



Detrital zircon geochronology and provenance of Pleistocene loess and contributing glacial sources, midcontinental USA

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ARTICLE INFO

Article history:

Received 20 May 2021

Received in revised form

17 September 2021

Accepted 19 September 2021

Available online xxx

Handling Editor: Xiaoping Yang

Keywords:

Quaternary

North America

loess

glaciation

detrital zircon geochronology

ABSTRACT

Midcontinental North America contains extensive loess deposits that have been studied with geochemical, mineralogical, and stratigraphic techniques to explore glacial history and sediment provenance. Much of this analysis has focused on loess deposits that accumulated during the last glacial maximum (LGM), in part because of the ubiquity of unweathered Peoria Silt deposits. We test the utility of detrital zircon (DZ) U–Pb dating, which offers a weathering-resistant approach to the determination of loess provenance and can uniquely be applied to both LGM and older (commonly more altered) pre-LGM loess units. We determined DZ U–Pb age distributions ($n = 1385$ U–Pb ages) for the lobes that contributed sediment to Mississippi and Illinois River valley loess: Des Moines Lobe, Superior Lobe, Green Bay Lobe, Lake Michigan Lobe and Huron-Erie Lobe. We also measured DZ U–Pb age distributions ($n = 4466$ U–Pb ages) sampled from loess sites located along the bluffs of the Illinois River Valley and Mississippi River Valley. Samples were collected from Peoria Silt (Wisconsin Episode; Marine Isotope Stage (MIS 2)), Roxana Silt (Wisconsin Episode; MIS 3), Loveland Silt (Illinois Episode; MIS 6), and Crowley's Ridge Silt (pre-Illinois Episode).

LGM glacial tills provide distinct DZ age signatures that can be used to identify glacial source contributions to loess deposits. Loess DZ age signatures in the Peoria Silt of the Illinois River Valley and the Roxana Silt of the northern lower Mississippi River Valley change temporally in a manner consistent with blockage and avulsion of the ancient Mississippi River, representing a proof-of-concept for the DZ loess provenance method in the midcontinent. The loess DZ record also provides insight into the pre-LGM drainage network and glacial lobe extents. DZ signatures for the MIS 3 Roxana Silt, along the Mississippi Valley, implies minimal sediment input from the Des Moines Lobe, suggesting this lobe was short-lived, existed further northward, or provided only limited sediment to meltwater valleys during this time. The dominant Huron-Erie Lobe signature throughout pre-LGM loess units shows that ice flow from the eastern Labrador Dome was a persistent feature during earlier glaciations. Finally, some western-derived DZ ages in pre-MIS 2 loess of the middle and lower Mississippi River Valley suggests that drainage networks that followed the modern Missouri River system were present prior to the LGM and integrated with the Mississippi River system.

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1. Introduction

The glacial loess record has been extensively studied over the

past several decades to understand glaciation and its impact on outwash in midcontinental North America (Aleinikoff et al., 2008; Bettis et al., 2003; Schaetzl et al., 2018). A combination of detailed mapping of loess thickness (e.g., Fehrenbacher et al., 1986; Smith, 1942; Thorp and Smith, 1952), magnetic susceptibility (Grimley et al., 1998), mineralogy (Grimley, 2000; Muhs et al., 2018), elemental geochemistry (Muhs et al., 2018), and geochronology

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(Pigati et al., 2015) have been used to define the timing and sources of contributing meltwater and sediment to downstream river valleys and ultimately the accumulation of thick loess proximal to these valleys. This research has revealed important events and sources of last glacial loess, such as the contributions of specific glacial lobes to loess of the Illinois River Valley, which changed with the diversion of the Mississippi River (Aleinikoff et al., 2008; Grimley, 2000), as well as non-glacial and glacial contributions to loess in central Nebraska and the Missouri River Valley (Aleinikoff et al., 2008). In such studies, loess provenance is typically ascertained with matching or mixing models of bulk sediment mineralogy or geochemistry (i.e., elemental ratios) with those of the hypothesized sources, typically the end moraines of glacial ice lobes or other non-glacial sources. These bulk sediment techniques, even with the additional separation of specific grain size classes (Muhs et al., 2018), naturally average together the contributions of multiple sediment sources. This can be addressed by comparing multiple methods of analysis to achieve an envelope of reasonable source contribution, but specific provenance details remain elusive. Single-grain geochemical analysis, such as DZ U–Pb dating, offers an additional window into the source regions of glacial loess (Schaetzl et al., 2018) that is directly tied to the source bedrock terrain.

DZ U–Pb dating has become a commonly used tool for provenance analysis in a variety of geologic settings (Gehrels et al., 2008). The technique has been successfully deployed in previous loess studies, primarily focused on Asian loess provenance (Gehrels et al., 2011; Stevens et al., 2010). Whereas many minerals and elements are susceptible to weathering, particularly in Plio-Pleistocene and older loess, the provenance signal from DZ U–Pb analysis maintains its fidelity because zircon is resistant to alteration. Furthermore, when sample sizes are sufficiently high (i.e., $n = 300\text{--}1000$), robust statistical analysis can reveal the fractional contribution of individual sources, and test source mixing hypotheses (Pullen et al., 2014). Thus, DZ U–Pb geochronology is a potentially useful tool that can be applied to loess deposits in uplands adjacent to large meltwater valleys of the central USA (Missouri, Mississippi, Illinois, Wabash and Ohio River Valleys). The immediate deflation source of loess in this region traces back to outwash deposited in broad meltwater valleys that were windswept by predominantly westerly to north-westerly winds (Conroy et al., 2019). Yet, sediment deposited by meltwaters in the valleys was, in turn, predominantly sourced from glacial lobes to the north (Grimley, 2000); we consider these lobes as the ultimate loess source regions. As determined in this study, Wisconsinian, Illinoian and pre-Illinoian Episode loess deposits of the central USA contain ubiquitous detrital zircon and represent a sedimentary record with multiple input sources distributed across a wide region of the Laurentide Ice Sheet. Yet Quaternary DZ loess provenance studies are rare in midcontinental North America (Aleinikoff et al., 1999, 2008; Kassab et al., 2017), with no published results for loess deposits of the Illinois or Mississippi River Valleys.

In this study, we present DZ U–Pb age distributions of Pleistocene loess units at sites along the Illinois and Mississippi River Valleys, as well as till samples attributed to five Wisconsin Episode glacial lobes. As our study exclusively investigates loess deposits with a generally accepted glacial origin (Muhs et al., 2018), we focus on the provenance of these loess deposits in relation to glacial sediment sources. Specifically, the DZ signatures of each glacial lobe are used to represent loess provenance and to infer relative spatial and temporal changes in distribution of both the river drainage network and contributing glacial lobes. As these loess units are exceptionally well-defined and well-correlated across the region, with ample age control (e.g., Rodbell et al., 1997; Pigati et al., 2015; Markewich et al., 2011; Nash et al., 2018), DZ results can be placed

in the temporal context of specific glacial episodes. Our DZ results provide several new insights into the evolution of glacial sediment source contributions from the pre-Illinoian Episode to Wisconsin Episode. The results also exhibit aspects of large-scale ice sheet distributions and the evolution of the Mississippi River drainage network during the last and penultimate glacial episodes, serving as a proof-of-concept for the utility of DZ U–Pb age distributions to identify loess source regions in midcontinental North America.

2. Study site background and methodology

2.1. Glacial lobe characterization

We assessed till samples from glacial lobes of the southern Laurentide Ice Sheet and used their DZ U–Pb age distributions as provenance reference types for middle to late Pleistocene loess deposits along the Illinois and Mississippi River Valleys. From west to east these lobes are the Des Moines Lobe, Superior Lobe, Green Bay Lobe, Lake Michigan Lobe, and Huron-Erie Lobe (Fig. 1, Table 1).

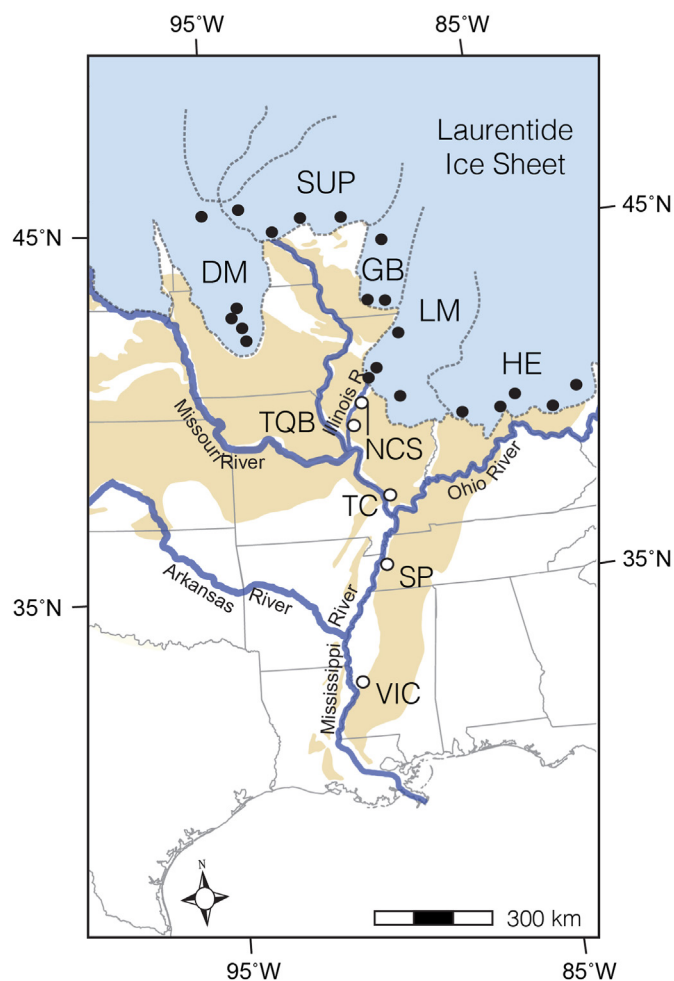


Fig. 1. Glacial till and loess sample locations. Dashed grey lines represent Laurentide Ice Sheet extent and reconstructed glacial lobe distribution during the Last Glacial Maximum. Solid circles indicate glacial till sample sites within labeled glacial lobes: DM = Des Moines Lobe, SUP = Superior Lobe, GB = Green Bay Lobe, LM = Lake Michigan Lobe, HE = Huron-Erie Lobe. Tan shading indicates loess distribution (adapted from Muhs et al., 2018). Open circles indicate locations of loess sampled at multiple depths: NCS = New Cottonwood School, TQB = Thomas Quarry, TC = Thebes Core, SP = Swimming Pool Section, VIC = Vicksburg Section. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Composite till sample source locations, references and mixing weights.

