2013

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Quaternary Research 80 (2013) 468–481

Contents lists available at SciVerse ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

Chronology and provenance of last-glacial (Peoria) loess in western Iowa and paleoclimatic implications

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ARTICLE INFO

Article history:
Received 11 December 2012
Available online 17 October 2013

Keywords:
Peoria loess
Iowa
Optically stimulated luminescence dating
Trace element geochemistry
Magnetic minerals
Last glacial period
Stratigraphy
Laurentide ice sheet
Paleoclimate

ABSTRACT

Geologic archives show that the Earth was dustier during the last glacial period. One model suggests that increased gustiness (stronger, more frequent winds) enhanced dustiness. We tested this at Loveland, Iowa, one of the thickest deposits of last-glacial-age (Peoria) loess in the world. Based on K/Rb and Ba/Rb, loess was derived not only from glaciogenic sources of the Missouri River, but also distal loess from non-glacial sources in Nebraska. Optically stimulated luminescence (OSL) ages provide the first detailed chronology of Peoria Loess at Loveland. Deposition began after ~27 ka and continued until ~17 ka. OSL ages also indicate that mass accumulation rates (MARs) of loess were not constant. MARs were highest and grain size was coarsest during the time of middle Peoria Loess accretion, ~23 ka, when ~10 m of loess accumulated in no more than ~2000 yr and possibly much less. The timing of coarsest grain size and highest MAR, indicating strongest winds, coincides with a summer-insolation minimum at high latitudes in North America and the maximum southward extent of the Laurentide ice sheet. These observations suggest that increased dustiness during the last glacial period was driven largely by enhanced gustiness, forced by a steepened meridional temperature gradient.

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Introduction

One of the most remarkable aspects of the last glacial period was the increase in overall planetary dustiness. Deep-sea cores, ice cores, lake cores, soils, and loess deposits all document greater entrainment, transport and deposition of dust over much of the Earth at the time of the last-glacial maximum, or LGM (Mahowald et al., 2006; Kohfeld and Tegen, 2007; McGee et al., 2010; Muhs, 2013). The cause of the greater global dust flux during the LGM, as well as previous glacial periods, has been hypothesized to include such factors as stronger winds, increased aridity, a decreased intensity of the hydrological cycle, decreased vegetation cover, increased source areas (such as continental shelves), and increased sediment availability (such as glaciogenic silts). In a recent review, McGee et al. (2010) speculated that of these factors, increased "gustiness," defined by them as the strength and prevalence of dust-transporting winds, was the primary driver of greater global dustiness. [We note for clarity that the definition of "gustiness" as given by McGee et al. (2010) is not identical with that of the World Meteorological Organization (2008) wherein gustiness is defined as "…the extent to which wind is characterized by rapid fluctuations, and single fluctuations are called gusts."]. Enhanced gustiness, as defined by McGee et al. (2010), is inferred to be due to a greater meridional temperature contrast during the LGM.

Western Iowa is home to some of the thickest deposits of last-glacial age (Peoria) loess in the world (Fig. 1). Peoria Loess is found in the north–south-trending, ~300 km long, Loess Hills area of western Iowa and part of adjacent Missouri, with thicknesses ranging from ~25 to ~40 m. Loess in western Iowa has attracted the attention of geologists for almost a century (Carman, 1917, 1931; Kay and Apfel, 1929; Hutton, 1947; Ruhe, 1954, 1969, 1983; Simonson and Hutton, 1954; Daniels and Handy, 1959; Daniels et al., 1960; Bettis, 1990; Forman et al., 1992; Muhs and Bettis, 2000, 2003; Forman and Pierson, 2002). Despite the many years of study, there are still uncertainties about the depositional history of loess in western Iowa. Foremost among these are the precise chronology and conflicting hypotheses about the source of the loess. Both issues are critical to modeling dust flux and its effects on climate (Mahowald et al., 2006; Kohfeld and Tegen, 2007).

Uncertainties about the timing of loess deposition in western Iowa stem largely from a lack of suitable materials for radiocarbon dating. The existing radiocarbon chronology, summarized by Bettis et al. (2003), is based primarily on ages reported by Ruhe (1969, 1983), Ruhe et al. (1971), and Forman et al. (1992). Although these ages confirm that Peoria Loess in western Iowa is indeed of last-glacial age, the

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0033-5894/$ – see front matter. Published by Elsevier Inc. on behalf of University of Washington.
http://dx.doi.org/10.1016/j.yqres.2013.06.006

