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New insights on the loess/paleosol Quaternary stratigraphy from key sections in the U.S. Midwest

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Abstract

Three key Quaternary loess/paleosol sections were examined in the Missouri Valley (Iowa), Eustis Ash Pit (Nebraska), and in the Wittsburg Quarry (Arkansas) to gain insights into the sedimentation, environment and climate change of the U.S. Midwest. Four loess units are present separated by three well-developed paleosols. Crowley's Ridge Loess (Oxygen Isotope Stage (OIS) 8) is pre-Illinoian in age, and is the oldest loess unit investigated. A well-developed paleosol, interpreted as Yarmouth Soil (OIS 7), is found in this loess in all three sections. Overlying the Yarmouth Soil is Loveland Loess (OIS 6) which has been pedogenically altered by the Sangamon Soil (OIS 5). It has luvisolic properties but a more clayey pedogenic texture than modern luvisols and has no clear eluvial horizon. The overlying Roxana Silt (OIS 4) is pedogenically altered. At Wittsburg and Missouri Valley, the Farmdale Soil (OIS 3) is developed in the Roxana Silt. Based on pedogenic features, we correlate this paleosol to that developed in the Gilman Canyon Formation at Eustis. In Missouri Valley and Eustis sections, the paleosol has chernozemic properties and therefore, the gleyic features observed at Missouri Valley are interpreted as later alterations. Overlying the Farmdale Soil is the widespread Peoria Loess (OIS 2).

Keywords: Paleosols; Loess; Quaternary; U.S. Midwest

1. Introduction

The Quaternary loess/paleosol stratigraphy of the Midwest U.S. is an important proxy record for North American ice sheet activity and environmental changes. Loess/paleosol sequences are observed mainly along wide river valleys, commonly from the lower Mississippi Valley north to the Platte and Upper Missouri River basins. The loess and paleosol horizons within this region can be traced thousands of kilometres and record more than 600 ka of terrestrial sedimentation history. This area has at least five main Quaternary loess units alternating with paleosols (Fig. 2). Paleosurfaces and numerous features of continuous environmental processes are displayed within the sequences. Since loess was first noted by Lyell along the Mississippi River in 1846, its genesis and distribution became the focus of Quaternary research (see Follmer, 1996). Later research indicated that the dark-coloured layers in loess were fossil soils and subsequently associated with interglacial epochs (Leighton and Willman, 1950; Thorp et al., 1951; Ruhe, 1965, 1974; Follmer, 1978).

Recently, most loess/paleosol research is based on the use of multiple techniques and supplementary proxy records. The correlation of eolian deposits and till as well

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as isotope dates provides support for the loess/paleosol stratigraphy (Frye et al., 1974; McKay and Follmer, 1985; Leigh and Knox, 1994; Grimley et al., 1998, 2003). Mineralogical analysis, magnetic susceptibility and detail grain size distribution are additional techniques for loess source determination (Frye et al., 1962, West et al., 1980; Feng et al., 1994; Grimley, 1996, 1998; Grimley et al., 1998). Since the 1990s, magnetic parameters have been an important tool for paleoenvironment reconstruction (Evans and Heller, 2001, 2003). In the Midwest U.S. magnetic susceptibility has already been applied to Quaternary loess/paleosol series for both environmental reconstruction and regional stratigraphic correlation (Markewich, 1993; Feng et al., 1994, Rousseau and Kukla, 1994; Grimley, 1996, 1998; Grimley et al., 1998, 2003).

This paper focuses on three Quaternary loess/paleosol sections of the mid-continent area of the U.S. They include Wittsburg Quarry at Crowley's Ridge, northeastern Arkansas (35°11′N, 90°42′W), Eustis Ash Pit on the Platte River, southern Nebraska (40°38′N, 100°04′W), and Missouri Valley Section in the Loess Hills, western Iowa (41°34′N, 95°54′W) (Fig. 1). The first two sections have been studied extensively (e.g., West et al., 1980; Johnson et al., 1984; Guccione et al., 1988; Porter and Bishop, 1990; Rutledge et al., 1990; Feng et al., 1994; Mirecki and Miller, 1994; Rousseau and Kukla, 1994; Maat and Johnson, 1996). The Missouri Valley section, described herein for the first time, is situated just 7 km from the Loveland paratype section (Daniels and Handy, 1959; Forman et al., 1992). These sections were selected as major loess/paleosol records of terrestrial sedimentation and weathering in the U.S. Midwest (Follmer, 1996).

The objectives are: (1) to determine the paleosol genesis and depositional/climatic environments, with an emphasis

Fig. 1. Map of the Midwest US showing the location of sites under study. Explanation: 1 – Quaternary glacial border (after: Follmer, 1996); 2 – International borders; 3 – sites under study.

on magnetic susceptibility and soil micromorphology; and, (2) to compare and correlate the results with other sequences across the Midwest U.S.

2. Loess stratigraphy from previous studies

Early studies conducted on Midwest loess/paleosol sequences identified four main phases of loess deposition along the Mississippi Valley, punctuated by three soil-forming intervals (Leighton and Willman, 1950; Willman and Frye, 1970) although some investigators distinguished more units along the Missouri Valley (Reed and Dreeszen, 1965; Shultz, 1968). Few changes or additions have been made to the sequences since then, although some points are still under debate (for example see reviews by Follmer, 1996 and by Rutledge et al., 1996). Five Quaternary loess units with four interlayered paleosols are currently the most complete sequence for the Missouri and middle Mississippi River Valleys based on glacial and periglacial deposit correlation and ^{14}C and thermoluminescence (TL) ages (Fig. 2).

The Middle Pleistocene sequence of eolian deposits in the middle Mississippi River Valley consists of the Marianna (or Fifth) Loess and the Crowley's Ridge (or Fourth) Loess with corresponding paleosols, and the Loveland (or Third) Loess of presumably Illinoian age (Fig. 2) (Rutledge et al., 1990; West and Rutledge, 1994; Follmer, 1996). The Fourth (Crowley's Ridge) Loess was dated as 125–135 ka BP near Vicksburg, Mississippi and was considered to be Illinoian in age (Miller et al., 1986; McCraw and Autin, 1989 as cited in Rutledge et al., 1990). However, TL and ^{10}Be dates indicate that the Crowley's Ridge Loess in western Tennessee and eastern Arkansas is older than 200–250 ka and, therefore, is pre-Illinoian (Markewich et al., 1998). Two pre-Illinoian paleosols (Yarmouthian and Aftonian paleosols) separated by silt sediments were described by Willman and Frye (1970) for Illinois. Later, several authors described one or more pre-Illinoian paleosols at sections along the upper Mississippi and Illinois River Valleys, but their correlations with Middle Pleistocene paleosols of Arkansas and Nebraska regions were equivocal (Hajic, 1986; McKay, 1986; Leigh and Knox, 1994; Grimley and Follmer, 1995; Follmer, 1996). Reed and Dreeszen (1965) described eleven loess units in Nebraska, seven of which are pre-Illinoian but are not recognized outside of Nebraska (Follmer, 1996). In addition, Feng et al. (1994) noted several pre-Wisconsinian loess units in Kansas and Nebraska.

The most widely recognized loess horizon of the Middle Pleistocene in the U.S. Midwest is the Loveland Loess with the overlying Sangamon Soil (Fig. 2). This loess is Illinoian by age, up to 10 m thick. McKay and Follmer (1985), followed by Grimley et al. (2003), correlate the Loveland

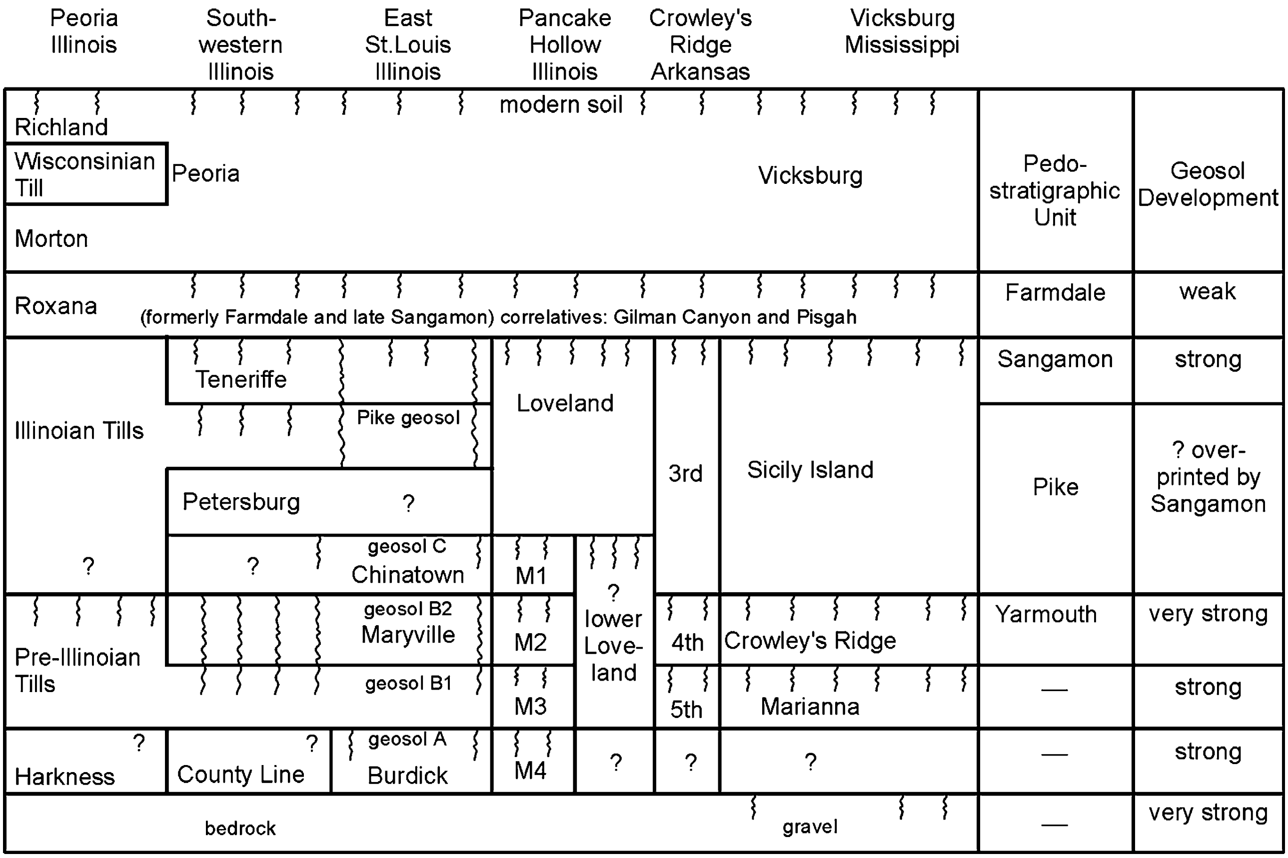

Fig. 2. Correlation of loess terminology and pedostratigrapic units in the Mississippi Valley region (after Follmer, 1996).