Glacial Lobe	Latitude	Longitude	Glacial Till Unit	Reference	Mass (g)
Des Moines	45.716	−94.955	New Ulm Formation	Grimley (2000); site 17	240
Lobe	42.715	−94.420	Alden Member,	Grimley (2000); site 36	270
Total Sample			Dows Formation		
983 g	42.080	−93.755	Alden Member,	Grimley (2000); site 40	120
	42.540	−94.083	Dows Formation	Grimley (2000); site 41	88
	43.0	−94.3	Alden Member,	site 51 (Algona Moraine)	133
	43.0	−94.3	Dows Formation	site 52 (Algona Moraine)	132
			Alden Member,		
			Dows Formation		
Superior	45.542	−90.363	Mikana Member,	Grimley (2000); site 5	250
Lobe			Copper Falls Formation		
Total Sample	45.622	−91.968	Sylvan Lake Member,	Grimley (2000); site 7	250
1000 g			Copper Falls Formation		
	45.087	−92.665	Sylvan Lake Member,	Grimley (2000); site 8	230
	45.820	−93.900	Copper Falls Formation	Grimley (2000); site 14	270
			Cromwell Formation		
Green Bay	43.066	−89.304	Horicon Member,	Grimley (2000); site 1	423
Lobe			Holy Hill Formation		
Total Sample	44.764	−88.524	Kewaunee Formation	Grimley (2000); site 2	334
913 g	43.088	−88.758	Horicon Member,	Grimley (2000); site 39 (Weis Drumlin)	107
			Holy Hill Formation		
	43.072	−89.264	Horicon Member,	Colgan et al. (1997); (Blooming Grove Drumlin)	49
			Holy Hill Formation		
Lake Michigan	40.241	−88.380	Batestown Member,	Grimley et al. (2016); outcrop MHT-14f	279
Lobe			Lemont Formation		
Total Sample	40.948	−89.528	Tiskilwa Formation	Stumpf (2010); site 1579 (3–4 m depth)	300
977 g	41.147	−89.267	Tiskilwa Formation	McKay et al. (2008) (Clear Creek Section)	190
	41.897	−88.351	Yorkville Member	ISGS Core Library; #C-31742 (2.4 m depth)	208
			Lemont Formation		
Huron-Erie	39.717	−86.499	Cartersburg Till Member	Loope et al. (2018); (Clayton Section)	161
Lobe			Trafalgar Formation		
Total Sample	39.717	−86.499	Center Grove Till Member	Loope et al. (2018); (Clayton Section)	168
977 g			Trafalgar Formation		
	39.838	−84.547	Miami Sublobe till (Wisconsin Episode)	roadcut along I-70 near Lewisburg, OH	203
	39.599	−85.204	Miami Sublobe till (Wisconsin Episode)	Hall (1992); (Snyder Farm Section)	140
	40.018	−82.852	Darby till, Scioto Sublobe	Frolking and Szabo (1998); (Rocky Fork Section)	98
	39.471	−83.265	Scioto Sublobe till (Wisconsin Episode)	roadcut along U.S. Highway 35	207

Previous till studies associated with these lobes centered on magnetic susceptibility, bulk mineralogy, and geochemistry as provenance indicators (Grimley et al., 1998; Grimley, 2000; Muhs et al., 2014, 2018). One preliminary study of DZ U–Pb age distributions, in the Lake Michigan, Saginaw, and Huron-Erie Lobe tills, found overall similarity among DZ U–Pb age distributions and concluded that they primarily reflect the DZ signature of the underlying Paleozoic sedimentary bedrock over which the ice sheet passed (Kassab et al., 2017). This study demonstrated the utility of DZ U–Pb ages for understanding till provenance and, by extension, glacial erosion and sediment transport pathways.

The glacial lobe DZ U–Pb age distributions presented here are larger in sample size and geographical scope than prior DZ U–Pb provenance studies of loess and glacial till in Midcontinental North America (Aleinikoff et al., 2008; Kassab et al., 2017). Furthermore, our study focuses on testing glacial lobe sediments as signatures of the ultimate sources for loess deposits. To characterize each glacial lobe, 4–6 till samples distributed across the frontal margin or central flow path of each lobe (Fig. 1) were mixed into a single representative sample. The intent of the sample distribution was to capture last glacial till units that represent the composition of glacial sediment released to meltwaters of the major river valleys. Each till sample was gently ground with a mortar and pestle and sieved to <500 μm . Each lobe till sample was then weighed and mixed in roughly equal proportions, dependent on sample

availability, to attain a sample mass of 900–1000 g prior to zircon processing with the aim to ensure >300 grains for robust analysis (Pullen et al., 2014).

To compare the age distributions of similar sized zircons in the till samples (sieved to < 500 μm) and loess samples (dominantly <63 μm), we identified zircon crystals with a maximum length <63 μm (minimum crystal size was 15 μm) after measurement utilizing Chromium Offline Targeting. This program collates length measurements of zircon crystals to their corresponding U–Pb age data directly from image mosaics. A comparison of the <63 μm sample fraction to the total <500 μm age distribution for each representative glacial lobe sample shows all major features are present in both distributions (Fig. S1). Thus, we continue to show the original <500 μm glacial lobe age distributions to represent a more robust signal.

2.2. Loess sampling

Loess samples were collected along a north-south transect from Illinois, Tennessee, and Mississippi (Fig. 1, Table 2) that traverses key confluences of the present-day and ancestral Mississippi River drainage. Throughout this paper, loess sample descriptions and discussion are organized by both spatial distribution (Fig. 1) and stratigraphy (Fig. 2). Lithostratigraphic units and depositional history are based on Grimley et al. (2003), Hansel and Johnson (1996),

Table 2
Loess sample source locations, references and mixing weights.

Loess Site	Latitude	Longitude	Unit	Depth	References	Mass (kg)
New Cottonwood School Core	40.024	−90.291	upper Peoria Silt	1.2–3.0 m	Nash et al. (2018); Willman and Frye (1970)	1.04
			middle Peoria Silt	4.1–5.8 m		1.00
			lower Peoria Silt	7.6–9.8 m		1.01
Thomas Quarry Section B	39.520	−90.516	lower Peoria Silt	~1.5 m above Peoria-Roxana contact	Nash et al. (2018); Grimley et al., 1998; Mason and Jacobs (1998)	~3
			Roxana Silt	~0.5 m below Peoria-Roxana contact		~3
Thebes Core	37.239	−89.453	middle Peoria Silt	2.8–4.8 m below surface	Grimley et al., 2003 (ISGS Core# C-14718)	1.50
			lower Peoria Silt	5.3–7.0 m below surface		1.25
			Roxana Silt	8.4–11.3 m below surface		2.40
			Loveland Silt	13.6–15.3 m below surface		1.30
			Crowley's Ridge (pre-Illinois Episode)	16.2–18.3 m below surface		1.10
Swimming Pool Section	35.318	−90.061	lower Peoria Silt	8.15–8.45 m	Pigati et al. (2015); Wang et al. (2020)	1.00
			Roxana Silt	4.45–4.75 m		1.00
			Loveland Silt	−0.7 to 0.8 m		1.00
Vicksburg Section	32.351	−90.808	Peoria Silt	10.5–10.2 m	Snowden and Priddy (1968); Pigati et al. (2015)	1.00
			Roxana Silt	8.1–7.5 m		1.00
			pre-Wisconsin sand	4.2 m–3.6 m		1.00

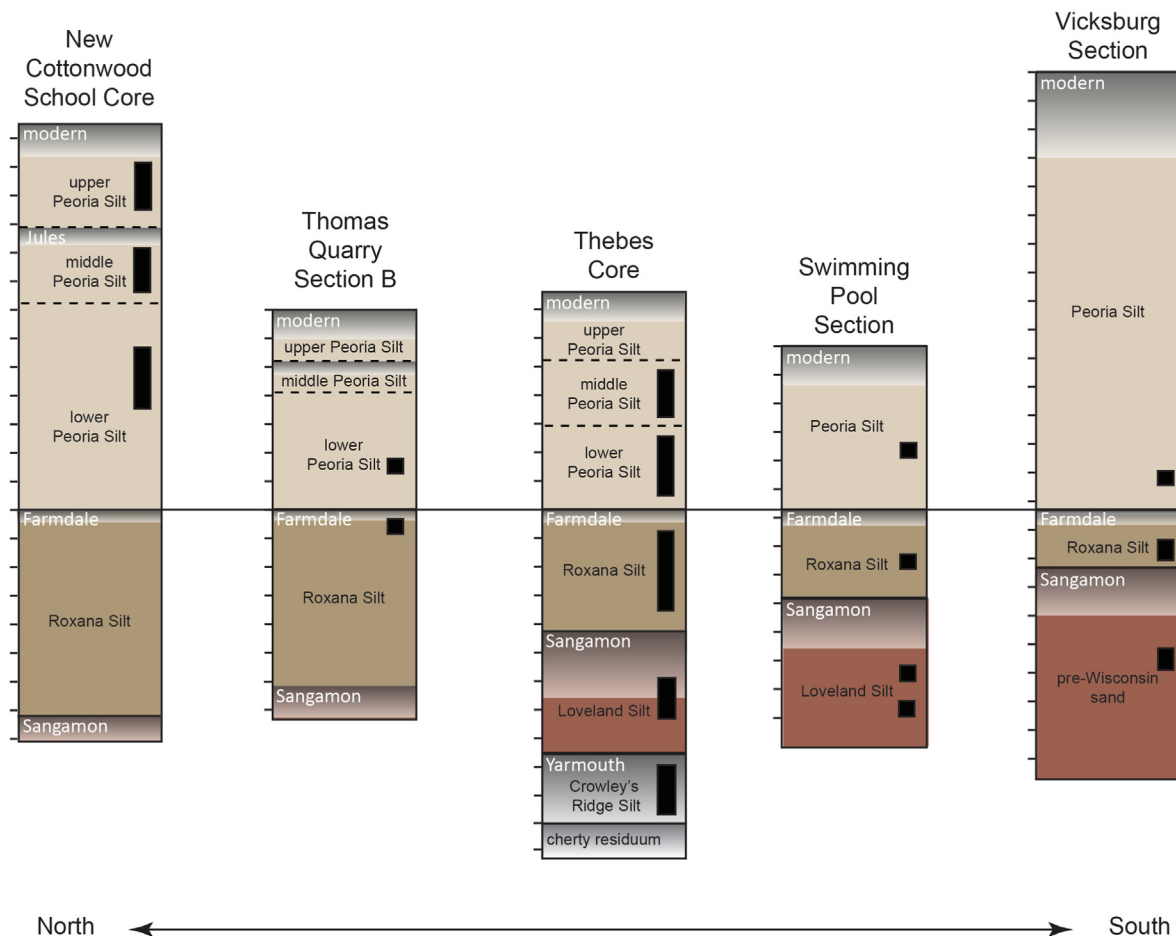


Fig. 2. Schematic overview of sedimentary units sampled at each sample site. Sites are organized from North to South reading from left to right. Site coordinates, unit depths, absolute ages, and sample weights are available in Table 2. Black rectangles in each unit indicate the depth intervals over which samples were collected and combined.

Nash et al. (2018), and Snowden and Priddy (1968). From youngest to oldest, the sampled loess units are the upper Peoria Silt, middle Peoria Silt, and lower Peoria Silt (all dating to the late Wisconsin

Episode, MIS 2), Roxana Silt (middle Wisconsin Episode, MIS 3), Loveland Silt (Illinois Episode, MIS 6), and Crowley's Ridge Silt (pre-Illinois Episode). Note that in Tennessee and Mississippi, Peoria Silt

and Loveland Silt are referred to as Peoria Loess and Loveland Loess, respectively, as is established practice in those regions. Sample locations from northernmost to southernmost are New Cottonwood School Core, Thomas Quarry Section B, Thebes Core, Swimming Pool Section, and Vicksburg Section. New Cottonwood School and Thomas Quarry are located within the Illinois River drainage basin, whereas all other sites are within the present-day Mississippi River drainage. However, both Illinois Valley loess sites are located within a valley that was once the ancestral Mississippi River Valley prior to the river diversion to its present course at $24,460 \pm 120$ cal yr BP (Curry, 1998).