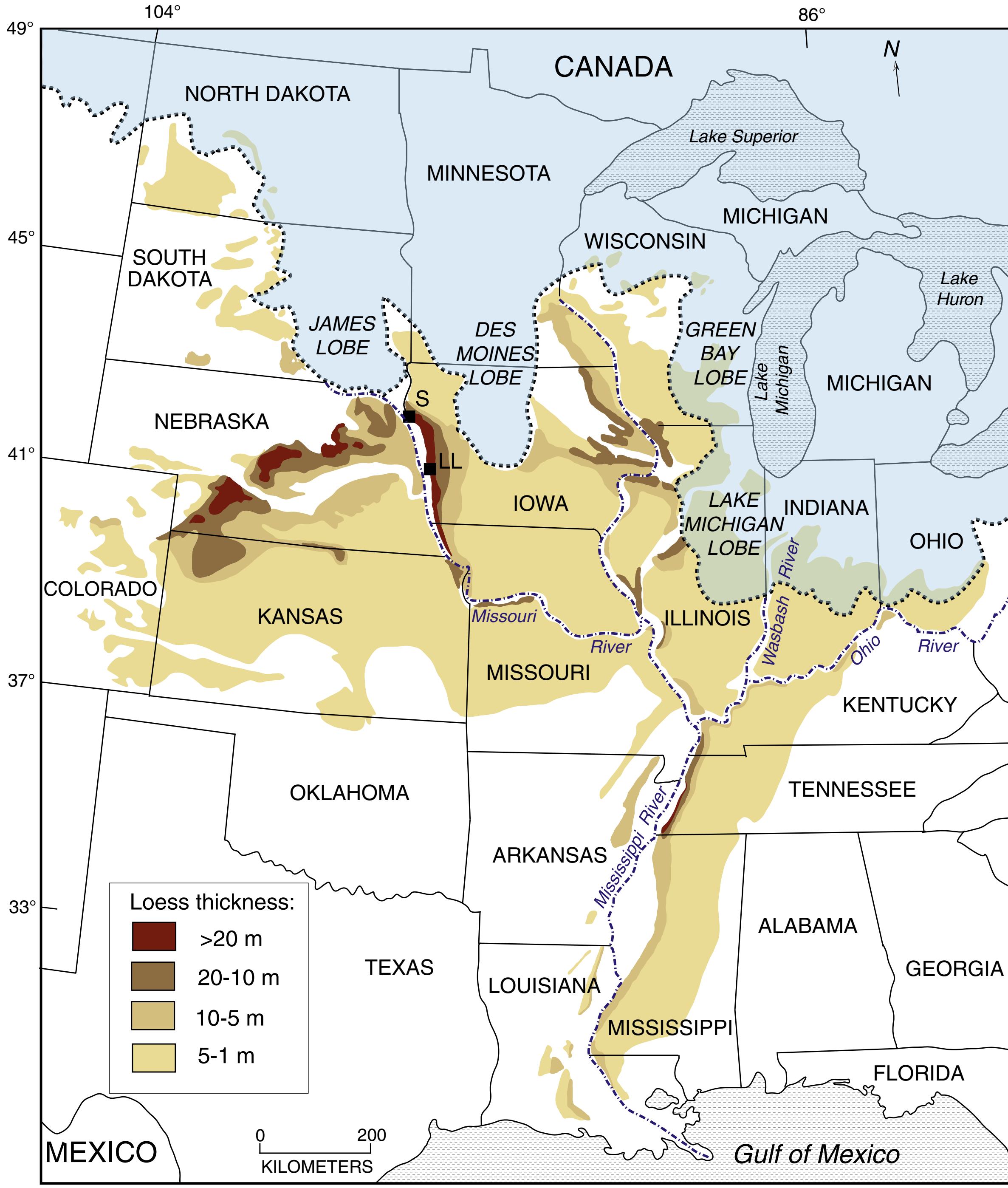

Figure 1. Distribution and thickness of loess, mostly Peoria Loess of last-glacial age, in central North America. Also shown (dashed line) is the maximum late-Wisconsin (last glacial) extent of the Laurentide ice sheet (light blue). Loess thickness and distribution taken from compilation in Bettis et al. (2003) and sources therein; Laurentide ice sheet extent generalized from Fullerton et al. (2003, 2004). LL, Loveland; S, Sioux City.

majority of radiocarbon determinations are maximum-limiting ages on organic materials in what was called the Farmdale Soil (=Farmdale Geosol) by Willman and Frye (1970), which underlies Peoria Loess. Far fewer ages are available for materials within Peoria Loess itself, and what few ages exist are mostly from disseminated organic matter of uncertain provenance.

The development of luminescence dating techniques has provided an independent means of dating eolian sediment that lacks organic materials suitable for radiocarbon dating. While early thermoluminescence (TL) dating in western Iowa yielded a number of stratigraphically inconsistent age estimates (Norton and Bradford, 1985), later work by Forman et al. (1992), using TL ages, and Forman and Pierson (2002), using infrared stimulated luminescence (IRSL) ages, gave better results. However, these studies were concerned primarily with pre-Peoria loess units, and only the oldest parts of Peoria Loess were dated.

Several studies (Daniels et al., 1960; Ruhe et al., 1971; Ruhe, 1983) have documented the existence of "dark bands," thin horizontal zones of darker color and slightly higher organic matter content, interpreted to be minimally developed soils. If this interpretation is correct, loess sedimentation was likely discontinuous, with periods slow enough for at least recognizable soil development. Furthermore, the lowermost zones of Peoria Loess in western Iowa do not contain

substantial amounts of carbonates, whereas the middle and upper zones are rich in carbonate (Ruhe, 1954). Ruhe (1983) offered two explanations for these differences: (1) the oldest Peoria Loess was derived from a non-calcareous (and possibly non-glacial) source and (2) the lower zones were subjected to syndepositional leaching during an initial period of slower loess sedimentation.

It has long been thought that Peoria Loess in western Iowa was derived from outwash on the Missouri River floodplain during the last glacial period (Carman, 1917; Kay and Apfel, 1929; Carman, 1931; Simonson and Hutton, 1954; Ruhe, 1969, 1983). Loess thins eastward from the Missouri River floodplain, displaying decreases in thickness that can be described mathematically (Ruhe, 1954; Muhs and Bettis, 2000). Nevertheless, alternative hypotheses for the origin of western Iowa loess have also been presented. As mentioned above, Ruhe (1983) suggests that at least the lower part of Peoria Loess could be derived from non-glacial sources, from local hillslope erosion of leached surface soils. Muhs and Bettis (2000) found distinct particle size differences within Peoria Loess at Loveland, Iowa. These investigators report coarse-grained lower and middle Peoria zones, and a fine-grained upper Peoria zone. They hypothesized that the lower and middle Peoria zones could be glaciogenic, derived from the Missouri River floodplain. In contrast, the finer-grained upper Peoria zone, however, was hypothesized to be the distal component of loess from Nebraska (Fig. 2), transported in high suspension across the Missouri River (Muhs and Bettis, 2000).

Aleinikoff et al. (2008) tested the distal-loess hypothesis of Muhs and Bettis (2000) by generating a U–Pb age spectrum of detrital zircons from the upper and lower Peoria zones at Loveland, Iowa. Peoria Loess in most of Nebraska is derived primarily from the Oligocene White River Group, a volcaniclastic siltstone. The White River Group contains abundant zircons that have a prominent mode at ~34 Ma, considered to be the age of the tephra-derived component of the unit. Neither lower nor upper Peoria Loess at Loveland, Iowa contain zircons of this age, but both have abundant zircons from Precambrian rocks of the Canadian Shield rocks that would have been traversed by the Laurentide ice sheet. Thus, Aleinikoff et al. (2008) concluded that