Loess of the Missouri and middle Mississippi River Valleys with Illinoian till and the Oxygen Isotope Stage (OIS) 6. Clark et al. (1989) and Mirecki and Miller (1994) concluded that the Loveland Loess is "pre-Wisconsin" or Illinoian in age, based on ages derived from amino acid ratios. Others correlate the Third (or Loveland) Loess with Early Wisconsinan Sicily Island Loess of Louisiana (Fig. 2) (Canfield, 1985; Miller et al., 1986; Pye and Johnson, 1988). Canfield (1985), for example, as cited by Rutledge et al. (1990) sampled the Third Loess "below the leached zone" in the Wittsburg Quarry section. He reported 85.3 ± 7.2 ka (partial bleach method) and 111.55 ± 11.6 ka (total bleach method) TL ages. As a consequence of the less reliable methods used to determine these ages, they are considered too young. Both ^{10}Be and TL ages of the lower part of the Loveland Loess are between 160 and 200 ka in the Missouri and middle Mississippi River Valleys (Forman et al., 1992; Markewich et al., 1998; Forman and Pierson, 2002).

In Nebraska and Kansas, the Loveland Loess is commonly subdivided into several units. The basal unit is a reworked volcanic ash which was Uranium fission-track dated in southern Nebraska at 620 ka by Shultz and Stout (1980, cited by Feng et al., 1994) and at 980 ± 300 ka by Feng et al. (1994), and recognized as the Lava Creek "B" ash layer. All silt sediments between the Gilman Canyon Soil and the Lava Creek "B" ash are described as Loveland Loess punctuated by four paleosols in Nebraska and Kansas (Reed and Dreeszen, 1965; Feng et al., 1994; Maat and Johnson, 1996). Some authors correlate the first paleosol above the basal ash layer in southern Nebraska and central Kansas with the Yarmouthian interglacial soil of the Mississippi Valley (Dreeszen, 1970), or with the Ingham Soil of an intra-Illinoian interstadial epoch (Shultz and Martin, 1970), or with OIS 11 (Feng et al., 1994). Dreeszen (1970) suggested two interstadial paleosols between the Yarmouth Soil and Sangamon Soil in the loess/paleosol series of Nebraska, a correlation supported by TL ages from central Kansas (Feng et al., 1994). Feng et al. (1994) present TL ages of 193 ± 22 ka, 260 ± 25 ka and 416 ± 35 ka for the first, second and third (lowest) paleosols, respectively situated below the Sangamon Soil and Gilman Canyon Soil. However, Wintle (2003) suggest s that ages over 100 ka may be unreliable. The data presented suggests to the authors that the Sicily Island and Loveland loesses are equivalent, and that the Loveland Loess and older units are pre-Sangamonian in age (Fig. 2).

The Sangamon Soil exhibits weathering characteristics comparable to the modern-day soil, and usually has a 1.8–2.5 m thick solum with a brownish argillic horizon. Regional changes in Sangamon Soil properties were relatively minor in comparison with the modern-day equivalents—southern reddish forest soils (Ruhe, 1965, 1974; Follmer, 1982). The Sangamon Soil was reported as the oldest paleosol in the Missouri River basin and in most parts of Iowa (Daniels and Handy, 1959; Ruhe, 1965; Forman et al., 1992). However, recent studies in these regions have separated till-derived and loess-derived material of the Sangamon Soil. The lower solum is correlated with the Yarmouth Soil of pre-Illinoian age (Guccione, 1983; Woida and Thompson, 1993; Rovey, 1997). One of the problems is the uncertainty of the elapsed time in the Sangamon Soil profile. Published ^{10}Be and TL ages from the parent (Loveland) loess and from the Roxana Silt immediately above the Sangamon solum suggest that the interval of the Sangamon formation is about 60–130 ka (Canfield, 1985; Norton and Bradford, 1985; Pye and Johnson, 1988; Forman et al., 1992; Maat and Johnson, 1996). Forman and Pierson (2002) reviewed data of 75 ± 10 ka loess accumulation and concluded that there might be more than one paleosol in the Early Wisconsinian loess stratigraphy of the mid-continental U.S., with morphologies similar to the Sangamon Soil. Studies of loess/paleosol series in Illinois support in places, a welded Farmdale, Sangamon and Yarmouth paleosol development (Grimley, 1996, 1998; Grimley et al., 1998, 2003). In summary, the soil profile usually recognized as the Sangamon Soil has a complicated history.

The Sangamon Soil is overlain by a pinkish–brown to grey–brown silt loam, exhibiting paleosol development. Regional names of this stratigraphic unit include the Roxana Silt (Mississippi River Basin), Pisgah Formation (Missouri River Basin) and Gilman Canyon Formation (Nebraska and Kansas) (Fig. 2) (Follmer, 1996). The change in names is primarily due to variations in geochemical characteristics and source of materials. The Roxana Silt and Pisgah Formation contain the Farmdale Soil. The Farmdale Soil is gleyed in many places and usually described as a weakly developed fossil soil that decreases in weathering intensity from its base to its gradational surface (Follmer, 1983; Norton et al., 1988; Leigh, 1994; West and Rutledge, 1994; Markewich et al., 1998). The Roxana Silt and the Farmdale Soil formed during OIS 3 and OIS 4. Radiocarbon and TL age estimates from the upper and middle part of Roxana Silt, range between 27 and 40 ka and between 25 and 35 ka in the Pisgah Formation. Berilium-10, ^{14}C, and TL dates from the lower part of the Roxana Silt indicate that it accumulated between 48 and 30 ka (Forman et al., 1992; Feng et al., 1994; Maat and Johnson, 1996; Markewich et al., 1998). The lowest unit of the Roxana Silt (Markham Member, a mixed zone of colluvium and eolian deposits) may have been deposited between about 55 and 75 ka along the Illinois and central Mississippi River Valley (Frye et al., 1974; McKay, 1986; Grimley, 1996; Grimley et al., 1998). Miller et al. (1986) conclude that the unit they correlated with the Sicily Island Loess of Louisiana was deposited during this same time interval. However, the correlation causes other correlation problems considering the various TL ages mentioned above. It may be correlative with Loveland Silt. The Gilman Canyon Formation, the equivalent of the Roxana Silt and Pisgah Formation, is found in

Nebraska and Kansas. The Gilman Canyon Soil, darker and more weathered than the Farmdale Soil, marks the upper boundary of the formation in which it is found. There are a number of radiocarbon ages that suggest that the top of the Gilman Canyon Soil varies between about 20 and 24 ka. It is difficult to bracket the age of the paleosol because some sections contain more than one paleosol. What can be said is that Gilman Canyon Silt began accumulating between 45 and 50 ka as suggested by TL ages (Johnson et al., 1984, 1998; Feng et al., 1994; Maat and Johnson, 1996). Together, the Farmdale Soil and the Gilman Canyon Soil developed during OIS 3 (Johnson, 1993).

The uppermost loess formation, the Peoria Loess, overlies the entire study area. It is characterized by a thick, calcareous silt loam that hosts the Holocene soil. The Peoria Loess accumulated during the Late Wisconsin Glaciation between about 10–23 ka in Nebraska, Kansas and Colorado (Feng et al., 1994; Muhs et al., 1999), and between about 12.5–25 ka along the Mississippi River Valley and most other regions of the Midwest U.S. (Leigh and Knox, 1994; Wang et al., 2003). Over most of the study region, this loess is described as a uniform, and the thickest loess unit.

3. Methods and materials

3.1. Field methods

Loess/paleosol sections were described at each site. Description focused on the physical characteristics of the sediments, and on the relationship between lithostratigraphic units and overprinted pedostratigraphic units. Once descriptions were completed, two suites of samples were collected from representative lithostratigraphic units and paleosol horizons: 1) bulk samples for geochemical, grain size and magnetic susceptibility analyzes; and 2) thin-section samples for micromorphological study. A total of 236 samples were collected: 118 oriented undisturbed blocks for thin section preparation and 118 bulk samples.

3.2. Laboratory methods

Several geochemical and physical laboratory techniques were used to analyze the bulk samples. Organic carbon (wt.%) was determined by $K_2Cr_2O_7$ oxidation by the Tyurin method (Zyrin and Orlov, 1980). Soil organic matter content (more accurately, the humus content) was calculated from the organic carbon results (wt.%) by the application of a conversion ratio equal to 1.732 as recommended by Zyrin and Orlov (1980). Carbonate content (wt.%) was determined by the volumometric Kozlovsky method and recalculated to $CaCO_3$ equivalent (Arinushkina, 1970). After the initial carbonate estimate, the grain size analysis for all bulk samples was performed by wet sieving ($>63\,\mu m$) and by X-ray Sedigraph[4] ($<63\,\mu m$) (Coakley and Syvitski, 1991). Samples that yielded high carbonate values (>4% by $CaCO_3$ equivalent) were pre-treated with 10% HCl prior to the 63 μm wet sieving, as recommended by Coakley and Syvitski (1991) to disaggregate particles cemented with secondary carbonate. Total iron, aluminium and silica were obtained by ignition from 80 selected samples and recalculated to sesquioxide ratios (SiO_2/Al_2O_3 and SiO_2/Fe_2O_3) to estimate the translocation of components by weathering processes[5] (Arinushkina, 1970). Particle density was determined by the pycnometer method for all lithological units in 23 selected samples (Blake and Hartge, 1986).