Samples from New Cottonwood School and Thomas Quarry, collected from uplands adjacent to the Illinois River valley, were described by Nash et al. (2018). Their study focused solely on the Peoria Silt of the Illinois Valley region. Representative samples of the upper, middle and lower zones of Peoria Silt from the New Cottonwood School Core were combined, leaving gaps near zonal contacts to avoid pedogenic mixing. For the purposes of this study, sub-samples across several intervals were combined to capture a representative sample of each unit. Nearby sample sites at Cottonwood School and Thomas Quarry, not included in this study, were described by Willman and Frye (1970), and Grimley et al. (1998) and Mason and Jacobs (1998), respectively.

Thebes Core (Illinois State Geological Survey # C-14718) was collected south of the Missouri River and is described in Grimley et al. (2003). The section was measured downward from the modern surface. For this study, archived samples of core were cleaned with a small metal spatula to expose undisturbed sediment for sampling of the middle Peoria Silt, lower Peoria Silt, Roxana Silt, Loveland Silt, and Crowley's Ridge Silt. Sediment was collected across a broad section of each unit within the core (Fig. 2) to attain a representative sample, with a margin at least 0.2 m above or below loess unit contacts to avoid pedogenic mixing.

Samples from two additional sections were collected for this study: Swimming Pool Section (Fig. 3) and Vicksburg Section

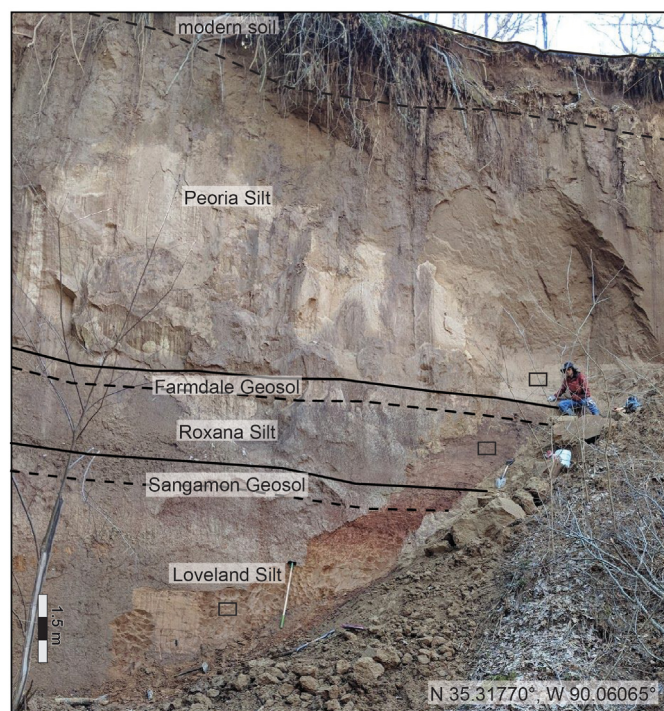


Fig. 3. Quaternary fluvial-terrace deposits at Swimming Pool Section. Rectangles indicate sampled sediment.

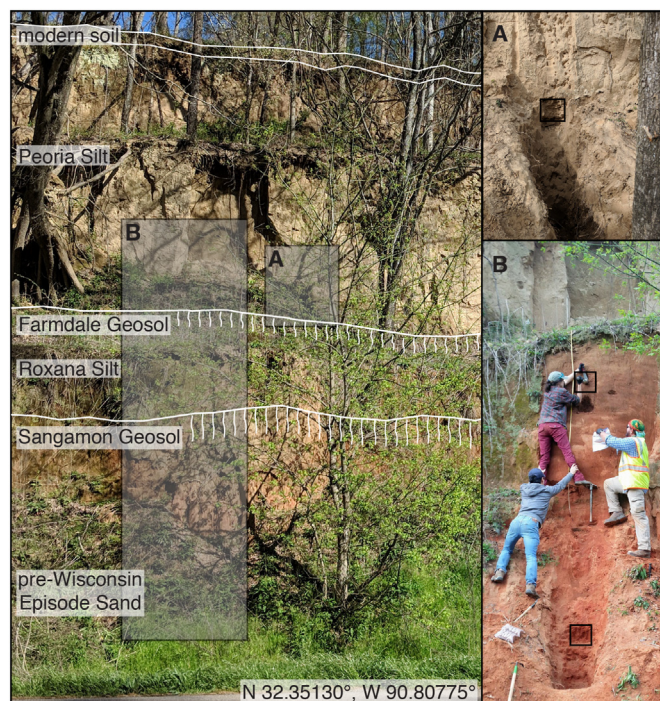


Fig. 4. Vicksburg Section. A) lower Peoria Silt unit. B) Roxana Silt and pre-Wisconsin Episode sand units. Each terrace is capped by a modern soil. Geosols are indicated with white hatching. Rectangles indicate sampled sediment.

(Fig. 4). These sections, or nearby sites, have been previously described in detail (Pigati et al., 2015; Snowden and Priddy, 1968; Wang et al., 2020). At both sites, samples were collected at least 0.5 m above or below the transitional unit contacts to avoid zones of potential pedogenic mixing and were sampled from bottom to top to avoid pour-over contamination from above. The exposure was pre-cleaned by digging into the slope with a shovel to expose undisturbed loess.

Swimming Pool Section was sampled from a gully with a fresh loess exposure within the Meeman-Shelby Forest State Park located along the Mississippi River, ~200 km south of the Ohio River confluence (N 35.31770°, W 90.06065°). An exposure of a nearby site has been described in Pigati et al. (2015), but this site was inaccessible. A new landslide at the Swimming Pool Section location revealed previously unexposed Loveland Silt and a ramp of debris provided access to ~10 m of Roxana and Peoria Silt. Another ~2 m of Peoria Silt was out of reach and capped by the modern soil. Peoria, Roxana, and Loveland silts were identified by distinct lithology and intervening weathering patterns characteristic of the Farmdale and Sangamon Geosols.

The Vicksburg Section was sampled at an exposure on the north side of Interstate 20 in Vicksburg, MS, located east of the Mississippi River and ~160 km south of the Arkansas River confluence (N 32.35132°, W 90.80775°). For reference, the section was described by Snowden and Priddy (1968) as Sample Station 17. Additionally, radiocarbon analysis of terrestrial gastropods preserved in the loess sequence was provided in Pigati et al. (2015). We were able to identify the location of the Pigati et al. (2015) site and measured each of the four road-cut benches separately from the bottom to create a composite depth profile with road level as the base of the section. The exposure contained 11.8 m of Peoria Silt, 1.9 m of Farmdale Geosol capped Roxana Silt, and 1.6 m of transitional Roxana Silt/Sangamon Geosol overlying pre-Wisconsin Sand.

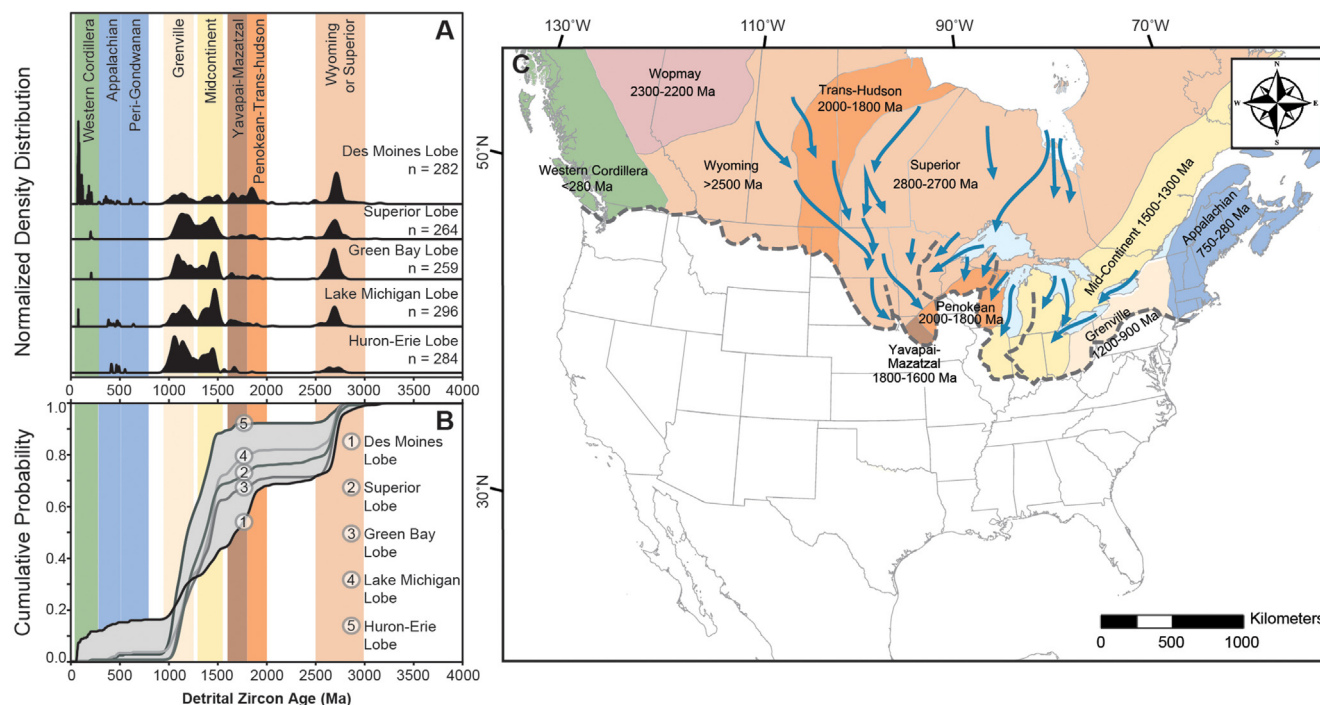


Fig. 5. Glacial lobe comparisons of detrital zircon U–Pb age distributions. Normalized Density Distribution Plots [A] and Cumulative Probability Plots [B] were generated from probability density estimates. Color bars in both plots indicate age ranges matching the underlying protolith source terrains for DZ in North America (modified from Blum et al., 2017) shown in panel [C] with LGM glacial extent and glacial flow paths (dashed grey lines and blue arrows, respectively; modified from Margold et al., 2015). These source terrains include only crystalline basement units that are zircon rich (e.g., basalts and gabbros of the Midcontinent Rift system are not included) and over which our lobes may have passed. We note though that sedimentary bed rock units could contain a mixture of these sources and recycled zircon grains were therefore incorporated into glacial lobes. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.3. U–Pb geochronology

Heavy mineral separation and zircon U–Pb measurements were conducted at the Arizona LaserChron Center at the University of Arizona following the methods of Gehrels et al. (2006, 2008). Detrital zircon was separated with a mining pan followed by heavy liquids and a Frantz magnetic separator such that all zircon crystals from each sample were retained in the final fraction and incorporated into an epoxy mount along with multiple fragments and loose crystals of SLM, FC-1, and R33 zircon crystals that are used as primary matrix-matched standards. Backscatter electron images were made using a Hitachi 3400 N Scanning Electron Microscope to create a mosaic image of each sample. U–Pb ages of zircon grains were determined by laser ablation-inductively coupled plasma mass spectrometry (LA-ICP-MS) with a Photon Machines Analyte G2 laser and a Thermo Element 2 single-collector ICP-MS. Each zircon crystal was ablated with a 40 μm cleaning spot, followed by a non-standard 15 μm beam diameter for analysis that was necessary to accommodate the small grains in our samples. Age data was reduced utilizing the E2agecalc Excel macro (Gehrels, 2010) with a 20% maximum discordance filter. The age cutoff for $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{207}\text{Pb}$ was set to 900 Ma.