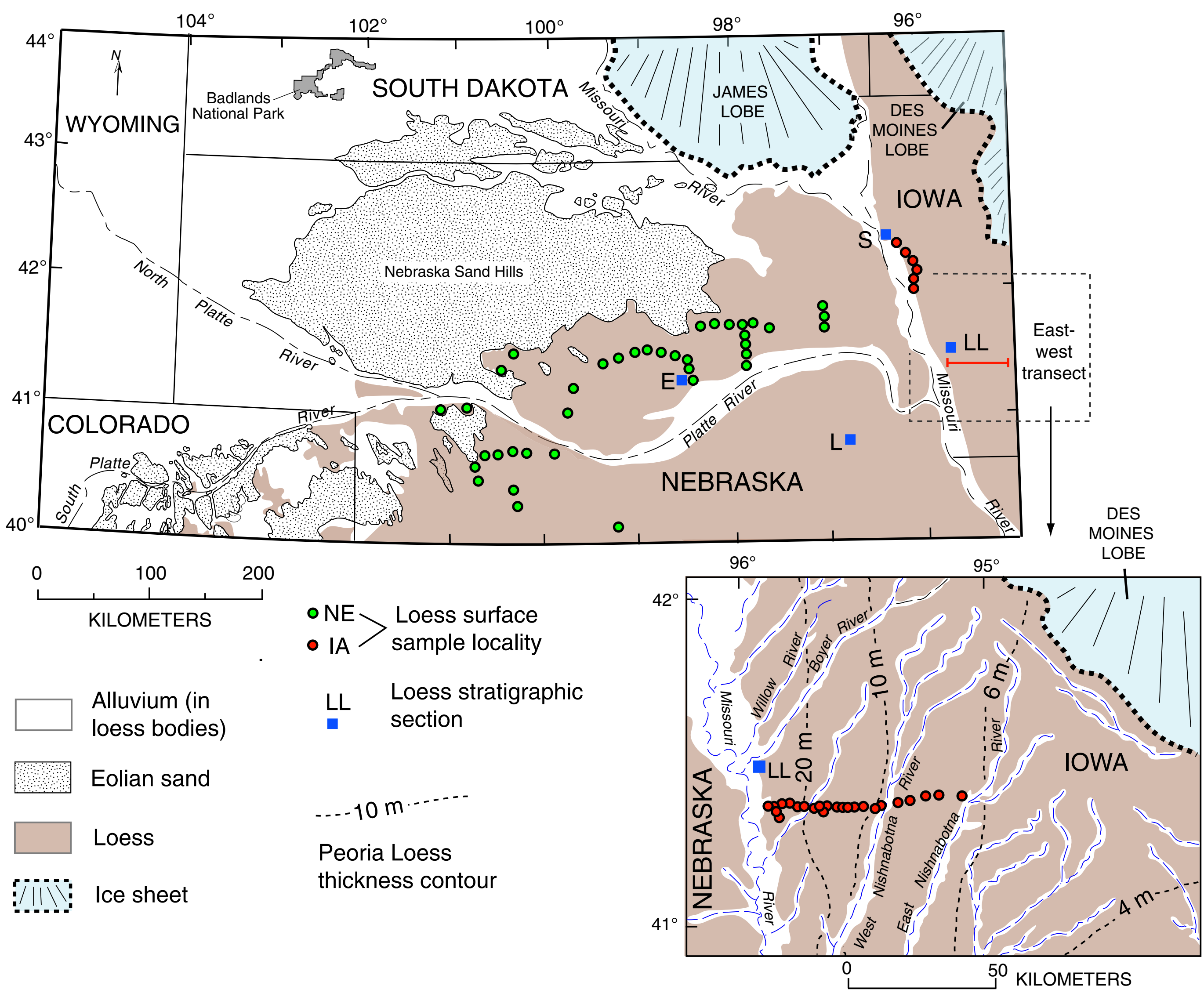

Figure 2. Map showing the distribution of loess and eolian sand in western Iowa, Nebraska and adjacent states, as well as sample localities, locations of loess sections, and other features referred to in the text. Abbreviations: E, Elba; L, Lincoln; LL, Loveland; S, Sioux City (Sergeant Bluff). Loess and eolian sand distribution based on Hallberg et al. (1991), Swinehart et al. (1994), Muhs et al. (1996, 1999), and Mason (2001). Enlarged map of southwestern Iowa (lower right) shows location of east–west loess transect, location of the loess section at Loveland, and contours of loess thickness (thickness data from Hallberg et al., 1991).

most or all Peoria Loess at Loveland, Iowa was derived from glaciogenic sediments from the Missouri River floodplain, a return to the traditional interpretation.

If distal Peoria Loess from Nebraska never reached Iowa, then there are important paleoclimatic implications about far-traveled dust that conflict with the conclusions of Roberts et al. (2003) and Mahowald et al. (2006) that loess transport distances and accumulation rates were dramatic in the Great Plains during the last glacial period. One limitation of using zircon for loess provenance is that it is a heavy mineral and also tends to be concentrated in the coarse silt and fine sand fractions. Such particles are winnowed out close to a source and may not be representative of the entire loess mineral suite. Indeed, Muhs and Bettis (2003) report that Zr concentrations in loess decrease systematically from west to east in a transect (Fig. 2) across western Iowa. Thus, zircon grains may not represent the transport history of lighter and finer-grained loess minerals that are capable of long-range transport.

Here, we attempt to resolve some of the issues regarding Peoria Loess deposition in western Iowa. Specifically, we test the existing hypotheses about the depositional chronology and sedimentation rates of loess by presenting optically stimulated luminescence (OSL) ages of loess through the entire last-glacial-age portion of the loess section at Loveland, Iowa. The site studied here is the Loveland Paratype Section of Daniels and Handy (1959), Bettis (1990), and Muhs and Bettis (2000), located at N41.50052°, W95.88934°. The stratigraphy and geochronology are augmented with new analyses of the magnetic properties of minerals throughout the section. We test hypotheses about the provenance of Peoria Loess in western Iowa using new major and trace element geochemistry for deposits at Loveland as well as loess in an east–west transect in western Iowa that was studied previously. Finally, in light of our findings in western Iowa, we evaluate the "gustiness" hypothesis of McGee et al. (2010) as an explanation for global dustiness during the LGM.

Methods

Geochemistry and sedimentology

Muhs et al. (2008) reported that K/Rb values effectively distinguish non-glaciogenic loess in Nebraska, derived from the Tertiary White River Group, from loess in northwestern Iowa, thought to be derived solely from glaciogenic outwash carried by the Missouri River. In light of these findings, we conducted new analyses of the loess section at Loveland for several major elements (K, Ca, Ti, Mn and Fe) and trace elements (Rb, Sr, Y, Zr, Nb, Ba, La, Ce), using energy-dispersive X-ray fluorescence (ED XRF), the method used by Muhs et al. (2008). All analyses were conducted on bulk loess or paleosol samples. USGS rock standard GSP-1 was included with each sample batch and resulting concentrations for this standard agree with published values within ~5% (K, Fe, Nb, Ba), ~1.6% (Rb, Sr), and ~0.5% (Ca). ED XRF analyses were also done on samples of loess from an east–west transect in western Iowa (Fig. 2). Muhs and Bettis (2000, 2003) reported particle size data for loess in this transect. We re-analyzed these samples using a sedigraph, which uses Stokes' Law of particle settling and measures particle concentrations by the degree of absorption of a low-power X-ray beam. Sedigraph particle size data are comparable to traditional sieve and pipette methods, but yield more details on measures of central tendency. Pretreatments for this procedure include destruction of organic matter with hydrogen peroxide, removal of carbonates with acetic acid, and dispersion of aggregates with Na-hexametaphosphate.

Magnetism measurements

Methods of magnetic mineralogical analyses of soils and loesses follow those of Rosenbaum et al. (1996). Five magnetic mineralogical parameters are presented in four plots: (1) magnetic susceptibility (MS) measured at low frequency (600 Hz), which is essentially a measure of total ferrimagnetic mineral (mostly magnetite and maghemite) content; (2) "hard" isothermal remanent magnetization (HIRM), a measure of high-coercivity magnetic minerals (e.g., hematite, although see cautionary notes by Liu et al. (2007)); (3) frequency-dependent magnetic susceptibility (FDMS), the difference between MS measured at 600 and 6000 Hz; (4) anhysteretic remanent magnetization (ARM), a measure of ferrimagnetic mineral content that is sensitive to extremely small (single domain) grains (Dunlop and Özdemir, 1997); and (5) the ratio ARM/MS. FDMS and ARM/MS values are measures of magnetic grain size, where higher values reflect higher proportions of ultrafine (superparamagnetic) and single domain grains, respectively.