Mass-specific low frequency magnetic susceptibility (MS_{lf}, 0.465 kHz) and high frequency magnetic susceptibility (MS_{hf}, 4.65 kHz) were measured for all 118 bulk samples.[6] Disaggregated bulk sub-samples were placed into 10 cm^3 cubic containers and measured using the Bartington MS2 meter and MS2B dual-frequency sensor. Frequency dependence of magnetic susceptibility (FD) was calculated to monitor possible neoformation of ultrafine superparamagnetic minerals (Evans and Heller, 2003).

Micromorphological description and microphotography were conducted on the thin sections to refine the interpretation of geochemical analyzes and to reconstruct the soils' genesis. The thin sections (about 30 μm thick) for all 118 undisturbed oriented samples were prepared by standard techniques (Murphy, 1986) and evaluated for microstructure and pedogenic features with a petrographic microscope.[7] Terminology used to describe microstructure and other features follows Bullock et al. (1985).

The World Reference Base for Soil Resources soil classification (Food and Agriculture Organization of the United Nations et al., 1998) was applied to the diagnosed paleosols. Textural classes are based on the Canadian System of Soil Classification (Soil Classification Working Group, 1998).

Loess horizons in trenches W-1b-99, E-1-99 and MV-1-99 have been sampled for grain surface texture and roundness. A 0.5- to 1.0-mm fraction was studied using procedures developed in the Institute of Geography, Russian Academy of Sciences (Velichko and Timireva, 1995).

All ages quoted in this paper are from the work of others and are referenced as such.

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[4] The X-ray grain-size analysis was carried out at the Department of Earth and Atmospheric Science of the University of Alberta (Edmonton, Canada) with the Micrometrics SediGraph 5100 system.

[5] Geochemical analyzes including organic carbon, carbonate content and total iron, aluminum and silica were performed at the Laboratory of Soil Geography and Evolution, Institute of Geography, Russian Academy of Sciences (Moscow, Russia).

[6] Magnetic parameters were measured at the Laboratory of Paleomagnetism and Petromagnetism, Department of Physics of the University of Alberta (Edmonton, Canada).

[7] Thin sections were prepared at the Laboratory of Soil Geography and Evolution, Institute of Geography, Russian Academy of Science (Moscow, Russia) and analyzed by T.D. Morozova.

4. Results and interpretation

4.1. Missouri Valley section

The section examined lies 7 km north of the Loveland paratype section (Daniels and Handy, 1959; Forman et al., 1992) at the town of Missouri Valley (Fig. 1). This new section is named Missouri Valley, and reveals a different stratigraphy than that of the nearby Loveland section. Pre-Illinoian till and glaciofluvial sands are exposed at its base with the loess/paleosol horizons exposed along the 80-m-long cliff of a former quarry. Four loess units are recognized.

The thick basal till (MV-1) contains well-developed carbonate concretions up to 30 cm long, polylithologic pebbles, and boulders up to 50 cm in diameter (Fig. 3; Table 1). The 1.2-m-thick stratified unit MV-2 above has silt loam to a sandy texture and contains some pebbles. The lower silt unit MV-3 is massive, has a silt loam texture, and a 45–52% coarse silt fraction. It is interpreted as loess. The MV-3 loess is altered by a paleosol, which is leached of carbonate. MS_{lf} and FD in the Ah2 horizons of this paleosol reach their highest values in this section (Fig. 3). Other pedogenic features include the presence of relatively high organic carbon, a few krotovinas and small iron–manganese nodules. Therefore, this paleosol is considered to be an interglacial paleosol. The upper boundary of the Ah horizon has an accretionary pattern indicated by humus and magnetic parameters.

The overlying 2.8-m thick MV-4 loess unit has a high (up to 45%) clay content. However, ratios of coarse silt fractions (31–50 μm : 10–31 μm) through MV-3 and MV-4 units show uniformity (Fig. 3). The data suggest that MV-4 and MV-5 are loess units with similar sources. Clay enrichment of MV-4 unit results from a paleosol altering the entire loess unit.

The paleosol, developed in the MV-4 unit, includes Ah1, Ah2, Bt, Bw, and C horizons, and has a slightly lower MS_{lf} and FD values with a peak in its Ah2 horizon, than the paleosol below in the MV-3 unit. The soil has a dark humus-rich Ah horizon, a reddish (Al and Fe sesquioxides) Bt horizon with clay enrichment (40–45%), and a Bw horizon with krotovinas. Angular aggregates, a speckled-b fabric, and numerous clay coatings are identified micromorphologically (Fig. 4a, b) and therefore, the soil is interpreted as a Luvisol. Based on well-developed luvic properties and an accretionary Ah horizon, the paleosol is correlated with the Sangamon Soil. Therefore, the loess unit MV-4 is the Loveland Loess and the paleosol below the Sangamon Soil is tentatively classified as the Yarmouth Soil, which is common for central and southern Iowa (Woida and Thompson, 1993; Rovey, 1997) as well as for southern Illinois (Grimley et al., 2003).

The younger silt unit MV-5, altered by pedogenic processes in the upper part, is 2.45 m thick and exhibits a relatively uniform texture dominated by silt (68–75%). Based on these characteristics, this unit is interpreted as loess. The upper part of this loess unit is altered by a paleosol with Ah, and Ck horizons. This paleosol appears to be weakly developed because of its relatively low colour values and distinct gleyic properties (Fig. 4c). However, the solum contains a humus-rich horizon near its surface, a high amount of pedogenic clay, and is leached of carbonate to a depth about 1.1 m. The most obvious feature is numerous krotovinas formed by burrowing animals in its lower part (Ck horizon). This suggest to the authors that the original soil developed under relatively well drained conditions providing habitat to animals more likely than in a water-saturated gleying environment. Micromorphology shows massive microstructure with occasional sub-vertical fissures. The paleosol is therefore classified as a Chernozem, later altered by gleying processes. Based on its stratigraphic position and gleyed properties, and the relationship with the Sangamon Soil, this paleosol is identified as the Farmdale Soil.

The silt loam unit MV-6 overlying the Farmdale Soil is 3 m thick, has high porosity, about 70–75% silt, and is carbonate-rich (8–14%). The unit is identified as a loess, and correlated with the Peoria Loess by its stratigraphic position and “typical” loess features. The Peoria Loess is generally homogeneous. Typical features are the dominance of 10–50 μm particles, low clay content, and presence of carbonates. The loess contains a high amount of half-mat and mat sand grains (64% in classes II and III) indicative of eolian transport (Fig. 4d). There are also poorly rounded grains with glossy surfaces, some with conchoidal fractures suggesting a “glacial derived” appearance, as well the presence of glossy alluvial grains. The roundness coefficient is 57%, and degree of matting 48%. It is suggested that the sequence is primarily loess with perhaps some particles deposited by other methods other than wind, such as fluvial and glacial processes. The modern-day overlying soil has phaeozem properties typical for the area.

In both the Loveland paratype section and the Missouri Valley section, the Late Pleistocene loess is separated by a paleosol, identified as Farmdale on the basis of TL and ^{14}C dates (34–24 ka, Forman et al., 1992). The loess units are underlain by an interglacial paleosol interpreted as Sangamon. The TL dating of the Loveland Loess (165–125 ka, Forman et al., 1992) in the Loveland section corroborates the interpretation. However, unlike the Loveland section, there is another paleosol in the Missouri Valley section between the Sangamon Soil and glacial deposits at the base of the section. This soil displays Ah horizons, some mottles and krotovinas and relatively high MS_{lf} signals. The profile is less defined than the Sangamon Soil. In southern Iowa, Yarmouth Soil has been described at the same stratigraphic level (Woida and Thompson, 1993; Rovey, 1997) as the pre-Sangamonian paleosol described here. Thermoluminescence ages of samples taken from the contact between the loess and glacial deposits (165 ± 20 ka, Forman et al., 1992) does