Age peaks and ranges described in the results section with Normalized Density Distribution Plots (NDDPs) and Cumulative Probability Plots (CPPs) were created with AgeCalcs, a package of Excel Macros provided by the LaserChron Center at the University of Arizona (Gehrels, 2010). Age peaks with < 3 zircon crystals are not considered statistically significant (Pullen et al., 2014) and so are not discussed here. Cross-correlation values, where a value of 1.0 indicates perfect similarity and a value of 0.0 indicates no similarity between compared age distributions, were generated with DZstats V2.3 (Saylor and Sundell, 2016) from probability

density distributions. Non-metric multidimensional scaling (NMDS) plots were also created to visualize the results of cross-correlation analysis, and objectively group samples based on similarity. The NMDS plots each age spectra as a point in two-dimensional space, such that differences (i.e. cross-correlation coefficients) among a selected group of sample age spectra appear as distances between points. The closer together two samples plot in NMDS space, the greater those two samples' cross-correlation coefficient. We return to these plots in the discussion section where we interpret our CPP and cross-correlation results. An additional suite of statistical comparisons of the sample age distributions derived from both probability density distributions and kernel density estimates using the same program are available on the Geochron EARTHTIME database at: <http://www.geochron.org>.

To better illustrate the age distributions, we have compared the NDDPs with known U–Pb zircon domains in North America (Fig. 5C; Blum et al., 2017). However, it is important to note that these domains represent crystalline basement terrains and not the near-surface bedrock, which in many cases is Phanerozoic sedimentary rock that contains recycled zircon crystals (Kassab et al., 2017). Our results section begins with a description of U–Pb ages for each glacial lobe, which provides a framework for further description and interpretation of the loess U–Pb age distributions.

3. Results

3.1. Detrital zircon U–Pb age distributions of glacial lobe sediment

3.1.1. Des Moines Lobe

The youngest Des Moines Lobe sample age peak ranges from 59 to 79 Ma and accounts for 14% of the zircon crystals; 52% of the Des Moines Lobe ages are within a broad peak from 946 to 1982 Ma and

Table 3

Cross-correlation of glacial lobe DZ U–Pb age distributions utilizing probability density estimates.

	Des Moines Lobe	Superior Lobe	Green Bay Lobe	Lake Michigan Lobe	Huron-Erie Lobe
Des Moines Lobe	1				
Superior Lobe	0.22	1			
Green Bay Lobe	0.30	0.82	1		
Lake Michigan Lobe	0.23	0.77	0.82	1	
Huron-Erie Lobe	0.08	0.68	0.51	0.58	1

another 23% has ages within a peak spanning 2579–2796 Ma. The corresponding NDDP (Fig. 5A) displays observable Paleocene and Cretaceous crystals that are not present (>3 crystals) in the other 4 glacial lobe samples. Peaks coincident with generation of Grenville and Midcontinental Granite-Rhyolite zircon are muted, whereas Trans-Hudson/Penokean-aged peaks are enhanced.

3.1.2. Superior Lobe

The youngest Superior Lobe sample peak ranges from 963 to 1586 Ma and accounts for 64% of the sample; 18% of the sample has ages that lie within a peak from 2568 to 2848 Ma and 6% within a peak from 1600 to 1910 Ma. The corresponding NDDP (Fig. 5A) shows well-formed Grenville, Midcontinent Granite-Rhyolite, and Superior-Wyoming peaks and muted Trans-Hudson/Penokean peaks.

3.1.3. Green Bay Lobe

The youngest Green Bay Lobe sample peak ranges from 955 to 1548 Ma and accounts for 57% of the sample; 25% of the sample is within a peak from 2541 to 2790 Ma. The corresponding NDDP (Fig. 5A) also shows well-formed Grenville, Midcontinent Granite-Rhyolite, and Superior-Wyoming peaks and muted Trans-Hudson/Penokean peaks.

3.1.4. Lake Michigan Lobe

The youngest Lake Michigan Lobe sample peak with >3 zircon ages ranges from 941 to 1844 Ma and accounts for 77% of the sample; 17% of the sample is within a peak from 2504 to 2788 Ma. The corresponding NDDP (Fig. 5A) exhibits a suite of Appalachian aged crystals, well-formed Grenville, Midcontinent Granite-Rhyolite, and Superior-Wyoming peaks and muted Trans-Hudson/Penokean peaks.

3.1.5. Huron-Erie Lobe

The youngest significant age peak of the Huron-Erie Lobe sample ranges from 914 to 1512 Ma and accounts for 86% of the sample. Additionally, the corresponding NDDP (Fig. 5A) shows a complete absence of young Paleocene and Cretaceous crystals, a similar abundance of Appalachian crystals as the Lake Michigan Lobe, an increased Grenville signal, an absence of Trans-Hudson age crystals and the lowest proportion of Superior-Wyoming age crystals relative to other glacial lobe samples.

3.1.6. Glacial lobe comparison

NDDPs and CPPs illustrate key differences between the age distributions of the five sampled glacial lobes (Fig. 5A and B). The Des Moines Lobe age distribution is distinctive due to the presence of Paleocene and Cretaceous-age zircon crystals. The Des Moines Lobe age distribution is also weakly correlated with the other four lobe age distributions (Table 3). The age distributions of the central glacial lobes (Superior Lobe, Green Bay Lobe and Lake Michigan Lobe) have slight differences in relative abundance of Grenville and Midcontinent Granite-Rhyolite ages, but their age distributions are similar, as indicated by high cross-correlation coefficients (Table 3).

Finally, the easternmost Huron-Erie Lobe has some shared age distribution characteristics with the central lobes, such as prominence of Grenville and Midcontinent Granite-Rhyolite ages, and smaller contributions from the Yavapai-Mazatzal and Appalachian domains, the latter of which is also apparent in the Lake Michigan lobe sample. Cross-correlation coefficients between the Huron-Erie Lobe and the central lobes are moderately high (Table 3). The key feature that distinguishes the Huron-Erie Lobe is the muted peak of Wyoming and Superior Province ages.

3.2. Temporal variation of loess U–Pb age distributions at individual sites

3.2.1. IL river valley sites: New Cottonwood School and Thomas Quarry

The youngest zircon age in the distribution of upper Peoria Silt from New Cottonwood School is 294.6 ± 10.7 Ma. Most of the sample, 71%, is composed of zircon ages between 921 and 1801 Ma with another 17% between 2597 and 2800 Ma. The Superior-Wyoming equivalent age peak is notable in the NDDP (Fig. 6A) along with broad Grenville and Midcontinent Granite-Rhyolite age peaks. Similar to the upper Peoria Silt sample, the youngest zircon age of the middle Peoria Silt at this site is 301 ± 8.5 Ma. Most of the sample, 62%, is composed of zircon ages between 987 and 1903 Ma with another 20% between 2619 and 2802 Ma. The NDDP of the middle and upper Peoria Silt are similar (Fig. 6A) and highly correlated ($r = 0.88$). However, the middle Peoria Silt cumulative probability (Fig. 6B, dot-dash line) shows a decrease in the proportion of zircon ages greater than ~1500 Ma. The lower Peoria Silt sample from New Cottonwood School contains four young zircon crystals between 64 and 79 Ma and nine zircon crystals between 271 and 645 Ma. Three major age peaks between 1048 and 1380 Ma, 1601–2009 Ma, and 2565–2792 Ma account for 17%, 24%, and 30% of the sample, respectively. The anomalous young age peak and low abundance of Grenville and Midcontinent Granite-Rhyolite age peaks is apparent in both the NDDP (Fig. 6A) and the CPP (Fig. 6B, dotted orange line), along with a slightly increased Superior-Wyoming age peak. The lower Peoria Silt at New Cottonwood School is not strongly correlated with the middle Peoria Silt ($r = 0.47$).

The lower Peoria Silt sample from Thomas Quarry contains zircon crystals with fourteen zircon ages ranging from ~93 to 761 Ma. The majority, 56%, of the age distribution is within a broad peak between 952 and 1935 Ma. Another 31% of the age distribution is between 2601 and 2921 Ma. The NDDP (Fig. 6A) shows the presence of young zircon ages as well as the Superior-Wyoming age peak. The two lower Peoria Silt age distributions of New Cottonwood School and Thomas Quarry are fairly well-correlated ($r = 0.64$), and the CPP (Fig. 6B, dotted blue line) highlights their main difference: a decreased abundance of zircon ages less than ~1000 Ma at Thomas Quarry. The Roxana Silt sample from Thomas Quarry contains three young zircon ages of 83.7 ± 2.0 Ma, 92.2 ± 3.9 Ma, and 98.2 ± 2.5 Ma. Most of the sample lies within two age peaks with ranges of 929–1917 Ma accounting for 74%, and

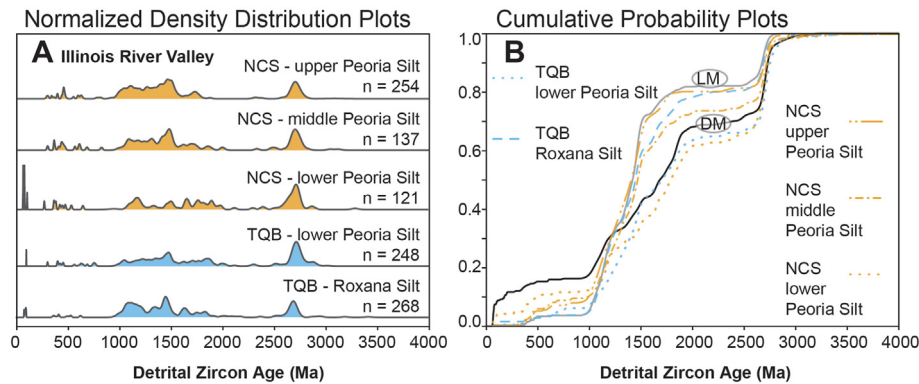


Fig. 6. Illinois River valley detrital zircon U–Pb age distributions at New Cottonwood School (NCS) and Thomas Quarry (TQB). Normalized Density Distribution Plots [A] and Cumulative Probability Plots [B]. NDDPs do not have a scale bar on the y-axis, as age distributions have been normalized to account for differences in the total number of zircon crystals (n) in each sample. Cumulative probability is expressed as a fraction of 100% on the y-axis of panel B. Grey and black lines in panel B represent the bounding glacial sources: Lake Michigan Lobe and Des Moines Lobe, respectively. Here, the Huron-Erie Lobe age distribution is excluded as there is no evidence of fluvial or aeolian transport that would have introduced this age population to the Illinois River valley.

Table 4

Cross-correlation of Illinois River loess samples and glacial lobe DZ U–Pb age distributions utilizing probability density estimates.

	Des Moines Lobe	Superior Lobe	Green Bay Lobe	Lake Michigan Lobe	Huron-Erie Lobe
New Cottonwood School upper Peoria Silt	0.27	0.73	0.76	0.84	0.54
New Cottonwood School middle Peoria Silt	0.35	0.67	0.78	0.77	0.34
New Cottonwood School lower Peoria Silt	0.63	0.31	0.38	0.28	0.07
Thomas Quarry Section B lower Peoria Silt	0.52	0.47	0.59	0.53	0.18
Thomas Quarry Section B Roxana Silt	0.36	0.82	0.86	0.89	0.57

2507–2770 Ma accounting for 18.5% of the total age distribution. The NDDP (Fig. 6A) shows an increased abundance of Grenville equivalent zircon ages and a reduced abundance of Superior-Wyoming zircon ages, relative to the lower Peoria Silt at Thomas Quarry.