OSL methods

Samples were prepared for luminescence dating using the procedures outlined in Roberts et al. (2003) and Roberts (2007). Quartz grains of 35–50 μm diameter were selected for dating because Peoria Loess at Loveland contains abundant coarse silt (Muhs and Bettis, 2000). To circumvent the potential problems of anomalous fading that are associated with feldspars (e.g. Huntley and Lamothe, 2001), the mineral selected for OSL dating was quartz. To remove feldspars and isolate quartz, the 35–50 μm fraction was treated for 7 days using fluorosilicic acid in a ratio of 40 ml 35% H_2SiF_6:1 g sediment (Berger et al., 1980), followed by a 45-min treatment with hydrochloric acid (37%). The H_2SiF_6-treated material was then re-sieved at 35 μm. This fluorosilicic acid treatment produced quartz suitable for luminescence dating (Roberts, 2006, 2007).

Luminescence measurements were made using several automated Risø [use of trade names throughout this paper is for descriptive purposes only and does not imply endorsement by the U.S. government] TL/OSL readers, each equipped with a $^{90}Sr/^{90}Y$ beta source for irradiation, blue LEDs (470 Δ 20 nm), and either infra-red (IR) (870 Δ 40 nm) LEDs or an infra-red (IR) laser-diode (830 Δ 10 nm). Detection was achieved using 7.5 mm Hoya U-340 filter. The equivalent dose (D_e) was determined using a modified single-aliquot regenerative-dose (SAR) protocol, namely the "double SAR" protocol of Banerjee et al. (2001), applied to quartz grains of 35–50 μm diameter (Roberts et al., 2003; Roberts, 2006). This procedure (Roberts and Wintle, 2001) involves using a range of thermal pretreatments from 160 to 300 °C for 10 s to remove any unstable trapped charge, then stimulation with IR at 125 °C to deplete the OSL signal from any feldspar remaining following chemical treatment. These steps were taken prior to stimulation with blue diodes at 125 °C to obtain the [post-IR] OSL signal from quartz, the mineral used for dating. SAR procedures correct for any luminescence sensitivity changes that may have occurred during burial, or caused by laboratory thermal pretreatments. The double SAR procedure used in this study has previously been applied to Peoria Loess from Nebraska (Roberts et al., 2003). Laboratory tests on several H_2SiF_6-treated samples from the mid-continent of North America, including the Loveland site, revealed that the D_e values obtained using the "double-SAR" protocol are in agreement with those determined using a more conventional SAR technique involving stimulation with blue diodes only (Roberts, 2006). This indicates that the feldspar contribution to the [post-IR] OSL signal is negligible for these samples, and that IR-exposure had no adverse effect on the quartz OSL signal (Roberts, 2006). The "double-SAR" protocol can therefore be safely implemented in this study as an additional security step, to ensure that the signal used for dating was derived from quartz.

For dose rate determinations, both field and laboratory measurements of U, Th, and K were conducted. In situ radioactivity measurements were made for each sample using a portable gamma spectrometer to determine the gamma dose rate. In the laboratory, thick-source alpha counting (TSAC) and beta counting using Risø GM-25-5 equipment were undertaken on powdered, dried bulk sediment to determine the alpha and beta dose rates, respectively. The

cosmic-ray dose rate was estimated for each sample as a function of depth, altitude and geomagnetic latitude (Prescott and Hutton, 1994). Sediment water content was assessed in the laboratory using sealed field samples, taken from both the face of the exposure, and also at depth from deep coring. Alpha and beta contributions to the dose rate were corrected for grain-size attenuation (Aitken, 1985). The calculated dose rates are shown in Table 1.

Loess stratigraphy at Loveland, Iowa

Physical stratigraphy

At the Loveland loess section, the oldest deposit exposed is a diamicton that predates the penultimate (Illinoian) glaciation or marine isotope stage (MIS) 6 (Bettis, 1990). The diamicton is described as “Kansan till” by Daniels and Handy (1959). This unit is overlain by Loveland Loess (Fig. 3), which has been considered to date from the Illinoian glaciation (Muhs and Bettis, 2000). Loveland Loess in this section is ~7 m thick and has been dated by Forman and Pierson (2002). Using the IRSL signal from polymineral fine grains measured with a multiple-aliquot additive dose (MAAD) method, they report ages from ~165 ka to ~146 ka, supporting a correlation to the Illinoian glaciation. Brown and Forman (2012), using TT-OSL methods, redated these samples and derived ages for Loveland Loess ranging from ~192 ka to ~133 ka. The last interglacial period (MIS 5) is represented by the Sangamon Geosol (informally referred to herein as the Sangamon soil) which is developed in Loveland Loess. A thin loess unit called the Pisgah Formation (Bettis, 1990), informally referred to herein as the Pisgah loess, overlies the Sangamon soil. Pisgah loess thickness varies from 4 m to 5 m over the outcrop at Loveland. In Ruhe (1983) and earlier studies, this unit was sometimes referred to as the “basal soil or basal loess soil,” and Daniels and Handy (1959) referred to it as the “Wisconsin loess, Farmdale increment.” The Pisgah loess has weak pedogenic alteration to the Farmdale Geosol (informally referred to herein as the Farmdale soil), expressed mainly as accumulation of organic matter, in the upper part of the unit. We also observed a number of burn zones and charcoal that can be found at some depths. The Farmdale soil at Loveland is equivalent to the Farmdale Geosol developed in Roxana Silt (loess) in the Mississippi River valley. Multiple-aliquot polymineral fine-grain IRSL ages of ~46 ka to ~35 ka by Forman and Pierson (2002) support a correlation of the Pisgah loess to the Roxana Silt in Illinois (Curry and Follmer, 1992) and loess of the Gilman Canyon Formation in Nebraska (Johnson et al., 2007).

Peoria Loess occurs above the Pisgah loess and is a light brown, massive silt loam. The contact between Pisgah loess and Peoria Loess at Loveland is not sharp, but is marked by a mixing zone, centered on about 41 m depth (Fig. 3). This mixing zone (~1 m thick) contains material from both units and is probably the result of faunal burrowing accompanying slow loess accumulation during the very earliest stages of Peoria Loess deposition. In total, Peoria Loess at Loveland is 40 m thick (Muhs and Bettis, 2000), although Daniels and Handy (1959), Forman et al. (1992) and Forman and Pierson (2002) reported that it is only 30 m thick. The difference in reported depths is due to the upper ~10 m of Peoria Loess at Loveland being exposed in a section some distance inward of the main exposure. Thus, the ~30 m of Peoria Loess reported by Forman et al. (1992) and Forman and Pierson (2002) is equivalent to Peoria Loess at depths of ~10 m to ~40 m reported by Muhs and Bettis (2000) and the present study.

Muhs and Bettis (2000) recognized three zones within Peoria Loess at Loveland (Figs. 3, 4). They refer to Peoria Loess at depths of ~32.5 m to ~41 m as “lower Peoria Loess.” This unit is characterized by alternations of coarse-silt-rich and coarse-silt-poor intervals, but overall the zone is particularly low in carbonate-mineral (calcite and dolomite) content. In contrast, “middle Peoria Loess,” from ~19.5 m to ~32.5 m, is rich in carbonates and is dominated by coarse silt throughout. The uppermost ~19.5 m of the section constitutes

Table 1
Equivalent dose (D_e), dose rates, and optically stimulated luminescence ages of loess from Loveland, Iowa.