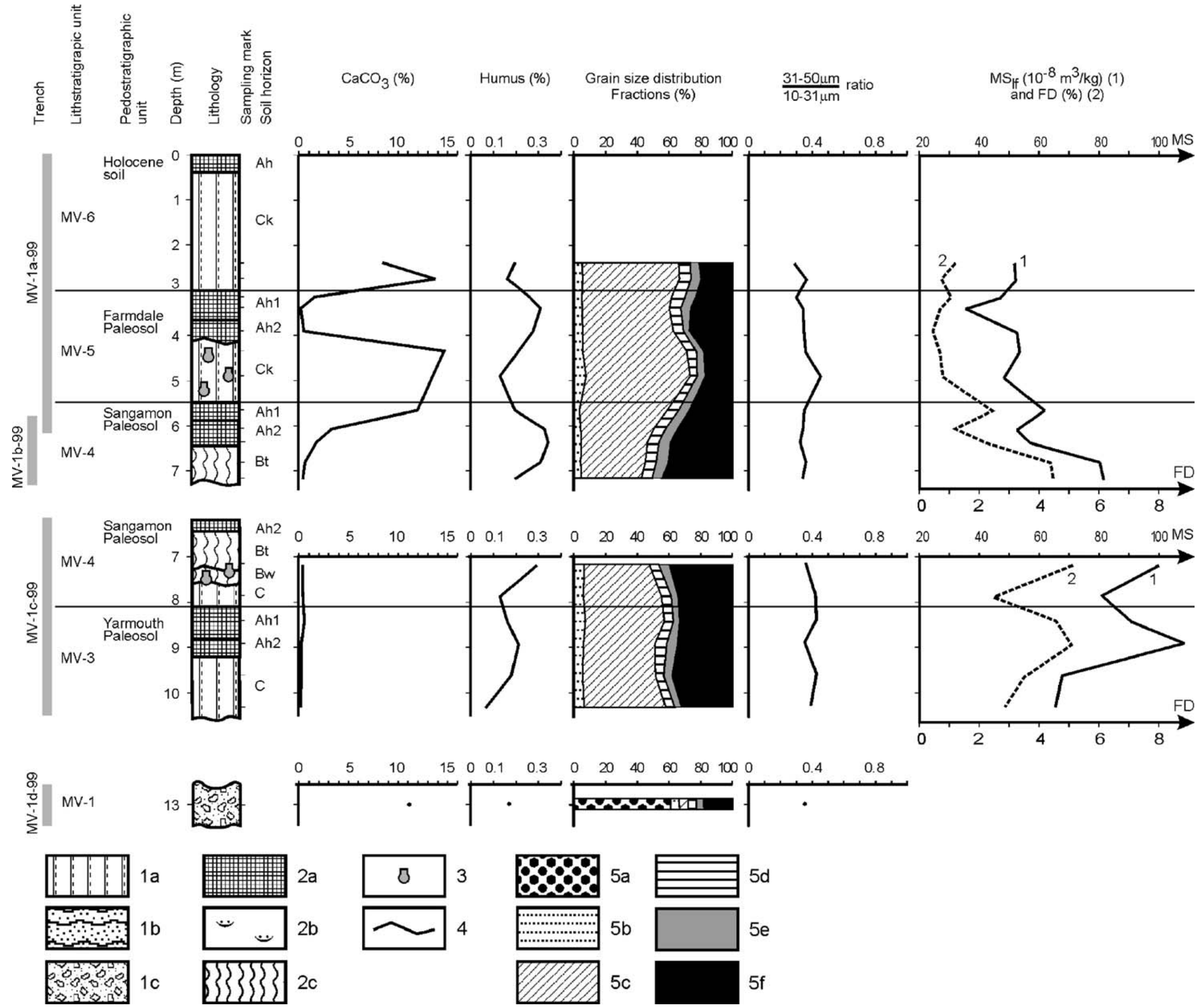

Fig. 3. Stratigraphy and selected analytical data for Missouri Valley section. Explanation for lithology and pedogenic properties: 1 – lithofacies, (1a) massive silt, (1b) laminated silt, (1c) diamicton and gravel; 2 – pedogenic horizons, (2a) Ah and AC horizons, (2b) Ae horizons, (2c) Bt and Bw horizons; 3 – krotovinas; 4 – irregular contacts; 5 – grain size fractions (μm), (5a) >1000; (5b) 50–1000, (5c) 10–50, (5d) 5–10, (5e) 2–5, (5f) <2.

Table 1
Description of the Missouri Valley section

Trench	Stratigraphic unit		Depth interval (m)	Soil horizon	Muncell colour	Texture class	Structure	Pedofeatures
	Name	Code						
MV-1a	Holocene Soil	MV-6	0.00–0.35	Ah	N2/m	SiL		
	Peoria Loess		0.35–3.00	Ck	2.5Y7/3d	SiL	Massive	Few carbonates along root traces, common gley mottles and weak bands (grey and rusty), lower contact abrupt
	Farmdale Soil	MV-5	3.00–3.65	Ah1	2.5Y6/3d	SiL	Massive, hard	Few carbonates along root traces, few Fe–Mn nodules, common gley mottles with carbonate nuclei (up to 6 × 8 cm)
			3.65–4.10	Ah2	2.5Y6/3d slightly lighter than above	SiL	Massive, hard	Bioturbations, common krotovinas (2 and 5 cm in diameter), few carbonates, few gley blotches, few Fe–Mn nodules, lower boundary slightly wavy
	Roxana Silt		4.10–5.45	Ck	2.5Y6/4d	SiL	Massive, soft	Many krotovinas in the upper portion (up to 15 cm in diameter, 2.5Y5/4d), few carbonate concretions. (up to 1 cm), few Fe–Mn nodules
	Sangamon Soil	MV-4	5.45–5.85	Ah1	2.5Y6/4d slightly darker than above	SiL	Massive, hard	Few carbonates along root traces (<1 cm), few rusty mottles (up to 1 cm), few darker layers at the top
MV-1b	Sangamon Soil	MV-4	5.85–6.45	Ah2	2.5Y5/4d	SiCL	Massive, hard to very hard	Few to common carbonate concretions (up to 2 cm), few gley mottles (up to 4 cm)
			6.45–7.55	Bt	10YR4/6d	SiC	Massive to weak fine blocky, very hard	Few carbonate concretions at the top (up to 1 cm), few rusty mottles at the top (up to 1 cm), few Fe–Mn nodules
MV-1c	Sangamon Soil	MV-4	7.55–6.45	Ah2	2.5YR5/4d	SiCL	Massive, hard to very hard	Few to common carbonate concretions (up to 2 cm), few gley mottles (up to 4 cm)
			6.45–7.40	Bt	10YR4/6d	SiC	Massive to weak fine blocky, very hard	Few carbonate concretions at the top (up to 1 cm), few rusty mottles at the top (up to 1 cm), few Fe–Mn nodules
			7.40–7.60	Bw	different colours	silt		Many krotovinas (up to 90%, up to 35 cm in diameter)
	Loveland Loess		7.60–8.20	C	10YR6/4d	SiCL	Massive, hard	Common krotovinas (up to 8 cm), few carbonate concretions along root traces
	Yarmouth Soil	MV-3	8.20–8.60	Ah1	10YR5/4d	SiCL	Massive, hard	Few Fe–Mn nodules (up to 1 cm), few brownish mottles in the lower part
			8.60–9.20	Ah2	10YR4/4d	SiCL	Massive, hard	Few Fe–Mn nodules, few krotovinas
	Crowley's Ridge Loess	MV-3	9.20–10.75	C	10YR5/4d	SiCL	Massive, hard	Few bioturbations, few Fe–Mn nodules (up to 1.5 cm)
	Pre-Illinoian glaciofluvial sediments	MV-2	10.75–12.30		10YR5/4d	SL to S	Stratified, consolidated at the bottom	Consolidated sand with small clasts (up to 2 cm), wavy darker stripes and lenses
MV-1d	Pre-Illinoian till	MV-1	12.30+		grey	skeletal loam	Consolidated, very hard, slightly friable	Clasts (up to 6 cm, subangular, subrounded), shield material, quartzites with Ca coatings, diagonal and vertical fractures with oxidation, common carbonate concretions (up to 30 cm)

Abbreviations for the texture classes are: HC – heavy clay; C – clay; SiC – silty clay; SiCL – silty clay loam; CL clay loam; SC – sandy clay; SiL – silt loam; L – loam; SCL – sandy clay loam; SL sandy loam; Si – silt; LS – loamy sand; S – sand (cf. Soil Classification Working Group, 1998).

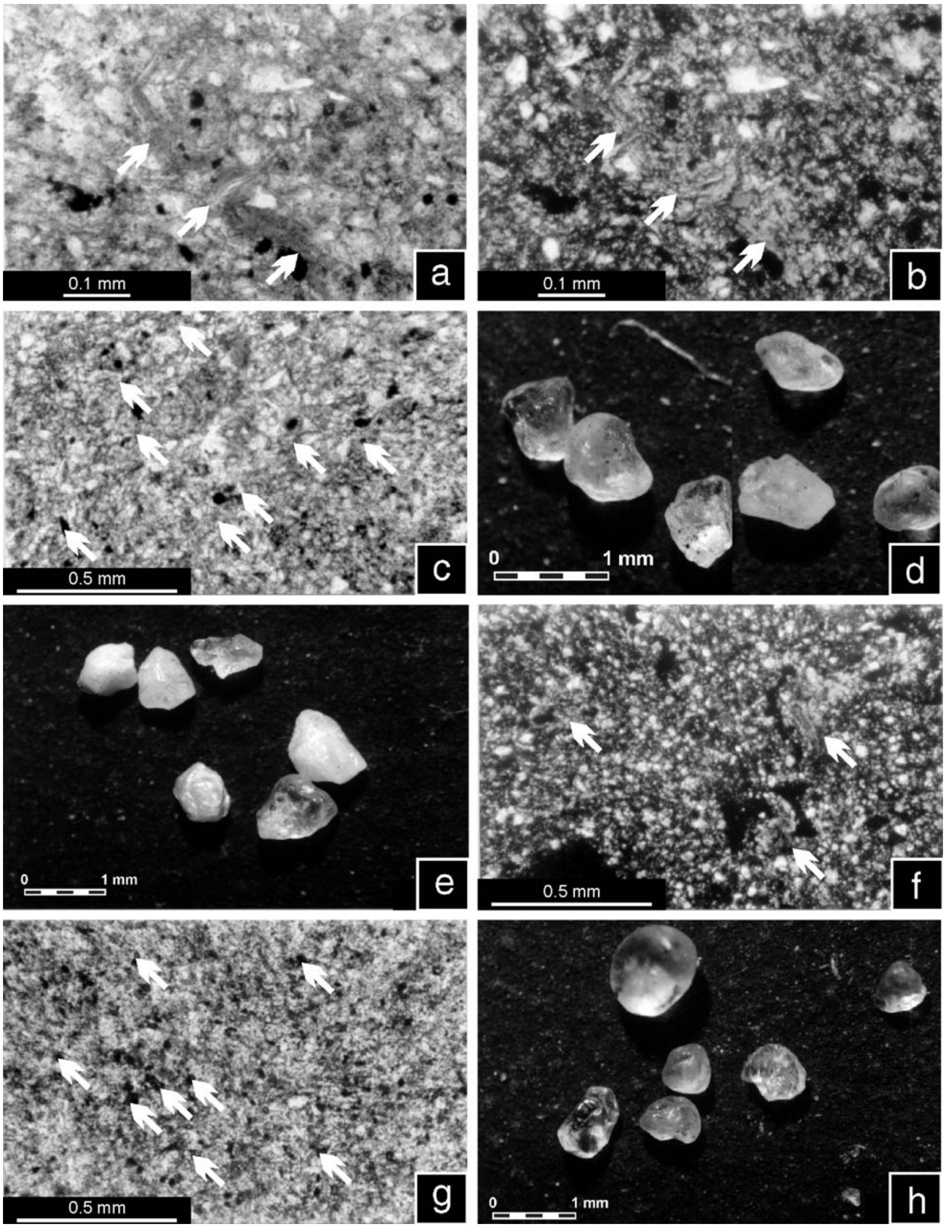

Fig. 4. Micromorphological features. Missouri Valley section: (a) Sangamon soil, Bt horizon: thick clay coatings, secondary iron nodules. Plane-polarized light (PPL). (b) The same: cross-polarized light (XPL). (c) Farmdale soil, Bw horizon: iron nodules, weak aggregation; PPL. (d) Peoria loess: micrograph of sand grains (0.5–1.0 mm), Eustis Ash Pit section. (e) Peoria loess: micrograph of sand grains (0.5–1.0 mm), Wittsburg Quarry section. (f) Sangamon soil, Bt horizon: thick clay coatings, XPL. (g) Farmdale soil, Bw horizon: iron nodules, weak aggregation (PPL). (h) Sangamon soil, Ah horizon: micrograph of sand grains (0.5–1.0 mm).

not rule out the possibility of both glacial deposits and the overlying loess belonging to the Illinoian.

