stagnation, such as eskers and kames. Importantly, the tunnel channels were eroding into loamy Saginaw lobe till, implying that the meltwater would have been silt-rich. Till from the northern and eastern parts of the study area that, through the tunnel channel network, hydrologically "connect" to the spillway, average 31 percent silt (Figure 12). Most of this silt is in the fine and very fine silt fractions, much like the silt in the loess (Figure 7). We argue that the Saginaw lobe tills were rich enough in silt, especially in the area that drained to the spillway, to have enabled the spillway to be a silt source as well.

We contend that the loess in southwestern Michigan exists because of a unique set of circumstances, many of which are due simply to favorable paleogeography. Widespread stagnation of the Saginaw lobe combined with a favorable ice margin geography, such that silt-rich meltwater could be funneled down one main, north–south trending spillway. This spillway happened to be cut into erodible, sandy sediment (i.e., ice-contact sand and gravel associated with the Kalamazoo head of outwash), facilitating valley widening. The wide valley, coupled with the temporally variable nature of the meltwater, probably led to a braided channel system with areas of subaerially exposed bars. The wide valley allowed wind to deflate silty sediment from within the valley and transport it (mainly) to the east. There, numerous flat, sandy outwash plains existed, most of which were by now abandoned and perhaps even minimally vegetated, enabling them to trap silt for the roughly 500 years that the spillway was active. The amount of loess generated is supported by the work of Kozlowski, Kehew, and Bird (2005), who concluded that multiple flood events might have occurred within the spillway.

Conclusions and Implications

Michigan has no soils that are formed entirely (to > 2 m thickness) in loess. All of the soils in Michigan with loess listed as a parent material are two-storied soils with a thin, silt loam-textured, loess mantle (Schaetzl and Loope 2008; Luehmann et al. 2013; Schaetzl and Attig 2013). For southern Michigan, only a few two-storied soils have OSDs that mention loess as the uppermost parent material. Even these were soils first described by other state surveys and the series concept was later brought to Michigan by NRCS mappers because the series descriptions fit reasonably well. If asked, few would have thought that loess is present here.

Nonetheless, our work has shown that measureable thicknesses of loess exist in southwestern Michigan. Most of this loess was mainly derived from a wide outwash spillway that today does not contain a major river. The spillway carried silt-rich meltwater from the melting Saginaw and Lake Michigan lobes, which converged into one main north–south trending channel. Had meltwater been more widely dispersed across several large outwash plains or into a proglacial lake, loess would not have been generated to the degree observed.

It has been difficult to recognize loess in Michigan's two-storied soils because it is sometimes mixed with sediment from below, blurring the sedimentological contact and changing the texture of the loess from silt loam to coarser textures. Our detailed textural analysis, coupled with our filtering algorithm and spatial approach, allowed us to confirm that the upper sediment is loess and that it has the clear spatial properties typical of silty eolian sediment.

Our work highlights the point that loess-enriched soils might not always be obvious and, thus, might be far more common than is assumed. Indeed, it is likely that most soils in southern Michigan have some amount of loess mixed into their upper profiles. To that end, we argue that geographic analysis of sediments produced by eolian systems can be both highly fruitful and insightful and, in some instances, the best way to understand the eolian system that is responsible for them.

Acknowledgments

This research was conducted as a part of a graduate seminar in Geography at Michigan State University (MSU). We thank the MSU Department of Geography for travel and logistical support. We also thank the several landowners and operators who kindly allowed us access to their land for soil excavation work: Tom Lutz, Dave and Stacey High, and Rob and Laurie Belson. Brad Miller assisted with data analysis and helped ensure that the filtering and QC algorithms were up to date. We also thank Alex Shackleton, who did much of the early, pioneering work on the loess of Berrien County. Reviews of this article by NRCS personnel working in Michigan, particularly Martin Rosek and Matt Bromley, helped strengthen the article and widen its application. We also thank Alan Kehew for reviewing a previous draft of the article and for providing helpful comments. Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement of the U.S. Government.

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Funding

Alex Shackleton's work was supported by grant BCS-0850593 made to Randall Schaetzl by the National Science Foundation (NSF), GSS Program. Any opinions, findings, and conclusions or recommendations expressed are, however, those of the authors and do not necessarily reflect the views of the NSF.

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MICHAEL D. LUEHMANN holds a Geography PhD from Michigan State and is currently a GIS analyst for Atwell, LLC, a land development and environmental consulting firm in Southfield, MI 48076. E-mail: mluehman@gmail.com. His position at Atwell involves cartographic design and analyzing both geologic and cultural information within a GIS environment.

BRAD G. PETER is a graduate student in the Department of Geography at Michigan State University, East Lansing, MI 48823. E-mail: brad.peter@utexas.edu. His research interests include GIS, remote sensing, cartography, and spatiotemporal niche modeling.

CHRISTOPHER B. CONNALLON is a recent graduate of the Master's program in the Department of Geography at Michigan State University, East Lansing, MI 48824. E-mail: connallon@gmail.com. His research interests include surficial geology, geomorphology, and soils.

RANDALL J. SCHAETZL is a Professor in the Department of Geography at Michigan State University, East Lansing, MI 48824. E-mail: soils@msu.edu. His research interests include soils, landforms, and their coevolution throughout the Quaternary.

SAMUEL J. SMIDT is a PhD student in the Department of Geological Sciences at Michigan State University, East Lansing, MI 48824. E-mail: smidtsam@msu.edu. His research interests include water transport, land use, and environmental policy.

WEI LIU is a PhD student in the Department of Geography at Michigan State University, East Lansing, MI 48824. E-mail: liuwei11@msu.edu. Her research interests include spatial analysis, coupled human–environment modeling, and agent-based modeling.

KEVIN A. KINCARE is a Research Geologist for the U.S. Geological Survey at Manistee, MI 49660. E-mail: kkincare@usgs.gov. His research interests include glacial geomorphology and sedimentology of the Great Lakes region.

TONI A. WALKOWIAK is a graduate student in the Department of Geography at Michigan State University, East Lansing, MI 48824. E-mail: walkow14@msu.edu. Her research interests include spatial analysis with an emphasis on human–environmental biomimicry.

ELIN THORLUND is a recent graduate in the Department of Geography at Michigan State University, East Lansing, MI 48824. E-mail: elin.thorlund@gmail.com. Her research interests include sustainability, human–environment interactions, and climate change.

MARIE S. HOLLER is a graduate student in the Department of Urban Planning at the University of Sheffield, Sheffield, South Yorkshire S10 2TN, UK. E-mail: mariesuzanneholler@gmail.com. Her research interests include spatial analysis, GIS, and natural resource management.

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