The CPP (Fig. 6B) and correlations between age distributions of loess units of the Illinois River Valley and age distributions of measured tills show the upper and middle Peoria Silt are highly correlated with the central glacial lobes (Table 4). The age distribution of lower Peoria Silt at New Cottonwood School is most like Des Moines Lobe ($r = 0.63$), whereas lower Peoria Silt at Thomas Quarry is closely aligned with the Des Moines Lobe and the central lobes (Table 4). The CPP (Fig. 6B) also demonstrates that the lower Peoria Silt age distribution at both sites is most like Des Moines Lobe but lies outside the range of the lobe cumulative probabilities. The Roxana Silt at Thomas Quarry has an age distribution most like the three central lobe age distributions, with higher cross-correlation values than even the upper and middle Peoria Silt (Table 4).

3.2.2. Upper MS river valley: Thebes Core

The middle Peoria Silt sample from Thebes Core contains three Paleogene-aged zircon crystals of 32.7 ± 0.5 Ma, 44.2 ± 0.5 Ma, and 46.8 ± 0.7 Ma. The NDDP of the age distribution (Fig. 7A) shows 25 zircon crystals dating to the Cretaceous, an age peak containing nine zircon crystals from 403 to 462 Ma, and small age peaks from 601 to 643 Ma. The majority, 59%, of the age distribution is within a broad range from 900 to 1889 Ma. Another 11% of the age distribution lies between 2434 and 2765 Ma.

The lower Peoria Silt sample from Thebes Core contains three zircon crystals with Paleogene ages of 53.8 ± 0.8 Ma, 57.7 ± 1.2 Ma, and 64.0 ± 1.1 Ma. The first age peak occurs from 71 to 77 Ma,

followed by a group of small age peaks ($3 < n < 5$) scattered between 86 and 650 Ma. Most of the age distribution (~57%) dates between 915 and 1921 Ma. Another 12% of the distribution has ages between 2638 and 2856 Ma. The middle Peoria Silt and lower Peoria Silt have fairly similar DZ age distributions in the Thebes Core ($r = 0.60$), although the lower Peoria Silt has muted Grenville and Midcontinent equivalent peaks and an increased Superior Province equivalent peak.

The Roxana Silt sample from Thebes Core contains 22 zircon crystals with ages ranging from 21 to 987 Ma. Three prominent age peaks from 1005 to 1559 Ma, 1577–1894 Ma, and 2612–2778 Ma constitute 56.5%, 16.8% and 12% of the sample, respectively. The NDDP (Fig. 7A) shows an increased Grenville/Midcontinent equivalent signal and decreased Appalachian, Peri-Gondwanan and Trans-Hudson/Penokean equivalent signals. The scarcity of zircon crystals with ages <1000 Ma is most visible in the CPP (Fig. 7B).

The Loveland Silt sample from Thebes Core contains 4 zircon crystals between 85 and 89 Ma (Cretaceous). Most of the zircon ages (71%) are between 990 and 1937 Ma with another 12% between 2645 and 2780 Ma. The Loveland Silt has a similar age distribution to the younger Roxana Silt at this location ($r = 0.63$). The disparity between the two distributions is chiefly the result of seven zircon ages between ~450 and 550 Ma (Fig. 7).

The Crowley's Ridge sample from Thebes Core contains 3 significant Phanerozoic peaks with ranges of 72–77 Ma, 91–100 Ma and 390–450 Ma. Much of the sample, 52.5%, contains zircon crystals with ages between 940 and 1555 Ma. Another 8% and 6% of the sample contain zircon crystals with ages between 1579–1784 Ma and 2625–2783 Ma, respectively. An anomalously muted Superior-Wyoming equivalent age peak is apparent in the NDDP (Fig. 7A). Crowley's Ridge Silt and the overlying Loveland Silt have a cross-correlation value of ($r = 0.48$).

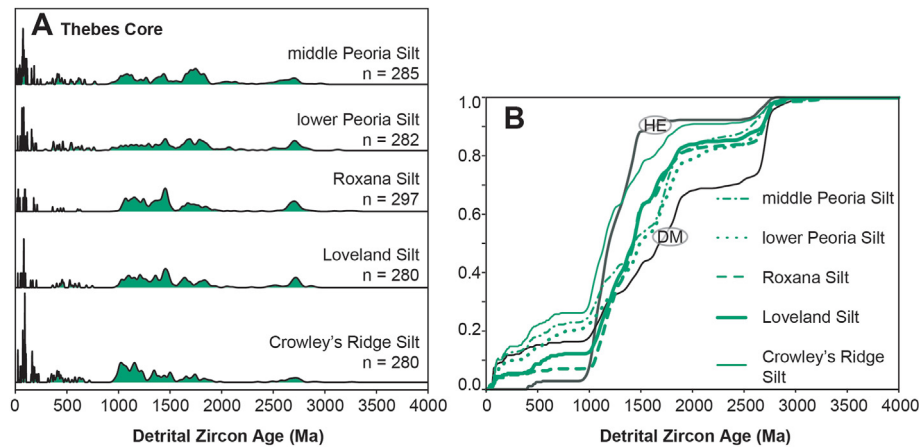


Fig. 7. Thebes Core detrital zircon U–Pb age distributions. Normalized Density Distribution Plots [A] and Cumulative Probability Plots [B]. Grey and black lines in panel B represent the bounding glacial sources: Huron-Erie Lobe and Des Moines Lobe, respectively.

Table 5

Cross-correlation of Thebes Core loess samples and glacial lobe DZ U–Pb age distributions utilizing probability density estimates.

	Des Moines Lobe	Superior Lobe	Green Bay Lobe	Lake Michigan Lobe	Huron-Erie Lobe
Thebes Core middle Peoria Silt	0.26	0.25	0.25	0.27	0.24
Thebes Core lower Peoria Silt	0.39	0.34	0.36	0.42	0.19
Thebes Core Roxana Silt	0.12	0.38	0.35	0.40	0.28
Thebes Core Loveland Silt	0.29	0.66	0.61	0.75	0.53
Thebes Core Crowley's Ridge Silt	0.17	0.48	0.37	0.45	0.70

Overall, statistical correlations between age distributions of Thebes Core loess units and measured glacial lobes are lower relative to those of New Cottonwood School and Thomas Quarry (Table 5). However, some loess units are highly correlated with specific lobes, and overlap is also apparent between the till and loess CPPs (Fig. 7B). Notably, the relationship between the loess and glacial lobe age distributions varies for ages above and below ~950 Ma. In the >950 Ma fraction of Thebes Core units, middle and lower Peoria Silt DZ U–Pb age distributions resemble the Des Moines Lobe and central lobes. The Roxana Silt and Loveland Silt age distributions are most like those of the central glacial lobes. Finally, the Crowley's Ridge Silt age distribution is most like that of the LGM Huron-Erie Lobe. The <950 Ma fraction of all Thebes Core samples is often inundated with Phanerozoic zircon ages. Similar young ages present in the Des Moines Lobe age distribution would have been transported to the middle and lower Mississippi Valley, contributing to loess deposits at the Thebes Core site. The Missouri River would also have provided sediment from the James Lobe and from nonglacial sources (Grimley, 2000; Aleinikoff et al., 2008). This additional fluvial transport and nonglacial input may confound identification of glacial lobe signatures in loess south of the Missouri River confluence. The middle Peoria Silt has a high abundance of zircon ages <950 Ma in comparison with the lower Peoria Silt unit and the age distribution reaches a minimum cumulative fraction in the Roxana Silt. The Loveland Silt has a slightly increased proportion of zircon ages between ~450 and 550 Ma. The pre-Illinois Episode Crowley's Ridge Silt has a high abundance of Phanerozoic zircon ages.

3.2.3. Central MS river valley: Swimming Pool Section

The lower Peoria Silt sample from the Swimming Pool Section contains 3 Cretaceous zircon crystals with ages of 93.0 ± 1.3 Ma, 95.1 ± 0.9 Ma and 97.1 ± 1.4 Ma. The major age peaks occur between 921 and 1689 Ma, 1692–1914 Ma, and 2551–2758 Ma accounting

for 67%, 8% and 14% of the age distribution, respectively. The NDDP of the age distribution (Fig. 8A) exhibits a subdued Grenville peak, a pronounced Midcontinent Granite-Rhyolite peak, and a moderate Superior-Wyoming peak.

The Roxana Silt sample from Swimming Pool Section contains 3 zircon ages between 407 and 419 Ma. Significant age peaks occur between 897 and 1527 Ma, 1618–1891 Ma, and 2658–2798 Ma accounting for 70%, 11%, and 5% of the age distribution, respectively. The NDDP (Fig. 8A) exhibits a well-defined double Grenville peak, while the Superior-Wyoming peak is small. The CPP (Fig. 8B, dashed line) shows a similar distribution and proportion of zircon ages <1000 Ma and an increased slope at ~1000 Ma relative to lower Peoria Silt, reflecting the presence of the increased Grenville component.

The Loveland Silt sample exhibits an age peak from 381 to 405 Ma which contains only 7 zircon crystals. Two additional age peaks occur between 412–427 Ma and 431–464 Ma containing 4 and 10 zircon ages, respectively. Approximately 75% of the age distribution is between 929 and 1522 Ma. The second largest age population accounts for 8% of the distribution with ages between 1580 and 1833 Ma. The NDDP (Fig. 8A) shows an increased proportion of zircon ages between ~400 and 500 Ma and a muted Superior-Wyoming peak.

Overall, loess units at Swimming Pool Section do not contain detrital zircon ages diagnostic of the western Des Moines Lobe and are more strongly cross-correlated with central and eastern glacial lobes (Table 6). The DZ age distribution of lower Peoria Silt at Swimming Pool Section most closely resembles the Lake Michigan Lobe age distribution. The Roxana Silt, which exhibits an increased proportion of Grenville ages and a decreased Superior-Wyoming age peak, is most similar to the Huron-Erie Lobe. The Loveland Silt has a pronounced increase in ~400–500 Ma zircon ages, a further increased Grenville component, and an altogether absent Superior-Wyoming age peak; thus, the Loveland Silt is most like the

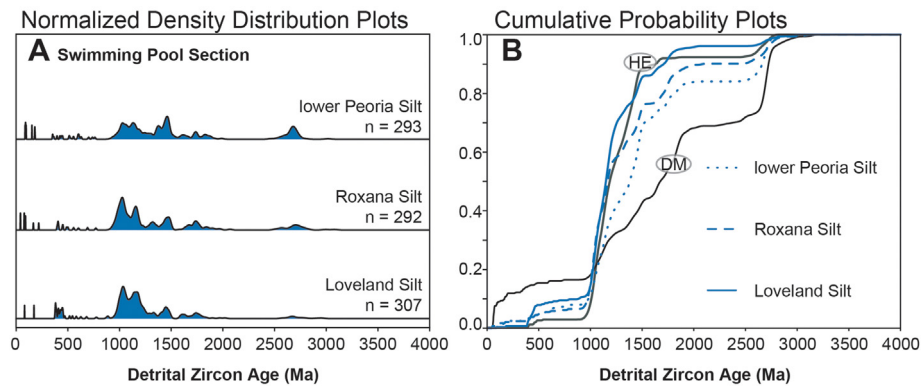


Fig. 8. Swimming Pool Section detrital zircon U–Pb age distributions. Normalized Density Distribution Plots [A] and Cumulative Probability Plots [B]. Grey and black lines in panel B represent the bounding glacial sources: Huron-Erie Lobe and Des Moines Lobe, respectively.