4.2. Eustis Ash Pit section

The second section investigated was the Eustis Ash Pit (Fig. 1) in southern Nebraska. Up to seven loess units were identified (Fig. 5; Table 2). The basal lithological unit E-1 is represented by a redeposited loess/volcanic ash. It is recognized as the Lava Creek “B” ash layer dated at 980 ± 300 ka (Shultz and Stout, 1980; Feng et al., 1994). Unit E-2 is relatively thick and has high sand, and low clay content. It is interpreted as a loess, because of the high coarse silt fraction and the lack of lamination. The paleosol developed near the top of E-2 is weakly developed, but does exhibit a slightly higher chroma (10YR6/4d) than the bounding loess units (10YR6/3d) and has weak angular blocky to platy structure. The pedogenitically altered AC horizon is 0.3-m thick, leached of carbonate, is interpreted as a Regosol. Occasional krotovinas are found at 2 m and 3 m below the paleosol’s surface.

The pedocomplex developed in E-4 and E-3, has two profiles indicating a complex history. Analytical investigations of units E-4 and E-3 indicate that the parent material is

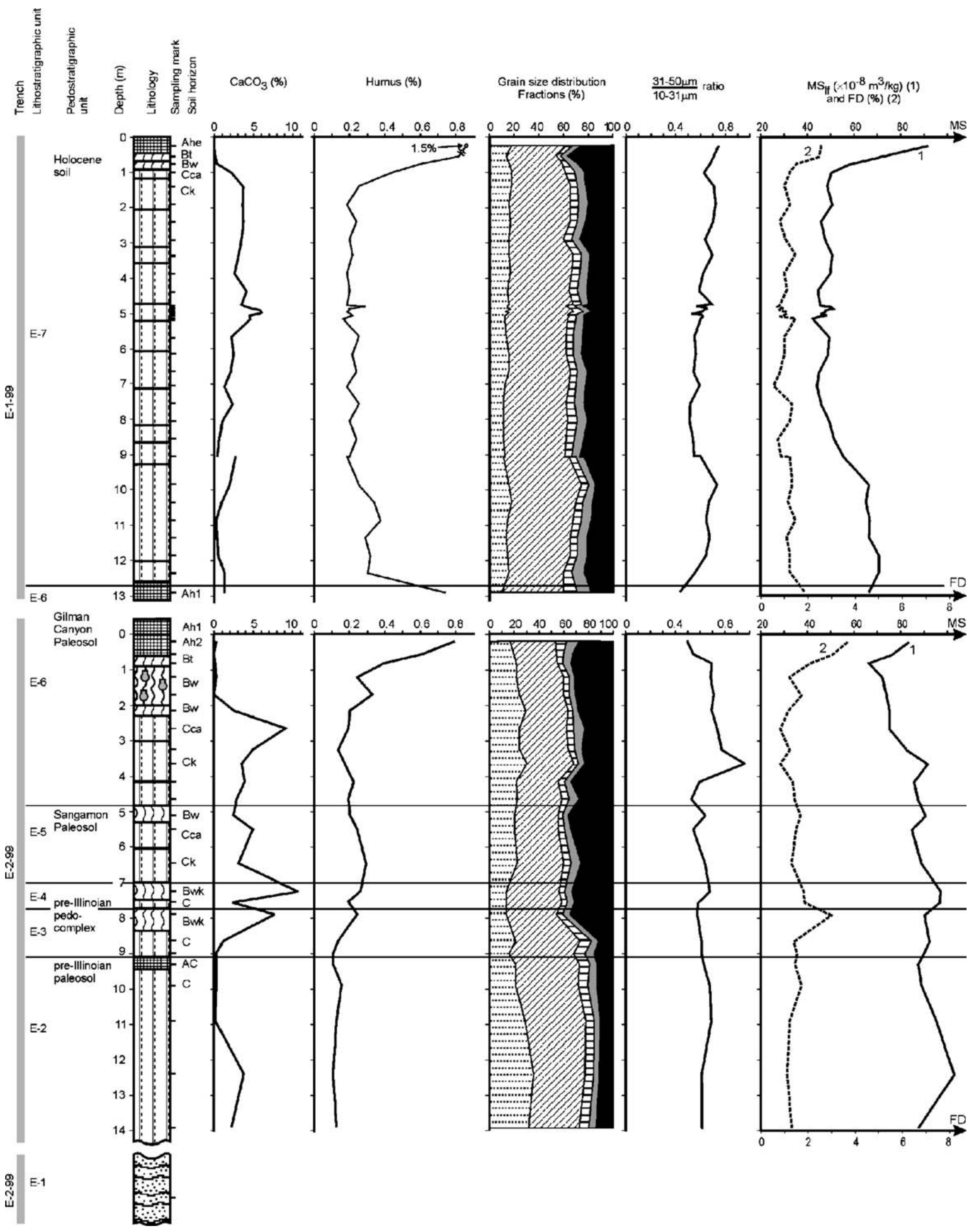

Fig. 5. Stratigraphy and selected analytical data for Eustis Ash Pit section: (a) upper part; (b) lower part. For explanation, see Fig. 3.

loess based on grain-size distribution. Both of the paleosols have distinct Bwk horizons and a reddish hue (7.5YR6/4d). Other features include weakly expressed peaks of humus, and MS_{lf} and FD associated with variations in the calcic Bwk horizons. The younger profile formed in E-4 may be defined as Calcisol. The older paleosol developed in E-3 has stippled b-fabric and occasional clay coatings indicating moderate mobility of plasma. Therefore, the older paleosol may be interpreted as an initial phase of the pedocomplex, when soil formation proceeded in relatively wet conditions, resulting in formation of a Calcisol with weak lamellic properties.

The silt unit E-5 has a high content of clay (26–36%) and coarse silt (35–38%), and is classified as loess (Fig. 5). This unit is TL dated at 163 ± 34 ka and interpreted as the Loveland Loess of Illinoian age (Maat and Johnson, 1996).

The paleosol developed in E-5 has a Bw and Cca horizon. The Ah horizon is eroded, with inclusions of brown

Table 2
Description of the Eustis Ash Pit section

Trench	Stratigraphic unit		Depth interval (m)	Soil horizon	Muncell colour	Texture class	Structure	Pedofeatures
	Name	Code						
E-1	Holocene Soil	E-7	0.00–0.45	Ahe	7.5YR4/1d	SiL	Moderate columnar+weak granular	Common living roots
			0.45–0.68	Bt	10YR4/2d	SiCL	Moderate columnar+medium angular blocky, hard	
			0.68–0.91	Bw	10YR5/3d	SiCL	Weak fine columnar+ subangular blocky, hard	Carbonates along aggregate surfaces
			0.91–1.17	Cca	10YR6/3d	SiL	Medium columnar+fine subangular blocky, slightly hard	Carbonated, bioturbations (up to 1 cm)
	Peoria Loess		1.17–2.05	Ck	10YR7/3d	SiL	Massive, soft	Few carbonates along pores, few molluscs shells
			2.05–3.10		10YR6/3d	SiL	Weakly stratified, single grain, soft	Few carbonates along pores, few Fe–Mn nodules, many gley mottles and bands (10YR7/8d and 10YR7/2d)
			3.10–3.55		10YR7/8d	SiL	Single grain, soft	Few carbonates along pores, few gley mottles
			3.55–4.70		10YR7/8d	SiL	Weakly stratified, single grain, soft	Few carbonates along pores, many gley mottles and bands, few Fe–Mn nodules
			4.70–5.18		10YR7/8d	SiL	Weakly stratified, single grain, soft	Few carbonates along pores, few gley bands, bioturbations at the base (up to 1 × 4 cm)
			5.18–6.70		10YR7/8d	SiL	Weakly stratified, single grain, soft	Few carbonates along pores, common gley mottles
			6.70–7.13		10YR6/3d	SiL	Weakly stratified, single grain, soft	Banding is wavy, few molluscs shells, common gley mottles
			7.13–8.15		10YR6/4d	SiL	Massive, soft	Common mollusk shells, few carbonates along pores
			8.15–8.65		10YR6/3d	SiL	Weakly stratified, single grain, soft	Fe mottles along pores, common gley mottles
			8.65–12.1		2.5Y7/3d	SiL	Massive, soft	Common root traces with oxidation rings, few carbonates
			12.10–12.70		2.5Y7/3d darker than above	SiL	Massive, soft	Common root traces with oxidation rings
	Gilman Canyon Soil	E-6	12.70–13.10	Ah1	10YR5/3d	SiL	Single grain, soft	Porous, few root traces, few carbonate concretions (up to 0.2 cm)
E-2	Gilman Canyon Soil	E-6	−0.20–0.00	Ah1	10YR5/3d	SiL	Single grain, soft	Porous, few root traces, few carbonate concretions (up to 0.2 cm)
			0.00–0.65	Ah2	10YR4/3d more brownish to bottom	SiL to SiCL	Weak medium columnar+ weak coarse platy or fine angular blocky, slightly hard	
			0.65–0.90	Bt	10YR5/6d	CL	Massive, hard	Few carbonate concretions (up to 0.5 × 3 cm), few bioturbations (up to 0.1 cm)
			0.90–2.00	Bw	10YR6/4d	CL	Massive, hard	Few carbonate concretions, common bioturbations, common krotovinas (up to 10 cm in diameter)
			2.00–2.30	Bw	10YR6/4d	CL	Massive, hard	More sand than above and below
	Gilman Canyon Silt		2.30–3.00	Cca	10YR6/4d	SiL	Massive, hard	Calcareous, few carbonate concretions (up to 0.5 × 3 cm)
			3.00–4.10	Ck	10YR7/4d	SiL to L	Massive, hard	Few carbonate concretions at the top (up to 0.3 cm)
			4.10–4.80		10YR6/4d	SiL to CL	Massive, hard	Few carbonate concretions (up to 0.5 × 3 cm)