Sample No.[a]	Depth (m)	D_e (Gy)[b]	‘n’[c]	U (ppm) [d]	Th (ppm) [d]	K (%)[d]	Infinite α dose rate[e]	Infinite β dose rate[e]	External α dose rate ‘wet’[e]	External β dose rate ‘wet’[e]	External γ dose rate ‘wet’[e]	Cosmic[e]	Total dose rate[e]	Age (ka)
69LVL13	0.85	55.1 ± 0.8	20	2.69 ± 0.12	8.03 ± 0.34	1.44 ± 0.07	15.3	2.11	0.255	1.72	1.04	0.204	3.21 ± 0.13	17.1 ± 0.7
69LVL14	1.30	56.1 ± 1.8	9	3.19 ± 0.13	8.10 ± 0.34	1.66 ± 0.08	16.4	2.12	0.274	1.73	1.04	0.190	3.23 ± 0.13	17.4 ± 0.9
69LVL16	10.00	62.1 ± 2.5	9	2.81 ± 0.12	7.79 ± 0.34	1.48 ± 0.08	17.4	2.18	0.290	1.77	1.03	0.087	3.18 ± 0.13	19.5 ± 1.1
69LVL17	18.00	64.7 ± 1.9	12	2.73 ± 0.12	7.66 ± 0.33	1.39 ± 0.07	16.6	2.05	0.278	1.66	1.05	0.050	3.04 ± 0.13	21.3 ± 1.1
69LVL18	19.00	67.7 ± 0.9	17	3.06 ± 0.13	7.42 ± 0.32	1.48 ± 0.07	17.5	2.17	0.293	1.76	1.10	0.047	3.20 ± 0.13	21.2 ± 0.9
69LVL19	21.00	68.2 ± 0.7	14	2.88 ± 0.13	6.99 ± 0.31	1.39 ± 0.07	17.0	2.00	0.283	1.62	0.985	0.042	2.93 ± 0.12	23.2 ± 1.0
69LVL12	31.00	72.9 ± 0.7	13	2.97 ± 0.12	8.65 ± 0.36	1.59 ± 0.07	17.7	2.17	0.296	1.77	1.03	0.025	3.12 ± 0.13	23.4 ± 1.0
69LVL11	33.00	72.8 ± 1.0	13	3.58 ± 0.15	8.10 ± 0.33	1.57 ± 0.07	16.3	2.10	0.273	1.71	1.05	0.023	3.06 ± 0.13	23.8 ± 1.0
69LVL10	36.50	74.8 ± 0.9	9	3.19 ± 0.13	7.89 ± 0.33	1.59 ± 0.07	15.7	2.00	0.263	1.63	0.975	0.020	2.88 ± 0.12	25.9 ± 1.1
69LVL9	40.00	77.3 ± 1.2	11	2.87 ± 0.12	8.27 ± 0.35	1.43 ± 0.07	17.4	1.98	0.290	1.61	0.930	0.017	2.85 ± 0.12	27.1 ± 1.2
69LVL8	40.65	78.4 ± 1.0	11	3.13 ± 0.11	7.81 ± 0.28	1.31 ± 0.05	15.6	1.86	0.260	1.51	0.908	0.017	2.69 ± 0.11	29.1 ± 1.3
69LVL7	40.90	78.3 ± 1.0	15	3.32 ± 0.11	8.20 ± 0.28	1.48 ± 0.05	17.3	2.04	0.289	1.66	0.991	0.016	2.96 ± 0.12	26.5 ± 1.2
69LVL1	41.10	81.8 ± 1.5	16	3.34 ± 0.13	9.23 ± 0.37	1.74 ± 0.07	17.3	2.27	0.289	1.85	1.09	0.013	3.23 ± 0.14	25.3 ± 1.2
69LVL2	41.35	99.3 ± 2.5	12	3.00 ± 0.10	10.11 ± 0.33	1.78 ± 0.06	17.7	2.41	0.296	1.96	1.09	0.013	3.36 ± 0.14	29.6 ± 1.4
69LVL3	41.65	105.6 ± 4.8	9	3.18 ± 0.10	9.82 ± 0.32	1.80 ± 0.06	17.5	2.42	0.293	1.97	1.13	0.013	3.41 ± 0.14	31.0 ± 1.9
69LVL4	41.92	107.7 ± 4.3	15	3.54 ± 0.12	9.35 ± 0.31	1.79 ± 0.06	21.1	2.17	0.352	1.76	1.12	0.013	3.25 ± 0.14	33.2 ± 2.0
69LVL5	42.12	114.9 ± 2.5	9	3.35 ± 0.11	8.87 ± 0.30	1.65 ± 0.06	22.0	2.30	0.368	1.87	1.06	0.013	3.30 ± 0.14	34.8 ± 1.7
69LVL6	42.63	102.9 ± 2.2	12	3.08 ± 0.13	7.78 ± 0.33	1.44 ± 0.07	16.7	1.97	0.278	1.61	0.928	0.012	2.82 ± 0.12	36.4 ± 1.7
69LVL21	43.20	105.1 ± 2.0	9	2.97 ± 0.13	7.52 ± 0.33	1.42 ± 0.07	16.6	1.91	0.276	1.55	0.979	0.012	2.82 ± 0.12	37.3 ± 1.7
69LVL22	43.75	106.5 ± 2.0	18	3.35 ± 0.15	7.04 ± 0.31	1.29 ± 0.06	14.3	1.84	0.238	1.49	0.967	0.012	2.71 ± 0.11	39.3 ± 1.8
69LVL23	44.25	106.2 ± 2.2	9	3.51 ± 0.15	7.10 ± 0.31	1.34 ± 0.06	17.6	1.81	0.293	1.47	0.921	0.012	2.70 ± 0.11	39.4 ± 1.8
69LVL24	45.50	123.6 ± 3.1	9	2.99 ± 0.14	6.54 ± 0.30	1.18 ± 0.06	15.0	1.85	0.251	1.50	0.917	0.011	2.68 ± 0.11	46.1 ± 2.3

Luminescence ages are expressed as thousands of years before A.D. 2000, and calculated to 1 decimal place.
[a] Aberystwyth Luminescence Laboratory sample code prefix: *Aber*/69LVL.
[b] The error shown on D_e is the standard error on the mean.
[c] ‘n’ is the number of D_e determinations used.
[d] Concentrations of U, Th and K were determined from *in situ* measurements using a portable gamma spectrometer and are shown to 2 decimal places.
[e] Alpha, beta, and gamma dose rate values (Gy/ka) were determined using thick source alpha counting, beta counting, and field gamma spectrometry, respectively, and using the conversion factors of Adamiec and Aitken (1998). Cosmic dose rates were calculated according to Prescott and Hutton (1994). Dose rates were calculated assuming a water content (expressed as % dry mass) of 15 ± 5%, and using an a-value of 0.040 ± 0.002 (Rees-Jones, 1995). Dose rates are shown rounded to 3 significant figures, but the total dose rates and ages were calculated using values prior to rounding. Central values are given for dose rates; errors are incorporated into that given for the total dose rate.