Table 6

Cross-correlation of Swimming Pool Section loess and glacial lobe DZ U–Pb age distributions utilizing probability density estimates.

	Des Moines Lobe	Superior Lobe	Green Bay Lobe	Lake Michigan Lobe	Huron-Erie Lobe
Swimming Pool Section Peoria Silt	0.26	0.72	0.78	0.86	0.68
Swimming Pool Section Roxana Silt	0.12	0.38	0.33	0.43	0.72
Swimming Pool Section Loveland Silt	0.07	0.47	0.33	0.41	0.81

Huron-Erie Lobe at Swimming Pool Section (Fig. 8A).

3.2.4. Lower MS river valley: Vicksburg Section

The lower Peoria Silt sample from Vicksburg Section contains fourteen Phanerozoic zircon crystals with ages between ~ 74 and 445 Ma before the first well-formed age peak at 454 Ma, followed by several minor age peaks at 547 Ma, 609 Ma and 625 Ma with only 3–4 zircon ages in each peak. Most of the age distribution is within two age peaks with ranges between 948 – 1921 Ma and 2633–2748 Ma, accounting for 73% and 12% of the age distribution, respectively. The NDDP (Fig. 9A) shows the highest age peak at 1450 Ma. The CPP (Fig. 9B, dotted line) highlights the presence of the zircon age peaks <1000 Ma.

The Roxana Silt sample from Vicksburg Section contains 4 Phanerozoic DZ age peaks, each containing 4 to 6 zircon ages, from 36 to 40 Ma, 42–46 Ma, 70–74 Ma, and 159–169 Ma. The youngest age populations overlap with ages previously observed in Peoria

Silt from Nebraska and western Iowa, which was sourced from the White River Group (Aleinikoff et al., 2008). However, 76% of the age distribution lies between the ages of 919–1895 Ma. The NDDP (Fig. 9A) exhibits well-pronounced Midcontinent Granite Rhyolite and Yavapai-Mazatzal peaks and an absence of the Superior-Wyoming peak. The CPP (Fig. 9B, dashed line) highlights the increase in zircon ages <1000 Ma as well as Trans-Hudson zircon age peaks.

The pre-Wisconsin Episode fine fraction (<150 µm) sample from Vicksburg Section also exhibits a scattering of Phanerozoic zircon ages with minor age peaks, each containing between 3 and 5 zircon ages. Much of the sample is contained within two age peaks, with 60% of the age distribution within an age range of 941 Ma – 1512 Ma and 15% within a range of 1618 Ma – 1817 Ma. The corresponding NDDP displays an age distribution that resembles the Roxana Silt at the site, with well-pronounced Midcontinent Granite Rhyolite and Yavapai-Mazatzal peaks and an absence of the

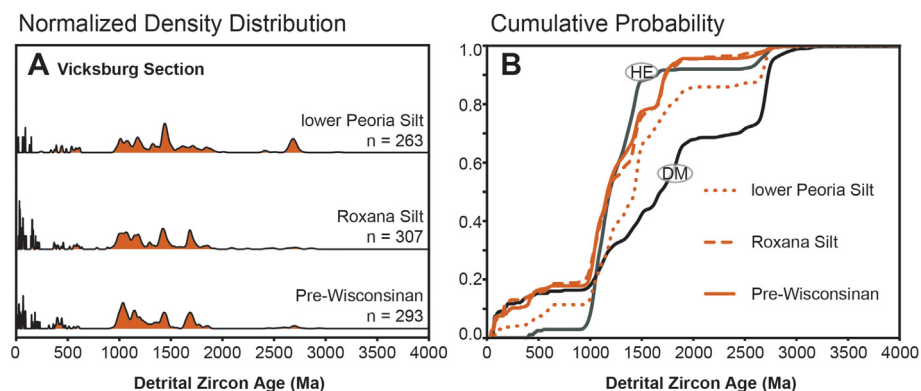


Fig. 9. Vicksburg Section detrital zircon U–Pb age distributions. Normalized Density Distribution Plots [A] and Cumulative Probability Plots [B]. Grey and black lines in panel B represent the bounding glacial sources: Huron-Erie Lobe and Des Moines Lobe, respectively. Pre-Wisconsinan curves in panels A and B represent detrital zircons from the fine size fraction of this sample: <150 µm.

Table 7

Cross-correlation of Vicksburg Section loess and glacial lobe DZ U–Pb age distributions utilizing probability density estimates.

	Des Moines Lobe	Superior Lobe	Green Bay Lobe	Lake Michigan Lobe	Huron-Erie Lobe
Vicksburg Section Peoria Silt	0.28	0.53	0.63	0.75	0.45
Vicksburg Section Roxana Silt	0.16	0.29	0.23	0.32	0.45
Vicksburg Section pre-Wisconsinan (fine fraction)	0.12	0.41	0.34	0.44	0.71

Superior-Wyoming peak. Additionally, the CPPs also show remarkable similarity and the cross-correlation between the two distributions is 0.63. The youngest zircon age present in the pre-Wisconsin-coarse fraction (un-sieved) is 35.6 ± 0.5 Ma. Cross-correlation between the coarse- and fine-fraction samples is 0.63. The proportion of ages <1000 Ma is much higher than the pre-Wisconsin-fine sample, while the distribution >1000 Ma is roughly the same as exhibited in both the NDDP and the CPP.

The DZ age distribution of the lower Peoria Silt at Vicksburg Section most resembles the Lake Michigan Lobe ($r = 0.75$), partly because of the presence of a Superior-Wyoming age peak. It is also highly correlated statistically with the other central lobes (Table 7). However, the lower Peoria Silt age distribution also contains abundant zircon ages <950 Ma. The number of Roxana Silt DZ ages <950 Ma is high relative to the lower Peoria Silt, whereas the age distribution >950 Ma suggests greatest similarity with the eastern Huron-Erie Lobe. The pre-Wisconsin fine fraction is similar to the Roxana Silt ($r = 0.64$) but has a stronger correlation with the Huron-Erie Lobe ($r = 0.71$). A comparison of the pre-Wisconsin Episode fine fraction with the pre-Wisconsin Episode coarse fraction shows an increased abundance of DZ U–Pb ages <940 Ma in the un-sieved sample with an otherwise statistically similar age distribution (Fig. S2).

4. Discussion

DZ U–Pb ages have strong potential to expand our knowledge of Pleistocene loess provenance in the Mississippi River Valley and hence ice lobe activity, particularly for pre-LGM units. In this section, we first highlight the distinctive age distributions of till samples representing five glacial lobes draining into the Mississippi River Valley during MIS 2. We then discuss the viability of using age distributions of these tills to identify sources of loess deposits along the ancestral and present-day Mississippi River Valley. We show proof-of-concept with the Peoria Silt of the Illinois River Valley, as previous mineralogical studies of the Illinois Valley Peoria Silt revealed shifts in the Mississippi River drainage network through time. Finally, we use the DZ age distributions of older loess units to provide new insights into loess sediment sources and pathways prior to the LGM.

4.1. Glacial lobe DZ signatures

Last glacial till samples representing five glacial lobes show distinct DZ age signatures that can fingerprint source-to-sink patterns in LGM loess. A comparison among DZ age distributions of the western Des Moines Lobe, the central lobes (Superior Lobe, Green Bay Lobe, and Lake Michigan Lobe) and the eastern Huron-Erie Lobe shows that each contains distinct relative abundances of DZ ages representative of differences in the glacial paths over the underlying substrate. These underlying source terrains include both crystalline basement (first cycle zircon grains) and sedimentary units (recycled zircon grains), the latter of which can consist of either bedrock or Pleistocene glacial sediment. For example, although the central lobes do not pass over Grenvillian aged

crystalline terrains, they likely incorporated some Grenville-aged zircon grains from sedimentary units associated with the Mid-continent Rift that contain recycled crystals of that age (Malone et al., 2016); basalts and gabbros of the rift itself would not have contributed zircon. The central lobes are relatively similar to one another, whereas the Des Moines Lobe and Huron-Erie Lobe are more distinct. These observations are highlighted by cross-correlation values (Table 3) and an NMDS plot, which groups the Superior, Green Bay, and Lake Michigan Lobes close together and separate from the western and eastern lobes (Fig. 10).

The Des Moines Lobe is distinct from the central lobes due to the presence of young DZ ages (<275 Ma), a low relative abundance of Grenville and Midcontinent DZ ages, and an increased relative abundance of Yavapai and Trans-Hudson age DZ grains. The presence of young DZ ages (<275 Ma) within the Des Moines Lobe is a particularly important indicator as it is not significantly present in any other glacial lobe till samples. This young age signature matches zircon U–Pb ages for grains derived from the Western Cordillera magmatic province. First-cycle zircon grains from the Cordillera were deposited in Cretaceous–Paleogene foreland basin strata in western Canada and the northern Great Plains (Blum and Pecha, 2014; Laskowski et al., 2013). Though we have not sampled the James Lobe as part of this study, a previous study presented U–Pb geochronologic analysis for a single till sample containing 41

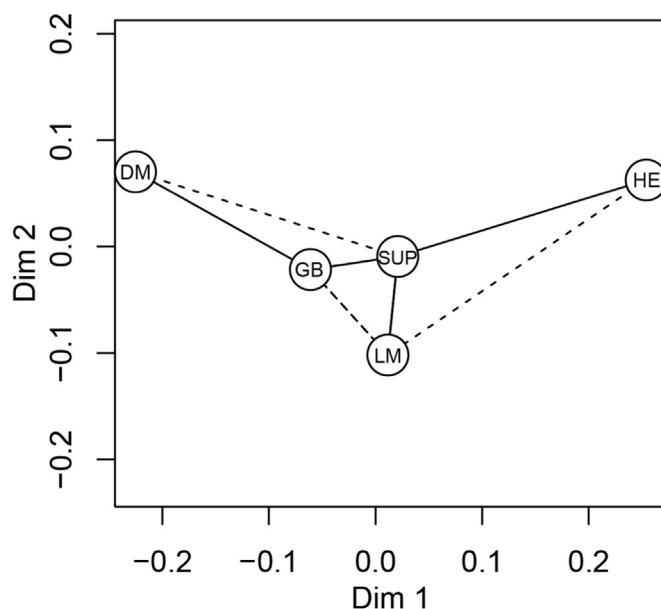


Fig. 10. Multidimensional scaling plot (see Vermeesch, 2013) **of representative glacial lobe samples.** Statistical analysis is based on the Kolmogorov–Smirnov distance between samples. Axes are dimensionless (DIM = dimension) as proximity is proportional to cross-correlation between samples such that samples that plot closer together have higher cross-correlation values. Solid lines represent the most similar nearest neighbors, while dashed lines indicate the second nearest neighbor. DM = Des Moines Lobe, SUP = Superior Lobe, GB = Green Bay Lobe, LM = Lake Michigan Lobe, HE = Huron-Erie Lobe.

zircon grains from the southern margin of the LGM James Lobe (Aleinikoff et al., 2008). Though the sample is too small to make relative comparisons, all major DZ age components of their James Lobe till sample are also present in our Des Moines Lobe till sample. Data from the Des Moines Lobe suggests that zircon grains from foreland strata sedimentary units were in turn incorporated along the lobe's glacial flow path. The Huron-Erie Lobe is also distinguishable from the central lobes by an absence of Trans-Hudson age DZ grains, exceptionally low relative abundance of Superior age DZ grains, and a greater abundance of Grenville age DZ grains, all of which are consistent with a glacial flow path from a more eastern source. Our data suggest that the Huron-Erie Lobe flow path would have led to glacial incorporation of zircon grains from Paleozoic sedimentary units and Proterozoic crystalline basement dominated by a Grenville age signature, with little input from Superior or Trans-Hudson sources, in agreement with the hypothesis put forward by Kassab et al. (2017) that glacial tills incorporate zircon grains that are primarily transported from nearby regions. The combination of observable differences (NDDPs), statistical differences (cross-correlation values), and agreement with previous studies of glacial flow paths gives confidence that we can use the DZ age distributions as fingerprints to distinguish 3 different (western, central, and eastern) glacial lobe sources for downstream loess units.