(continued on next page)

Table 2 (*continued*)

Trench	Stratigraphic unit		Depth interval (m)	Soil horizon	Muncell colour	Texture class	Structure	Pedofeatures
	Name	Code						
E-2	Sangamon Soil	E-5	4.80–5.30	Bwk	10YR5/4d	CL	Massive, hard	Few carbonate concretions, porous, few Fe–Mn nodules (<1 mm in diameter)
			5.30–6.05	Cca	10YR6/4d	SiCL	Massive, hard	Common carbonate concretions (up to 0.5 × 3 cm)
	Loveland Loess		6.05–7.00	Ck	10YR6/4d	SiL	Massive	Few carbonate concretions (up to 0.3 cm)
	Pre-Illinoian pedo-complex	E-4	7.00–7.48	Bwk	7.5YR6/4d	SiCL	Massive, hard	Common carbonate concretions (up to 0.4 cm at upper portion and up to 2 × 4 cm at lower portion), few small brownish veinlets (up to 15 cm deep)
			7.48–7.73	C	7.5YR6/4d	SiCL	Massive, hard	Carbonate pedofeatures: common dense elongate blotches (up to 1 × 20 cm); few low-dense blotches (up to 1 × 3 cm)
		E-3	7.73-8.30	Bwk	7.5YR5/4d	SiCL	Massive, hard	Carbonate pedofeatures: common stringers, pseudo-micilla and nodules (up to 2 × 4 cm)
	Pre-Illinoian loess		8.30–9.16	C	10YR6/4d	SiL	Massive, hard	Few carbonate concretions (up to 1 cm in diameter and up to 1 × 3 cm)
	Pre-Illinoian paleosol	E-2	9.16–9.45	AC	10YR6/4d darker than above	SiL	Very weak angular blocky to platy, hard	Few carbonate concretions
	Pre-Illinoian loess		9.45–14.9	C	10YR6/3d	SiL	Single grain, soft	Single krotovina at 10.4 m and 11.6 m (up to 11 cm in diameter), few carbonates
	Lava Creek B volcanic ash	E-1	14.90+		10YR7/3d	SiL	Stratified ash and silt layers	Light and dark bands (1 to 4 cm thick)

Abbreviations for texture classes see Table 1.

material within the overlying E-6 loess unit. The 0.5-m-thick Bw horizon is light reddish brown, loose, and has a weak subangular blocky microstructure. The groundmass has a weakly pronounced b-fabric, primarily speckled. The Cca horizon is relatively massive with channel voids. Micritic carbonates impregnate the groundmass and form void coatings. There is no evidence of clay migration in the profile, so the paleosol is identified as a Calcisol, and is equated to the Sangamon Soil.

Grain-size analysis of silt unit E-6 produced varying ratios of coarse silt fractions (Fig. 5). This unit has high clay content (27–34%) and coarse silt (33–40%), but also has a high amount of fine to very fine sand (16–30%). Hence, it is classified as sandy loess. This unit yielded ages of 22 ka to 36 ka by ^{14}C and TL methods, and has been interpreted as Gilman Canyon Formation (Rousseau and Kukla, 1994; Feng et al., 1994; Maat and Johnson, 1996).

Unit E-6 contains evidence of varying degrees of pedogenesis. The paleosol is the best developed in this section with a complete profile consisting of Ah, Bt, Bw, and Cca horizons and can be identified as a Chernozem. It has maximum humus content of 0.8% and an aggregated Ah horizon with a spongy microstructure. Carbonates are absent in the horizon, except for small particles in the matrix. Micromorphological studies of Ah1 reveal a loose structured groundmass, speckled orientation in the humus-clay plasma and some plant remains. Judging from the relative position of the Ah1 horizon, it is suggested that the layer corresponds to the transition between optimal stage of chernozemic formation and the beginning of unit E-7 deposition. Micromorphological studies indicate that the Bt horizon is dense, light brown with clay coatings, non-aggregated, with inclusions of humus-rich material (derived from krotovinas). The b-fabric plasma shows a speckled pattern. The lower part of the horizon is impregnated with micritic carbonates. The proportion of $CaCO_3$ increases in the Cca horizon to 9.1%. These features have been described for the Gilman Canyon Soil in many sections along southern Nebraska and central Kansas (Johnson, 1993; Feng et al., 1994; Rousseau and Kukla, 1994; Maat and Johnson, 1996; Johnson et al., 1998).

The youngest and thickest unit is E-7. It is a silt loam with 15–18% sand. Based on grain size distribution and stratigraphic position this unit is identified as the Peoria

Loess. The loess is 10 m thick and forms the parent material for modern soils. It varies in structure showing subhorizontal lamination, with laminae 5–8 mm thick. Micromorphologically, the lamination exhibits interlayers of darker coloured silt and clay, and has a striated, weakly pronounced b-fabric. The lower part of the Peoria Loess is friable, with packing voids, characteristic of loess. The frequent textural variations within the Peoria Loess suggest change in depositional environments likely from climatic fluctuations during a cold stage. According to recent ^{14}C data, the Peoria Loess was deposited from about 20–12 ka BP in eastern Colorado (Muhs et al., 1999) and 24 ka BP to 10.5 ka BP in northwestern Nebraska and central Kansas (Feng et al., 1994; Rousseau and Kukla, 1994; Maat and Johnson, 1996). The available data indicate an abnormally high accumulation rate at the time of Peoria Loess deposition (3500 g m^2 a^{-1}) (Roberts et al., 2003).

The sand content of Peoria Loess consists of a majority of well rounded grains, with roundness coefficients varying from 42% to 65%, and degree of matting from 32% to 50% (Fig. 4e). Grain surfaces have pits of various sizes with fresh conchoidal scars dominating the surfaces. The majority of grains preserve their original appearance and have not been noticeably altered by eolian processes.

Prior to the Late Pleistocene, evidence from the Eustis Ash Pit reveals at least one interglacial stage displaying two phases of soil development, one in E-3 one in E-4. Although these soils can be distinguished, there is no unaltered loess separating them. The soils form a pedocomplex. This complex is underlain by relatively thick loess deposits containing a weak paleosol.

The Late Pleistocene of the Eustis section contains some datable material, but the results are often difficult to interpret. The interval contains two principal paleosols developed in E-5 and E-6. The older paleosol corresponds to Sangamon Soil based on a TL date of 163 ± 34 ka obtained by Maat and Johnson (1996) from loess E-5. However, as mentioned before, TL ages older than 100,000 ka are not reliable (Wintle, 2003). Taking into account that its upper part was eroded, this older paleosol is less developed than the younger one (Gilman Canyon Soil). On the other hand, the Gilman Canyon Soil pedogenic structure and characteristics are comparable with modern soils of Nebraska. It appears that C4 plants were dominant for the middle part of Gilman Canyon time and similar to the present day warm semiarid conditions at the Eustis site, whereas early and late Gilman Canyon time was characterized by a C3 plant environment—cool and moist (Johnson, 1993). The authors' best judgment is that the older paleosol is Sangamon based primarily on stratigraphic position.

4.3. Wittsburg Quarry section

The southernmost part of the Wittsburg Quarry was investigated in three sequences (Fig. 6; Table 3). Four loess units were identified above Pliocene basal gravel (WQ-1) in the Wittsburg Quarry and in a ravine directly west of the quarry. The upper parts of all four units have been pedogenically modified. As observed in the slopes of the ravine the lower loamy unit (WQ-2) is 4 m thick and is generally massive, whereas lamination was observed at the WQ-1 and WQ-2 contact and in the uppermost part of unit WQ-2. The high content of the 10–50 μm fraction and the lack of lamination indicate that WQ-2 is a loess unit. (Crowleys Ridge Loess, after Porter and Bishop, 1990). In the trench W-1b-99 this loess unit is covered by a 1-m-thick colluvial unit (WQ-3) containing a paleosol consisting of a 25-cm-thick Ah horizon overlying a brown Bt horizon about 1 m thick. The latter is underlain by a horizon with alternating brown (oxidized) and pale lamina with a few calcareous concretions 2 to 5 cm thick. This paleosol in the W-1b-99 trench has a distinct brown colour, with clay coatings; clay fraction and humus content increasing toward the base of the section, and MS$_{\mathrm{lf}}$ and FD with relatively high values.

The silty–clay loam unit WQ-4 has transitional contacts with WQ-3 and WQ-5 units and has uniform ratios of coarse silt fractions. The dominance of coarse silt and lack of lamination allow calling the WQ-4 unit as loess. The strongly developed paleosol in WQ-4 has altered the entire unit and partly overprinted the solum below. The paleosol in WQ-4 lacks carbonates and has a humus rich Ah horizon. It has a distinct concentration of pedogenic clay in its Bt horizon, along with depletion zones and other eluvial features in the Ahe horizon. The content of 10- to 50-μm-sized particles ranges from 51% to 57%, with clay content increasing in the Ah and Bt horizons to 34%. The MS$_{\mathrm{lf}}$ and FD of the Ah horizon contains the highest values in the section. The upper part of the paleosol has a brown humus horizon, unevenly coloured due to dark grey humus-rich aggregates. The plasma is rich in humus and clay, and features a speckled b-fabric and irregular shaped voids (Fig. 4f). The Ahe horizon is unevenly coloured due to alternating humus-rich aggregates and bleached zones depleted of plasma. Typical clay coatings are present, varying in colour from dark grey (enriched in humus) to brown to light brown. Accumulations of isotropic organic fine material of dark brown colour occur within humus-enriched zones. The Bt horizon is characterized by dark brown colour, with clay coatings and a clay content of 32–34%. Based on these characteristics, the paleosol is classified a Mollic Luvisol and correlated with the Sangamon Soil described previously (Rutledge et al., 1990).