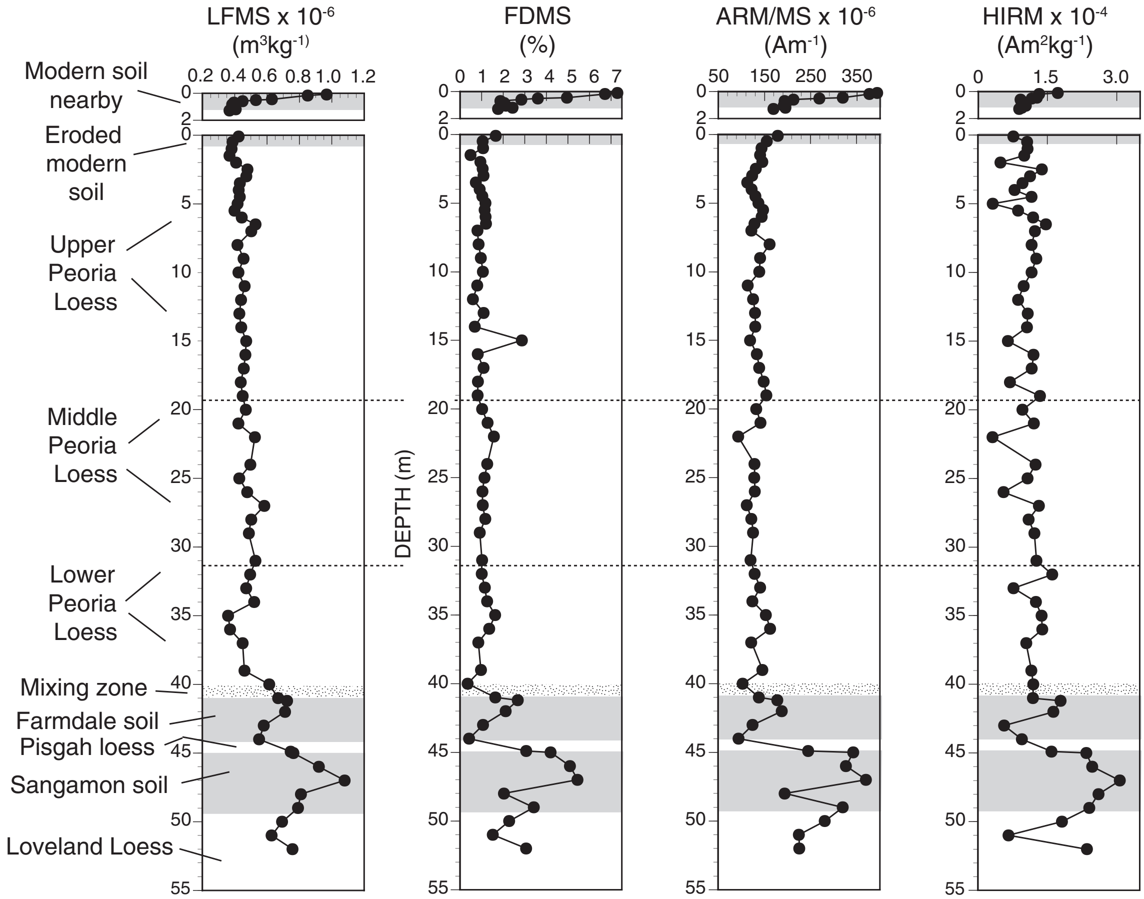

Figure 3. Stratigraphy of loess, paleosols and the modern soil at Loveland, Iowa (N41.500519°, W95.889344°), showing correspondence of these units with magnetic mineral properties. Note that the modern soil at Loveland is eroded, based on soil morphology. The "modern soil nearby" is an uneroded profile from a flat, stable upland location in an uncultivated cemetery, 2.9 km to the southeast of Loveland (N41.485246°, W95.860833°).

"upper Peoria Loess" and contains abundant carbonates, but has much lower amounts of coarse silt relative to fine silt and clay. The difference in particle size between middle Peoria Loess and upper Peoria Loess is so dramatic that is it easily detectable in the field. Land snails, dominated by the genus *Succinea*, are found within all three Peoria Loess zones, as well as within the Pisgah loess. The "dark bands," reported elsewhere in western Iowa and interpreted to be minimally developed paleosols (Daniels et al., 1960; Ruhe et al., 1971; Ruhe, 1983) were not observed by us at Loveland. Upper Peoria Loess at Loveland is capped by a minimally developed, and probably eroded modern soil with an A/AC/C profile. Elsewhere, on flat, stable upland divides near Loveland, we have found better developed modern soils with A/Bw/BC/C profiles as much as ~90 cm thick.

Magnetic measurements in loess and soils at Loveland

Magnetic measurements have been used extensively in studies of loess stratigraphy and paleoclimatic interpretations of loess-derived paleosols (see review in Singer and Verosub, 2007). Here we present a number of magnetic measurements of the Loveland section that elucidate the physical stratigraphy described above. In many loess/paleosol sequences, the most obvious trends are higher values of magnetic susceptibility (MS), particularly low-frequency magnetic susceptibility (LFMS) and anhysteretic remanent magnetism (ARM) in soils and paleosols, compared to unaltered loess. Both LFMS and ARM are measures of ferrimagnetic mineral content, but ARM is highly sensitive to extremely small, single-domain grains. Enhancement of LFMS and ARM values in soils and paleosols can be due either to pedogenic formation of ferrimagnetic minerals, such as maghemite, or enrichment of detrital, non-pedogenic ferrimagnetic minerals such as magnetite and titanomagnetite, due to carbonate leaching in zones of pedogenesis. Thus, in the latter case, lower values of LFMS or ARM in unaltered loess, compared to leached paleosols, can be due simply to dilution of detrital magnetic minerals by carbonate abundance.

At Loveland, LFMS values are high within the uneroded modern soil (collected nearby), the Farmdale soil developed in Pisgah loess, and the Sangamon soil developed in Loveland Loess (Fig. 3). Although carbonates are absent in these soils (see data in Muhs and Bettis, 2000), we interpret the higher LFMS values to be the result not only of carbonate removal, but also pedogenic growth of magnetic minerals. This interpretation is based on the higher values of both FDMS and ARM/MS in the soils and paleosols as these properties are not affected by apparent enrichment due to carbonate loss. High values of FDMS reflect higher proportions of ultra-fine (superparamagnetic) grains such as maghemite, which forms pedogenically. Higher amounts of slightly larger, single-domain grains are reflected in higher values of ARM/MS in the modern soil and paleosols at Loveland. Finally, HIRM is a measure of the abundance of hematite, a very slightly magnetic mineral (again, with cautionary notes on this interpretation from Liu et al. (2007)). HIRM values are highest in the modern soil and the two buried soils.

Apart from one unexplained high value of FDMS (at ~15 m depth), three magnetic properties, LFMS, FDMS, and ARM/MS, *within* Peoria Loess at Loveland are relatively low in all three zones and do not show much variability as a function of depth (Fig. 3). We interpret these observations as evidence that although loess sedimentation may not have been constant at Loveland during Peoria time, periods of subaerial exposure were short enough that little or no production of pedogenic magnetic minerals took place. Thus, even though Daniels et al.