4.2. Loess detrital zircon age shifts caused by major river diversions and avulsions

We first demonstrate the use of glacial lobe DZ signatures to understand changes in loess provenance with a comparison of loess samples collected at New Cottonwood School and Thomas Quarry in the Illinois River Valley. Here, changes in magnetic susceptibility and mineralogy across loess units have been used successfully to delineate glacial lobe sources during the LGM (Grimley, 2000; Grimley et al., 1998; Nash et al., 2018). DZ age distributions from Illinois River Valley loess do not exceed the range of cumulative probability for the Huron-Erie Lobe, in agreement with the basic observation that the Illinois River Valley/Ancient Mississippi River valley did not transport sediment from eastern glacial terrains (Fig. 6B). Critically, at these locations, the loess DZ age distributions show a marked transition between the middle Peoria Silt and the lower Peoria Silt. Specifically, the middle Peoria Silt contains zircon ages that align most closely with Lake Michigan Lobe and is notably missing a young (<275 Ma) western lobe DZ signal that is present in the lower Peoria Silt (Fig. 6). Thus, the middle Peoria Silt at these locations is close to the central lobes in NMDS space, whereas the lower Peoria Silt is grouped with the Des Moines Lobe (Fig. 11). This change in provenance for the Peoria Silt is consistent with divergence of the Mississippi River from a course that passed through the Illinois River Valley before $24,460 \pm 120$ cal yr BP to its present course due to glacial damming and subsequent overflow of Glacial Lake Milan (Curry, 1998). Evidence for this diversion comes from particle size analysis, radiocarbon dating of gastropods and woody debris, and the fossil ostracod succession at Lomax, IL (Curry, 1998). The timing of the transition between the lower and middle Peoria silt of the Illinois River Valley is $24,400 \pm 200$ cal yr BP, within error of the Curry (1998) diversion date (Nash et al., 2018). Thus, the lower Peoria Silt of the Illinois River Valley represents a broader drainage area that included the margin of the Des Moines Lobe. Following the drainage diversion, sediment in the Illinois River Valley would have been derived only from the central lobes immediately upstream. The DZ data in the context of the Mississippi River drainage diversion aligns with independent evidence for the diversion, providing confidence that DZ patterns can inform the provenance of LGM loess deposits when such independent

observations are lacking or offer an independent line of evidence for confirmation of interpretation.

Our data are additionally in agreement with geochronologic evidence of an earlier river avulsion at the confluence of the Ohio River and Mississippi River (Rittenour et al., 2007). Between 64 and 25 ka, flow from the upper Mississippi River was separated from the Ohio River/Cache Valley inputs by Crowley's Ridge. This timing is coincident with deposition of the Roxana Silt (Rittenour et al., 2007). Thus, the Roxana Silt at Swimming Pool Section, located east of Crowley's Ridge, should contain a DZ U–Pb age distribution with an enhanced Huron-Erie Lobe signature and decreased signatures of the central and western glacial lobes if the proposed fluvial arrangement persisted through this time (MIS 3). The DZ U–Pb age distribution of Roxana Silt at Swimming Pool Section exhibits an absent Western Cordillera age peak, Appalachian and Peri-Gondwanan age peaks, a dominant Grenville age peak and a nearly absent Superior age peak (Fig. 8) in agreement with a dominant contribution from the Huron-Erie Lobe and an absence of zircon contributed from Des Moines Lobe. Although there are no prior data constraining the location of the Mississippi River during MIS 6, the Loveland Silt DZ age distribution at Swimming Pool Section also resembles the Huron-Erie Lobe (Fig. 11), which suggests that the Mississippi River was west of Crowley's Ridge (here, Crowley's Ridge refers to the geomorphic feature) during Loveland Silt deposition. Rittenour et al. (2007) proposed the confluence of the Mississippi River and Ohio River was present north of the Swimming Pool Section location between 21 and 18 ka, coincident with deposition of the middle to upper Peoria Silt (MIS 2). Thus, the sampled lower Peoria Silt at Swimming Pool Section may be too old to have the expected DZ U–Pb age distribution representing a combined Huron-Erie Lobe and central lobe DZ signature. However, the DZ U–Pb age distribution of lower Peoria Silt at Swimming Pool Section does exhibit a decreased Grenville age peak and increased Mid-Continent and Superior/Wyoming age peaks consistent with additional inputs from the central lobes (Fig. 8). This suggests some contributions from the central lobes during lower Peoria Silt deposition (e.g., ~29–24 ka), which can be observed in Fig. 11A. Loess DZ ages thus provide an independent analytical method to both confirm and refine the proposed evolution of the Mississippi channel in the northern lower Mississippi Valley surrounding the Swimming Pool Section location.

4.3. Loess provenance through time: Illinois and Mississippi River valleys

In the absence of information on glacial lobe locations prior to the LGM, DZ age distributions of loess units have the potential to reveal information about pre-LGM drainage patterns and glacial flow paths. The provenance of Roxana Silt, an MIS 3 loess unit observed along nearly the entire length of the Illinois and Mississippi River Valleys (Follmer, 1996; Hansel and Johnson, 1996; Leigh, 1994; Leigh and Knox, 1993), provides one key opportunity to improve understanding of glacial extents in midcontinental North America. Similar to Peoria Silt, the Roxana Silt was most likely derived from valley-train deposits (Grimley, 2000; Johnson and Follmer, 1989), but few moraines or till units date to this time (Ceperley et al., 2019). At present, there are conflicting reconstructions of the extent of the Laurentide Ice Sheet during this period. For example, some reconstructions suggest a deglaciated Hudson Bay during MIS 3 (Batchelor et al., 2019), but this model is questionable due to inconsistency with geologic evidence (Miller and Andrews, 2019). A recent study by Kerr et al. (2021) also suggests that two major ice advances of an ancestral Des Moines Lobe may have occurred during MIS 3.

Along the Illinois River Valley, the DZ age distribution of Roxana

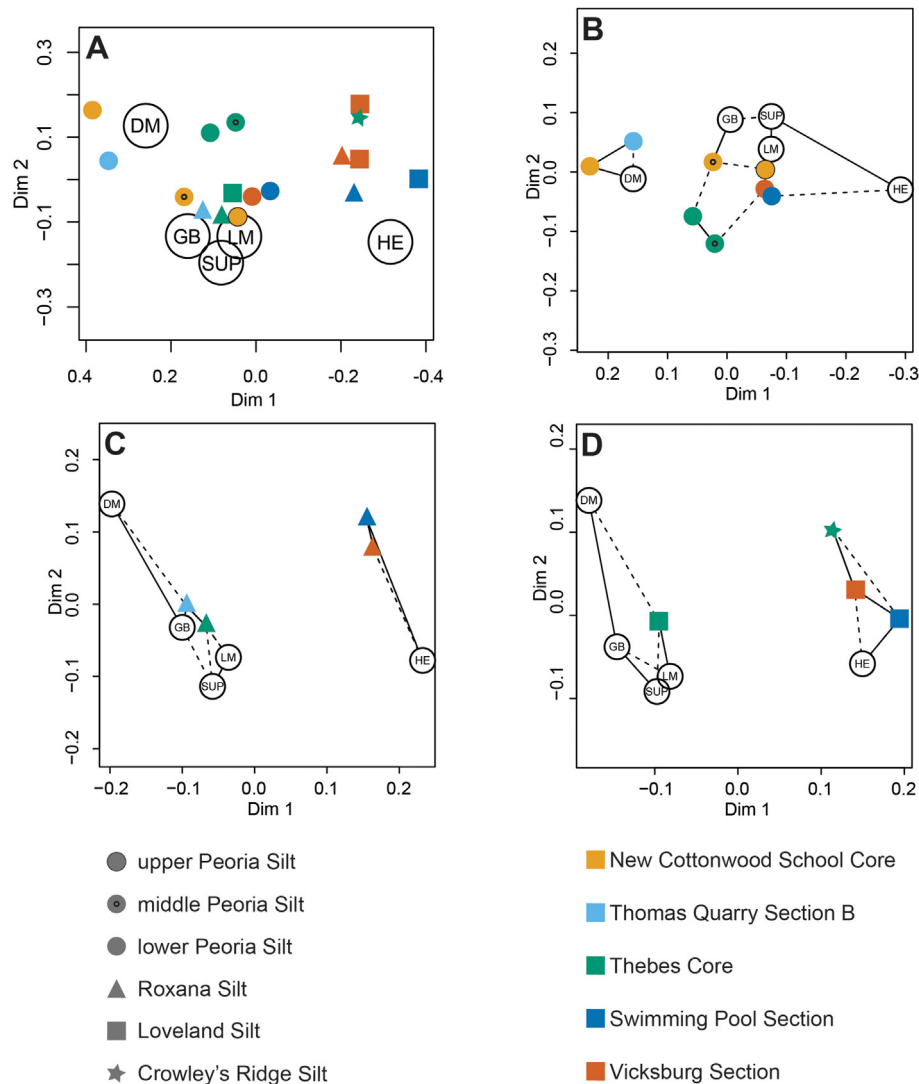


Fig. 11. Multidimensional scaling plots of loess and till samples. A) Comparison of cross-correlation between all sample distributions. B) Comparison of relative similarity between Peoria Silt samples. C) Comparison of relative similarity between Roxana Silt samples. D) Comparison of relative similarity between Loveland Silt and Crowley's Ridge Silt samples.

Silt at Thomas Quarry and New Cottonwood School (Fig. S3, panel 2B) most closely resemble the central lobes (Lake Michigan Lobe, Green Bay Lobe, and Superior Lobe). The absence of a Huron-Erie Lobe signature in Roxana Silt indicates no meltwater pathway from this lobe into the upper Ancient Mississippi Valley (present-day Illinois Valley) at the time. At the Thebes Core location, in southern Illinois, the Roxana Silt also has a central lobe signature. This supports prior interpretations of sediment provenance based on mineralogy (Grimley, 2000; Leigh and Knox, 1993), although the compositional data give somewhat more weight to the Superior Lobe and Des Moines Lobe. Although this central lobe resemblance is not supportive of the findings of Kerr et al. (2021), who argued that a Des Moines Lobe equivalent was contributing sediment to the Mississippi Valley during MIS 3, it also does not rule out the possibility of a short-lived lobe that provided minimal sediment to the Mississippi River drainage basin. In the Kerr et al. (2021) reconstruction, meltwater would have traveled down a paleo-Iowa river system, joining the Mississippi River north of present-day St. Louis. We suggest that, at the Thebes Core site located downstream of the paleo-Iowa river confluence, any potential

signal of Des Moines Lobe sediment was muted by greater input from central lobe sources. Kerr et al. (2021) also note that the Des Moines Lobe equivalent experienced two rapid advances and retreats during MIS 3. If their interpretation is correct, it is likely that little sediment was provided from the Des Moines Lobe to the Mississippi Valley system as the Roxana Silt is considerably thinner along the Mississippi Valley (ancestral Des Moines Valley) north of St. Louis than along the Illinois Valley (ancestral Mississippi Valley; Fehrenbacher et al., 1986). Further downstream, Swimming Pool Section was isolated from the Mississippi River at this time by Crowley's Ridge (Rittenour et al., 2007) and it is therefore not surprising that a Des Moines Lobe signature is largely absent in Swimming Pool Section Roxana Silt.