The upper and lower contacts of WQ-5 slope westward with an 8° declination. Fluctuations of coarse silt fractions ratios within unit WQ-5 suggest that it is colluvial by origin with a paleosol developed in its surface. Two horizons are distinguished: the upper 0.30-m-thick AC horizon and a 0.20-m-thick Bw horizon below, consisting of light-brown silt loam. Laboratory analyzes show the humus content is 0.26% in the upper horizon increasing with depth to 0.34%, whereas the carbonate decreases with depth from 5.5% to

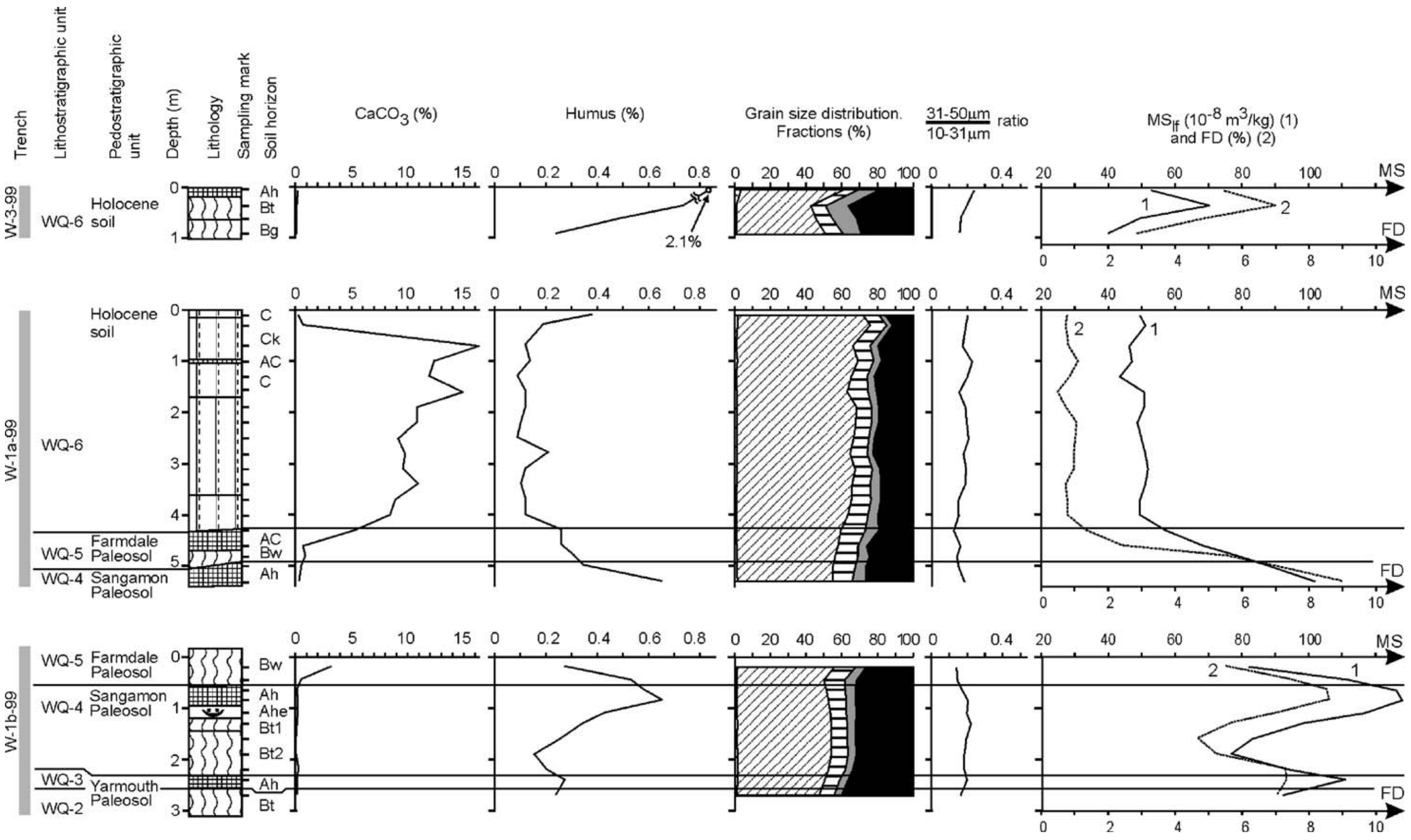

Fig. 6. Stratigraphy and selected analytical data for Wittsburg Quarry section. For explanation, see Fig. 3.

Table 3
Description of the Wittsburg Quarry section

Trench	Stratigraphic unit		Depth interval (m)	Soil horizon	Muncell colour	Texture class	Structure	Pedofeatures
	Name	Code						
W-3	Holocene Soil	WQ-6	0.00–0.15	Ah	10YR6/4d	SiL	Granular, soft	Many roots
			0.15–0.63	Bt	7.5YR5/6d	SiC to SiCL	Strong fine angular blocky, weak platy at the top	Thin clay coatings (5YR4/6d)
			0.63–1.00	Bg	7.5YR4/4d with 10YR8/3 mottles	SiCL	Fine subangular blocky	Gley mottles, few Fe–Mn nodules, bioturbation
W-1a	Holocene Soil	WQ-6	0.00–0.15	C	10YR5/4d	SiL	Massive, soft	Few organics, the soil solum was destroyed by quarry construction
	Peoria Loess	WQ-6	0.15–0.97	Ck	10YR6/4d	SiL to Si	Massive, soft	Few organics, few carbonate concretions
			0.97–1.06	AC	10YR6/4d	SiL	Massive, soft	Gley (grey and rusty) mottles
			1.06–1.70	C	10YR5/4d	SiL	Massive, soft	Faint organics along root system
			1.70–3.60		10YR5/4d and 10YR6/4d layers	SiL	Weakly stratified, soft	Faint organics traces along root system, few elongate carbonate concretes
			3.60–4.25		10YR5/4d	SiL	Massive, hard	Mn micronodules, gley mottles, few carbonate concretions Lower contact slopes West 8°–10°
	Farmdale Soil	WQ-5	4.25–4.55	AC	10YR5/4d	SiL	Massive, hard	Mn micronodules, gley mottles, few carbonate concretions (up to 1 cm)
			4.55–4.65	C	10YR5/4d	SiL	Massive, hard	Pale-yellow spots coarser than matrix, few krotovinas 5 cm in diameter
			4.65–4.90	Bw	10YR4/3d	SiL	Massive, hard	Common hard carbonate concretions some up to 6 cm, lower contact slopes, West 8°–10°
	Sangamon Soil	WQ-4	4.90–5.40	Ah	7.5YR4/3m	SiL	Massive, very hard	Micro-bioturbations, common carbonate concretions
W-1b	Farmdale Soil	WQ-5	0.00–0.55	Bw	7.5YR5/4d, slightly lighter at the bottom	SiL to SiCL	Massive, very hard	Few carbonate concretions (up to 3 cm)
	Sangamon Soil	WQ-4	0.55–0.95	Ah	7.5YR4/4d	SiCL	Massive, extremely hard	Root stringers, few carbonate concretions small vertical cracks up to 30 cm long with carbonate participation
			0.95–1.20	Ahe	7.5YR4/4d	SiCL	Massive, extremely hard	Small light-coloured spots
			1.20–1.45	Bt1	7.5YR5/4d	SiCL	Massive, very hard	Few carbonate concretions (up to 0.8 cm)
			1.45–2.30	Bt2	7.5YR5/4d darker than above	SiCL	Weak blocky, very hard	Few carbonate concretions (up to 1 cm)
	Yarmouth Soil	WQ-3	2.30–2.55	Ah	About 7.5YR6/6d	SiCL	Weakly stratified, hard	Layers are 2–5 cm thick, few carbonate concretions (up to 2 cm)
		WQ-2	2.55–3.10	Bt	About 7.5YR5/6d	SiC	Massive, hard	Few carbonate concretions (up to 2 cm)

Abbreviations for texture classes see Table 1.

0.9%. Micromorphological investigations show this paleosol is characterized by weakly developed pedality, massive microstructure and speckled b-fabric (Fig. 4g). There is some accumulation of micritic carbonate, carbonized plant remains, and a krotovina 4- to 5-cm in diameter. In addition, compact glaebules are present up to 6 cm in diameter composed of fine-grained carbonates with silicate mineral matter and a darker core about 2 cm in diameter. An X-ray diffraction analysis of a concretion revealed the presence of euhedral quartz, magnesium calcite, and plagioclase. It seems unlikely that the concretions are genetically related to this soil, perhaps reworked from Loveland Loess or earlier sediments. This paleosol is correlated to the Farmdale Soil and is interpreted as a weakly developed cumulic soil with some post development gleying.

The uppermost silt loam unit WQ-6 is the thickest and most typical loess in the section. It is light yellowish grey and it has a high proportion of 10–50 μm particles (up to 67%), whereas the clay fraction amounts to 18–23%. The humus content is low (0.14–0.21%, increasing near the surface of the Farmdale Soil underlying the loess. Carbonate content is high (9.1–16.4%, except the present-day soil solum) and oxides (SiO_2, Fe_2O_3, and Al_2O_3) are evenly distributed throughout the profile. Micromorphologically, the unit is not aggregated. The groundmass has a crystallite b-fabric as a result of a high content of micritic carbonate. Packing and biogenic voids, locally with micritic carbonate coatings, are pronounced, and vary from 0.6 to 1.0 mm in diameter. A few primary carbonate grains of about 0.05 mm in diameter occur. An analysis of sand grains from the Peoria Loess permitted us to distinguish two principal groups based on surface texture (Fig. 4h). The first group includes well-rounded sand grains (III and IV classes) which indicate eolian transport, with half-mat and mat surfaces. In the second group, grains are poorly rounded (I and II classes) with glossy and quarter-mat surfaces, slightly smoothed and pitted, probably formed in a water environment. The roundness coefficient is 55% and degree of matting 53%. The grains are presumably of fluvial origin, and subsequently subjected to some eolian transport. The WQ-6 unit is interpreted as loess and correlated with Peoria Loess of the middle Mississippi River Valley (West et al., 1980; Rutledge et al., 1990; Markewich et al., 1998). The present-day soil has distinct lamellic and weak gleyic properties.