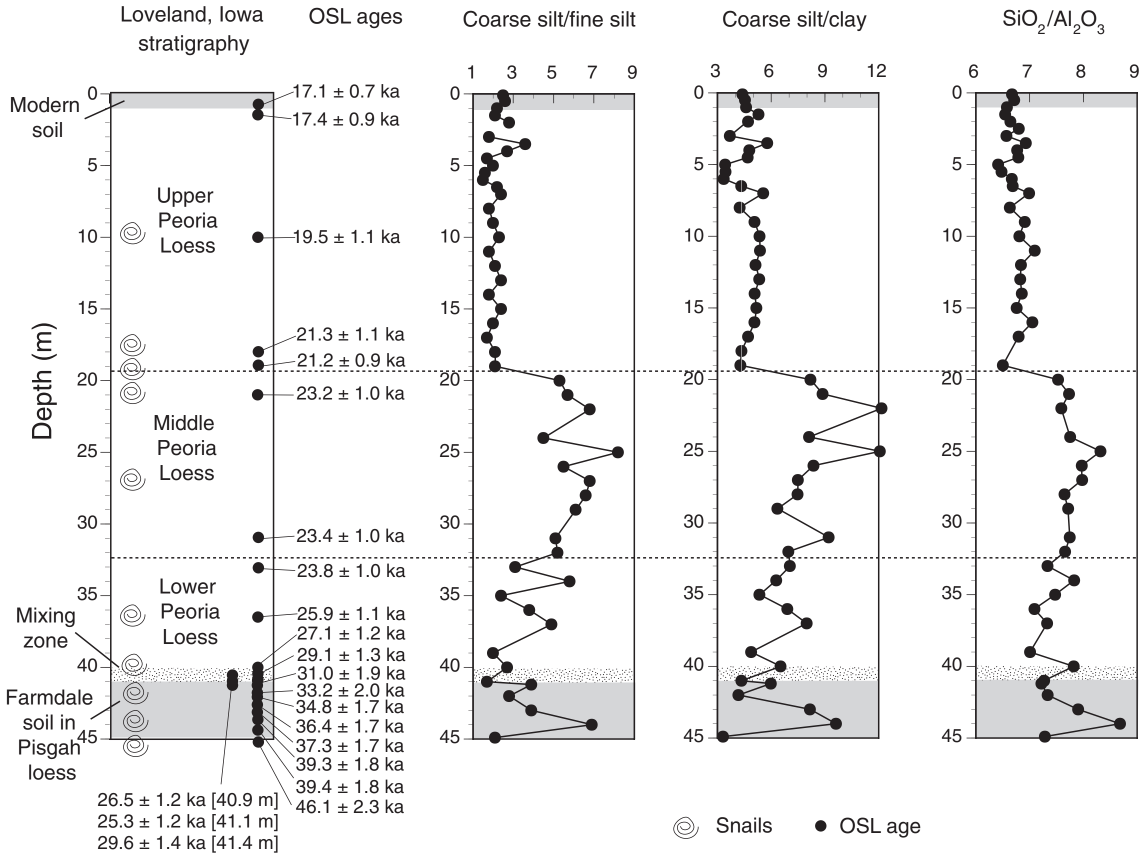

Figure 4. Stratigraphy, OSL ages, particle-size data, and SiO_2/Al_2O_3 for loess deposits at Loveland, Iowa. OSL ages are from this study (Table 1); particle size and geochemical data are from Muhs and Bettis (2000).

(1960), Ruhe et al. (1971) and Ruhe (1983) have documented the existence of "dark bands," interpreted to be minimally developed soils, in loess of western Iowa, we find no evidence for periods of pedogenesis that were long enough (or moist enough) to form abundant pedogenic magnetic minerals within thick Peoria Loess at Loveland.

OSL geochronology of Pisgah loess and Peoria Loess

The OSL chronology at Loveland we present here consists of 22 individual age determinations from the Pisgah loess and Peoria Loess (Table 1; Fig. 4). With minor exceptions (described in more detail below), the ages are internally consistent with the physical stratigraphy (Fig. 4) within the limits of analytical uncertainties. Our oldest age, from the base of the Pisgah loess at a depth of 45.5 m, is 46.1 ± 2.3 ka. Sub-meter sampling through the Pisgah loess shows a stratigraphically consistent suite of OSL ages indicating that loess accreted slowly over a period of ~15,000 yr. Loess in the upper Pisgah, at a depth of 41.35 m, has an age of 29.6 ± 1.4 ka.

The contact between Pisgah loess and Peoria Loess is at 41.0 m, and there are problems with one of the OSL ages near this contact (Table 1; Fig. 4). As we noted earlier, this is not a sharp contact, but a mixing zone. Immediately below the contact, we have an age of 25.3 ± 1.2 ka at a depth of 41.1 m and directly above the contact, at 40.9 m, we have an age of 26.5 ± 1.2 ka. These ages are in agreement with each other within limits of analytical uncertainty. However, an age of 29.1 ± 1.3 ka at a depth of 40.65 m, just above the contact, is not in agreement with the stratigraphically consistent ages below the contact, in Pisgah loess, or stratigraphically consistent ages above it, in Peoria Loess. We have no explanation for this apparent older age.

From OSL ages bracketing the contact and from within the deepest Peoria Loess, we can determine approximately when loess accretion began during the last glacial period. Above the Pisgah/Peoria contact at a depth of 40.0 m, an age of 27.1 ± 1.2 ka marks the earliest possible time of Peoria Loess deposition. It is difficult to interpret precisely when Peoria Loess deposition began, however, with the ages of ~26–25 ka (discussed above) that bracket the contact below this depth. All three ages (25.3 ka, 26.5 ka, and 27.1 ka), however, are within analytical uncertainty of one another. We conclude from this that Peoria Loess deposition probably began sometime from ~27 ka to ~25 ka.

OSL ages permit a temporal definition of the three Peoria Loess zones described earlier. What Muhs and Bettis (2000) refer to as lower Peoria Loess at Loveland extends from a depth of 40.0 m to 32.5 m. We have very close bracketing OSL ages of 23.8 ± 1.0 ka (at 33 m) and 23.4 ± 1.0 ka (at 31 m). Thus, lower Peoria Loess deposition began ~27–25 ka and continued until ~24–23 ka. Middle Peoria Loess occurs from 32.5 m to ~20 m. An OSL age of 23.4 ± 1.0 ka at 31 m is not analytically distinguishable from an age of 23.2 ± 1.0 ka at 21 m and permits the possibility of extraordinarily rapid loess deposition during middle Peoria Loess time. The sample at 21 m (23.2 ± 1.0 ka) and a sample at 19 m with an OSL age of 21.2 ± 0.9 ka bracket the boundary between middle and upper Peoria Loess, where there is a major shift in loess particle size distribution (Fig. 4). These ages indicate that the beginning of finer-grained sedimentation began ~23–21 ka. Loess sedimentation within the upper Peoria zone continued until 17.1 ± 0.7 ka, the OSL age of the uppermost loess just below the modern soil at Loveland.