The Loveland Silt was deposited along the Missouri and Mississippi River Valleys between 190,000 and 130,000 yr BP (MIS 6; Illinois Episode), when the Laurentide Ice Sheet extended into southern Illinois (Grimley et al., 2018; Markewich et al., 2011; Willman and Frye, 1970). The DZ signature of the Loveland Silt within the Thebes Core site, which would have been close to the margin of the MIS 6 Lake Michigan Lobe at the time of deposition,

most closely resembles MIS 2 central lobes (Fig. 11; Fig. S3, panel 2C). As this ancestral Lake Michigan Lobe followed the same flow path of the MIS 2 Lake Michigan Lobe (Curry et al., 2011; Willman and Frye, 1970), we conclude that the DZ age distribution of MIS 6 Lake Michigan Lobe sediment would be highly reminiscent of the MIS 2 central lobe DZ signature. The Loveland Silt at Swimming Pool Section most closely resembles the MIS 2 Huron-Erie Lobe (Fig. S3, panel 2C), which, as previously discussed, suggests the isolation of eastern-derived meltwater from the central Mississippi Valley by Crowley's Ridge during MIS 6, similar to the situation during MIS 3 (Rittenour et al., 2007). At Vicksburg Section, a Loveland Silt unit is not identified, but the DZ signature of the 'fine sand' underlying the Roxana Silt is closely aligned with both the Swimming Pool Section Loveland Silt and the MIS 2 Huron-Erie Lobe (Fig. S3, panel 2C). Thus, despite an expanded MIS 6 version of the Lake Michigan Lobe, the Huron-Erie Lobe equivalent was still a major source of sediment to the Mississippi Valley at the time. The margin of western (Keewatin source) glacial lobes during MIS 6 is not well known, with MIS 6 till units noted in Saskatchewan and Manitoba (Barendregt, 2011) but not found south of Minnesota (Roy et al., 2004).

Crowley's Ridge Silt is a pre-Illinoian loess unit (interpreted as MIS 12) that is also present in the Thebes Core (Grimley et al., 2003). This older loess has a DZ signature that again most closely resembles the MIS 2 Huron-Erie Lobe, suggesting an important eastern-derived source of sediment in the earlier glacial episode. However, the presence of young DZ ages in this unit (Fig. 7) also indicate a western sediment source region, although the proportion of these young grains is not large enough for the pre-Illinoian Crowley's Ridge Silt to plot close to the MIS 2 Des Moines Lobe in NMDS space (Fig. 11). Some input from western glacial sources is likely, as pre-Illinoian glaciers are known to have advanced as far south as northern Missouri between 0.4 and 1.3 Ma (Rovey and McLouth, 2015). Yet, our data suggest that the Crowley's Ridge Silt had a stronger component from eastern pre-Illinoian sources, such as Huron-Erie Lobe glaciers that advanced into eastern Illinois (Curry et al., 2011; Willman and Frye, 1970) and would have drained into the Ancient Mississippi Valley via the (now-buried) Mahomet Valley.

Many pre-LGM loess units, including the Roxana Silt at Vicksburg Section and Swimming Pool Section, the Loveland Silt at Swimming Pool Section, and the pre-Wisconsin sand of Vicksburg Section are most closely aligned with the Huron-Erie Lobe (Fig. 11). The overall dominance of an eastern sediment signature at Thebes Core, Swimming Pool Section, and Vicksburg Section, and the association of these older loess units most closely with the MIS 2 Huron-Erie Lobe, supports the presence of an ancestral Huron-Erie Lobe in earlier glaciations. This finding is consistent with field evidence from Illinois to Pennsylvania (Curry et al., 2011; Miller et al., 1987; Szabo and Totten, 1995) and with New York and New Jersey glacial records (Stanford et al., 2021). The persistence of this glacial lobe lends further credibility to the endurance of flow from the Labrador Ice Dome to the southern Laurentide ice margin, consistent with the MIS 3 ice sheet reconstruction of Gowan et al. (2021), as well as during MIS 6 and MIS 12 (Batchelor et al., 2019). The prominent central lobe and Huron-Erie lobe signature for MIS 3 loess supports previous DZ analyses of pre-LGM sediments in the Gulf of Mexico that suggest a reduced western, Missouri catchment sediment source from 70 to 30 ka (Fildani et al., 2018).

At Thebes Core and Vicksburg Section, a notable abundance of young (<275 Ma) zircon ages in MIS 3 and older loess units suggests that some fraction of the sediment was also transported from western source regions, although not necessarily from Des Moines Lobe-equivalent outwash, as these samples do not plot near the Des Moines Lobe in Fig. 11. The fluvial contributions of the Missouri

River (upstream at Thebes Core) and the Arkansas River (upstream at Vicksburg Section) may represent an unsampled, non-glacial source that contributed these young zircon grains, drawing these older loess DZ age distributions away from the Huron-Erie Lobe in NMDS space (Fig. 11). Whether these rivers followed their modern path is unclear, but a fluvial network that eroded and transported western U.S. Cenozoic and Mesozoic sediments, containing zircons derived from Cordilleran plutons, to the Mississippi River Valley, was also likely present during MIS 3, MIS 6, and MIS 12. Although young (<275 Ma) zircon ages are present at these downstream sites, Oligocene age grains associated with the White River and Arikaree Groups are almost completely absent. Zircon grains of this age form a dominant population mode in Peoria Silt within the Missouri River valley in central Nebraska and western Iowa (Aleinikoff et al., 2008). Their absence in MIS 2 loess from Mississippi River valley sites below the Missouri River confluence suggests that nonglacial inputs from either the White River and Arikaree Groups or recycled from periglacial erosion of Peoria Silt in the Great Plains were relatively minimal. We do observe some Oligocene age zircon grains in the Roxana Silt at Vicksburg Section that might be of White River and Arikaree Group provenance. We caution however that volcanic units associated with the Eocene-Miocene ignimbrite flare-up are widespread throughout Cenozoic sediments of the western U.S. and an ancestral, MIS 3 Arkansas River could also have sourced this material. The absence of Oligocene-aged zircon grains in Roxana Silt at Swimming Pool Section (i.e., upstream of the Arkansas) suggests that the Arkansas River was the more likely source for Oligocene grains at Vicksburg Section.

Evidence of some sediment contribution from western-sourced river systems prior to MIS 2 contrasts with DZ results from the Gulf of Mexico Pleistocene sediment record, which show more limited sediment from these western-sourced river systems prior to the LGM (Fildani et al., 2018). However, the Gulf of Mexico DZ record compiled by Mason et al. (2017) also focused on these same sediments approximating MIS 3-MIS 2. The results of the earlier study suggest low sediment inputs from the Arkansas and Ohio River systems into the lower Mississippi during this time, with most sediment originating from the Missouri River catchment. In the case of the Ohio River contribution, this inferred lack of sediment is interpreted as potentially the result of sediment impoundment within glacial lakes. These results also contradict our findings, but we caution that a direct comparison between our results and records from the Gulf is complicated given differences in endmembers. In this study, glacial endmembers are represented by glacial tills, whereas in the previous studies modern river sediment is used to approximate last glacial age river sediment inputs. Other differences in the study methodologies that limit direct comparison include sediment grain size (sand vs. silt), proximity to tributaries of sample sites (proximal vs. distal), and resolution of depositional ages, particularly in the context of different Marine Isotope Stages. Our data therefore emphasize the importance of considering upstream and downstream sediments as provenance indicators to best understand the extent of North American drainage integration in the Quaternary.

5. Conclusions

The DZ age distributions from LGM (MIS 2) loess and till deposits of this study, highlight the efficacy of this method for distinguishing glacial lobes and deciphering loess provenance in the midcontinental USA. LGM loess samples, proximal to the Illinois River Valley, have DZ age distributions that support prior interpretations of loess sediment sources. Specifically, they reveal, through the varying presence of a Des Moines Lobe DZ signature,

the divergence of the Ancient Mississippi River to its present course by the Lake Michigan Lobe at $24,460 \pm 120$ cal yr BP (Curry, 1998; Nash et al., 2018). Similarly, DZ data from loess in western Tennessee is consistent with the Ohio River's pre-LGM location on the eastern side of Crowley's Ridge during deposition of the Roxana Silt and lower Peoria Silt (Rittenour et al., 2007). Agreement between our results and previous studies serves as a methodological proof-of-concept and highlights the potential of future DZ studies in glacial loess deposits.

DZ ages from Roxana Silt in the Illinois River Valley indicate a limited contribution from a Des Moines Lobe equivalent during MIS 3, suggesting a short-lived, reduced or absent Des Moines Lobe during this time. The DZ age distribution from the Loveland Silt (MIS 6) at Thebes Core is closely aligned with MIS 2 central lobe till data, suggesting a strong component of sediment sourced from these lobes. Overall, there is a strong association between the DZ age distribution of the composite Huron-Erie Lobe till sample and pre-LGM loess samples, suggesting an important sediment contribution from the eastern glacial margin prior to the LGM. This finding suggests ice flow from the eastern Labrador Dome was a persistent feature during earlier glaciations (including MIS 3). Young (<275 Ma) western-derived DZ ages are also present in pre-LGM loess of the middle and lower Mississippi River Valley, which suggests that drainage networks equivalent to the modern Missouri and Arkansas River systems were integrated with the Mississippi River system and provided some combination of glacial and non-glacial sediment. Thus, the loess DZ record of midcontinental North America, unique in terms of its spatial and temporal extent, highlights the importance of considering upstream as well as downstream sedimentary units in the Mississippi River Basin to decipher the evolution of glacial lobe extent and drainage patterns through the Quaternary.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We would like to thank Dan Larson from the Department of Earth Sciences at the University of Memphis for his guidance to and at Swimming Pool Section. We would also like to express our appreciation to the undergraduate researchers, Donald Hamlin, Catherine Nield and Cam DeSilva who aided in lab work, and our colleagues who aided in fieldwork, Mingfei Chen and Jacob Dixon. We also thank Henry Loope and Jose Luis Antinao Rojas (Indiana Geological Survey) for aiding with sampling of till units at the Clayton Section, Indiana. We also thank Brandon Curry from the Illinois State Geological Survey for an early review of the manuscript. This research is primarily funded by NSF - EAR 1637481 to JLC, DAG, and WRG. We also acknowledge NSF - EAR 1649254 for support of the Arizona LaserChron Center.

Raw U–Pb age data for all samples are archived on the Geochron EARTHTIME database at: <http://www.geochron.org>

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quascirev.2021.107201>.

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