Based on the above, the youngest loess is Peoria (unit WQ-6) and the lower unit is colluvial Roxana Silt (unit WQ-5). The latter is the parent material of the Farmdale Soil. The distinct Sangamon Soil is developed in Loveland Loess (unit WQ-4). The old paleosol is less confidently identified. It is commonly correlated with the Yarmouth Soil. The oldest loess at this site is Crowley's Ridge (unit WQ-2) (Porter and Bishop, 1990), lying on Pliocene gravelly alluvium (unit WQ-1).

5. Discussion

The present investigation of three key sections allows us to discuss the chronostratigraphy, pedogenesis and loess characteristics in the general context of the succession of events during the Pleistocene in the Midwest U.S.

Previous TL and ^{14}C dating results and stratigraphic relations support the correlation of the Gilman Canyon Formation of Kansas and Nebraska and the Roxana Silt found in Mississippi and Missouri River Valleys, although paleopedological characteristics of Gilman Canyon Soil and Farmdale Soil are different. The Farmdale soil was described in middle Mississippi and Missouri River Valleys as a weakly developed soil, with common gleyic features developed in a relatively cool and wet climate. (Norton and Bradford, 1985; Markewich et al., 1998). Our investigation provides evidence for a warmer and drier environment during initial formation. The gleyic features: a non-aggregated matrix, relatively high density, and partial removal and transformation of magnetic minerals, could have formed in a post burial environment. Humic characteristics, carbonate distribution and presence of ancient krotovinas suggest chernozemic processes were in play in well-drained areas of western Iowa. In the Wittsburg Quarry, the Farmdale Soil studied on an 8° slope, has strong Ca–Fe nodules and some burrowing animal krotovinas indicating relatively better drained conditions, than the weak accretionary nature of the profile formed later. The chernozemic genesis of the Gilman Canyon Soil has been already reported (Johnson et al., 1998) and our recent interpretation corroborate this interpretation. What we suggest then, is changing climatic conditions from warmer to cooler during this time interval. Our new data, obtained from the Missouri Valley and the Eustis Ash Pits sections, suggest that the Farmdale Soil and the Gilman Canyon Soil can now be correlated on similar pedological features (Fig. 7), as well as on ages. Our correlation of the three sites is presented in Fig. 7.

Relatively thick Loveland Loess was reported for the Wittsburg Quarry (8.6 m by West et al., 1980) and Loveland paratype sections (5.7 m by Daniels and Handy, 1959; 8.5 m by Forman et al., 1992). These authors did not identify the Yarmouth Soil in the sections and extended the loess unit to the basal diamicton. Porter and Bishop (1990) reported a Yarmouth Soil below the Loveland Loess in the Wittsburg Quarry developed in pre-Illinoian loess. They noted the maximum thickness of 2.43 m for its parent material (Crowley's Ridge Loess). In many areas along the Mississippi and Missouri River valleys other authors have reported both the welding of Sangamon and Yarmouth paleosols and the separation of the two paleosols by Loveland Loess, or the Yarmouth Soil below the Loveland Loess (Rutledge et al., 1990; Woida and Thompson, 1993; West and Rutledge, 1994; Rovey, 1997; Grimley et al., 2003). In southern Nebraska, the Loveland Loess is considered by some authors to be a group rather than a formation and divisible into three loess units, separated by paleosols (Reed and Dreeszen, 1965; Feng et al., 1994). If the Loveland Loess is used sensu stricto (Illinoian by age), then one or more of the older paleosols are likely Yarmouthian.

Our data indicate that the Wittsburg Quarry stratigraphy is in some places closer to the stratigraphy of the unglaciated Illinois region (Rutledge et al., 1990; Grimley et al., 2003). We agree that the well-developed paleosol recognized immediately below the Sangamon Soil solum correlates with the Yarmouth soil. Therefore, the Loveland Loess should be interpreted as relatively much thinner, and

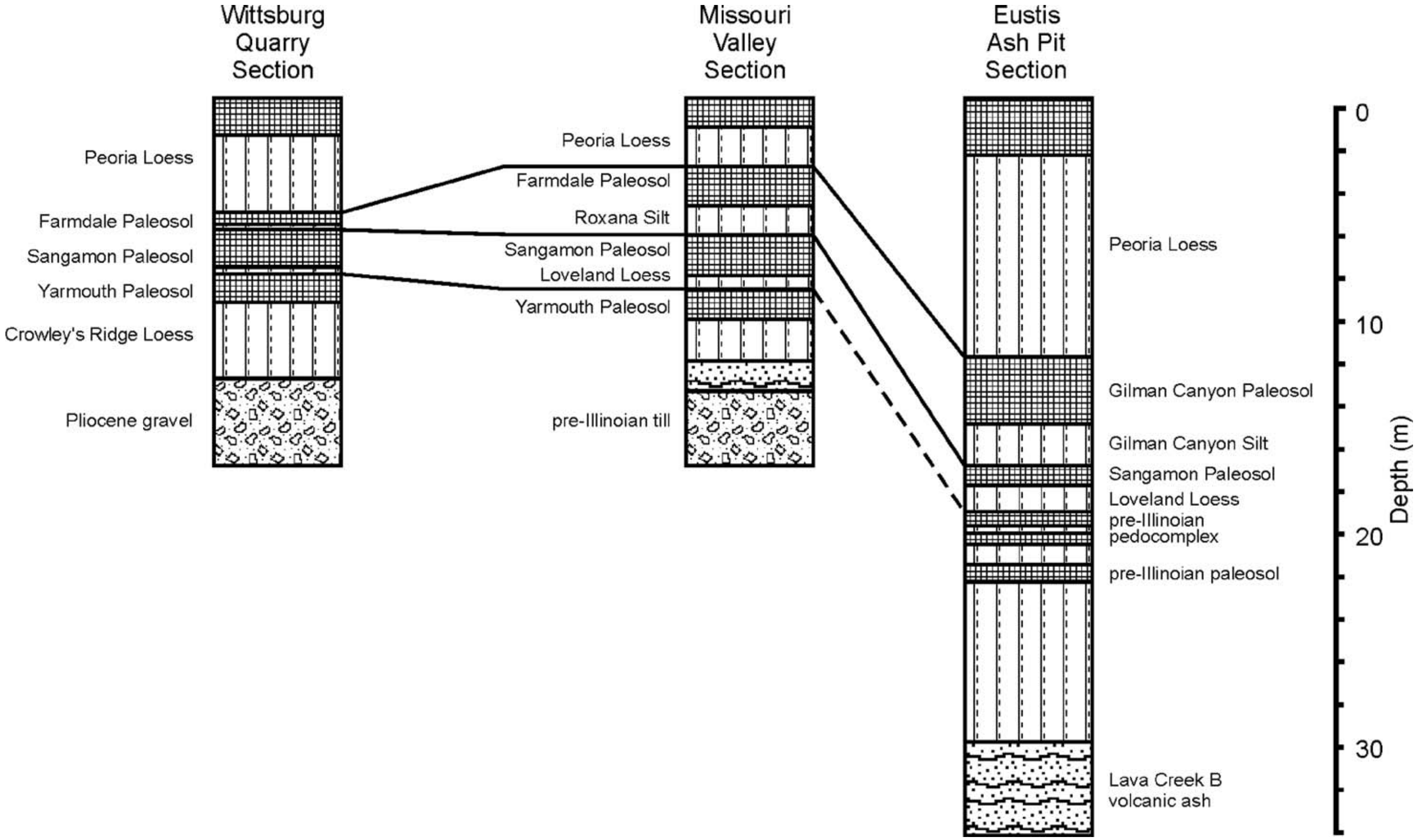

Fig. 7. Proposed correlation of Quaternary loess/paleosol units for investigated sections. For explanation, see Fig. 3.

the loess deposits below the Yarmouth Soil surface are interpreted as the Crowley's Ridge Loess. In western Iowa (Missouri Valley section) the Yarmouth Soil is similar in its relative degree of development as the Sangamon soil. Differences include fewer lessivage features, fewer krotovinas, and higher MS_{lf} and FD in the Yarmouth Soil. As a result, which of the two pre-Sangamon paleosols or both, of the Eustis section corresponds to the Yarmouth is questionable. We tentatively correlate our pre-Illinoian calcic paleosols found in the Eustis section with the Yarmouth Soil of Iowa and Illinois, although the complex nature of this paleosol leaves some doubt on this correlation. The Loveland Loess thickness observed in all sections did not exceed 3.7 m.

6. Conclusions

Detailed investigations of high resolution loess/paleosol sections in the Midwest U.S. has led to a more complete understanding of the stratigraphy and Late Pleistocene history of the region. Investigations included, among other things, magnetic susceptibility (MS_{lf} and FD), grain size determination, humus and carbonate content, and micromorphology.

New insights include:

1) The Farmdale Soil in the Missouri Valley section of western Iowa is interpreted as a chernozemic-like soil. Its gleyic properties are a result of post development processes that has compacted the paleosol and modified its colour.
2) The above soil then can be correlated with the Gilman Canyon Soil of southern Nebraska by both stratigraphic relationships and soil properties.
3) The Yarmouth Soil is identified in the Missouri Valley section (Loveland stratotype area, Iowa), and in the Wittsburg Quarry section (Crowley's Ridge, Arkansas). The soil is recognized immediately below the Sangamon Soil. Although the Sangamon Soil and Yarmouth Soil have many similar characteristics, they can be traced stratigraphically and allow correlation to the Yarmouth Soil described in many areas of the Mississippi River Valley.
4) The identification of the Yarmouth Soil in the Missouri Valley and Wittsburg Quarry sections below the Sangamon Soil revises the thickness of the Loveland Loess from 5.4 to 8.6 m as reported previously (Daniels and Handy, 1959; West et al., 1980; Forman et al., 1992) to a much thinner interval of 1.8–3.7 m.
5) The pedocomplex developed in pre-Illinoian loess at the Eustis Ash Pit section, Nebraska, suggests relatively wet conditions during the formation of the Yarmouth paleosol.
6) We tentatively correlate the Crowley's Ridge Loess to Oxygen Isotope Stage (OIS) 8, Yarmouth Soil to OIS 7, Loveland Loess to OIS 6, Sangamon Soil to OIS 5 (lower part of OIS 4?), Roxana Silt to OIS 4, Farmdale Soil to OIS 3 and Peoria Loess to OIS 2.

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