Loess geochemistry and provenance

Isotopic and geochemical studies by Aleinikoff et al. (2008) and Muhs et al. (2008) indicate that Peoria Loess in most of Nebraska has a different source than loess in adjacent northwestern Iowa,

near Sioux City (Figs. 1, 2). With the exception of localities immediately south of the Missouri River, Peoria Loess in Nebraska is derived largely from non-glacial sources, the most important of which is the Tertiary volcaniclastic siltstone of the White River Group. This rock unit is most notably exposed in Badlands National Park, South Dakota (Fig. 2), but is also found in Colorado, Wyoming and Nebraska. In contrast, Peoria Loess deposits in northeastern Nebraska, immediately south of the Missouri River, and at Sioux City, Iowa, have both detrital zircon age spectra and geochemical compositions that indicate sources from till of the James and Des Moines lobes of the Laurentide ice sheet (Fig. 2).

Muhs et al. (2008) found that K/Rb is a good geochemical discriminator for Missouri River-derived loess of northwestern Iowa vs. White River Group-derived loess of central and eastern Nebraska. Studies of volcanic rocks and ore deposit hosts have also used K/Rb, K/Ba, and Ba/Rb as provenance indicators (Hole et al., 1993; McCuaig and Kerrich, 1998; Parker et al., 2005). Both Rb and Ba substitute for K in K-bearing minerals such as K-feldspar and micas (Heier and Adams, 1964; Lange et al., 1966). Mineralogical analyses indicate that the major K-bearing mineral in loess of both Nebraska and northwestern Iowa is K-feldspar, with mica present in only small amounts within the clay fraction. Using loess geochemical data in Muhs et al. (2008), we examined whether Ba/Rb could provide an additional discriminator for loess bodies derived from different source rocks. Plots of K/Rb vs. Ba/Rb show that these element pairs are effective in discriminating loess bodies derived from different sources (Fig. 5). For example, loess in southern (Matanuska), central (Fairbanks), and northern (Kotzebue) Alaska, derived from different source rocks, define distinct geochemical fields with respect to K/Rb and Ba/Rb (Fig. 5A). Ba/Rb in loess from northwestern Iowa and Ba/Rb in loess from central and eastern Nebraska show no overlap; K/Rb from these two loess bodies shows only slight overlap (Fig. 5B).

With K/Rb and Ba/Rb as effective discriminators for Missouri River-derived loess (glacial-sourced) and White River Group-derived loess (non-glacial-sourced), we can test the hypothesis of Muhs and Bettis (2000) that middle Peoria Loess at Loveland is derived from the Missouri River and upper Peoria Loess at Loveland is distal loess from Nebraska. Results indicate that neither upper nor middle Peoria Loess at Loveland are dominated by a single source. Although some samples from each zone fall squarely within a particular loess source province, most fall between the two (Figs. 5B, C). When K/Rb and Ba/Rb are plotted as a function of depth, it is apparent that both the Missouri River and Nebraska contributed to loess buildup at Loveland in both the middle and upper Peoria zones (Fig. 6).

If Peoria Loess at Loveland is derived from both glacial (Missouri River) and non-glacial (Nebraska loess) sources, it is pertinent to investigate whether loess elsewhere in southwestern Iowa also shows evidence of both sources. To answer this question, we re-examined an east–west transect (Fig. 2) studied earlier by Muhs and Bettis (2000). We conducted new particle size analyses of loess samples from this transect, using a sedigraph, and confirmed the west-to-east trends in particle size changes reported earlier by Muhs and Bettis (2000). Median particle size, sand-plus-coarse-silt content, and coarse-silt-to-fine-silt ratios all decrease logarithmically from west to east, whereas

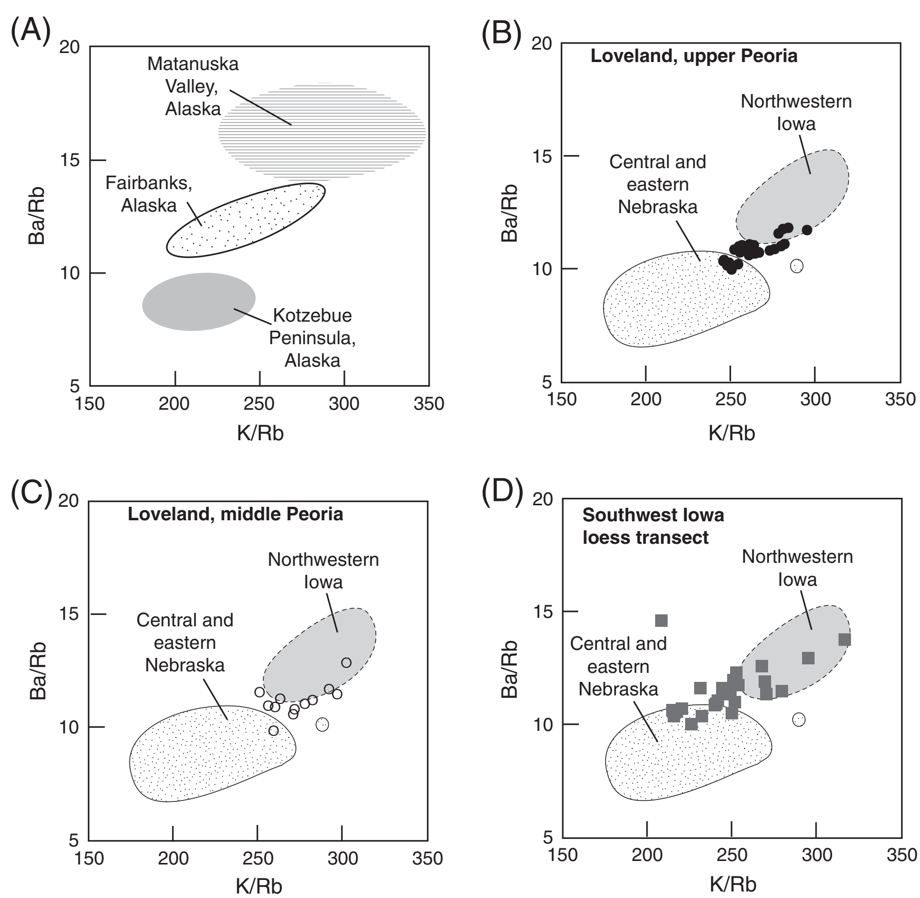

Figure 5. Range of K/Rb and Ba/Rb values observed in loess from Alaska (A) and central and eastern Nebraska and northwestern Iowa (B, C, D). Data from upper Peoria Loess at Loveland (filled circles in B), middle Peoria Loess at Loveland (open circles in C), and loess transect in southwestern Iowa (filled squares in D) are shown for comparison. Fields for Alaska, Nebraska, and northwestern Iowa are from Muhs et al. (2008); individual data points are from this study. Note single Nebraska loess sample with anomalously high K/Rb.

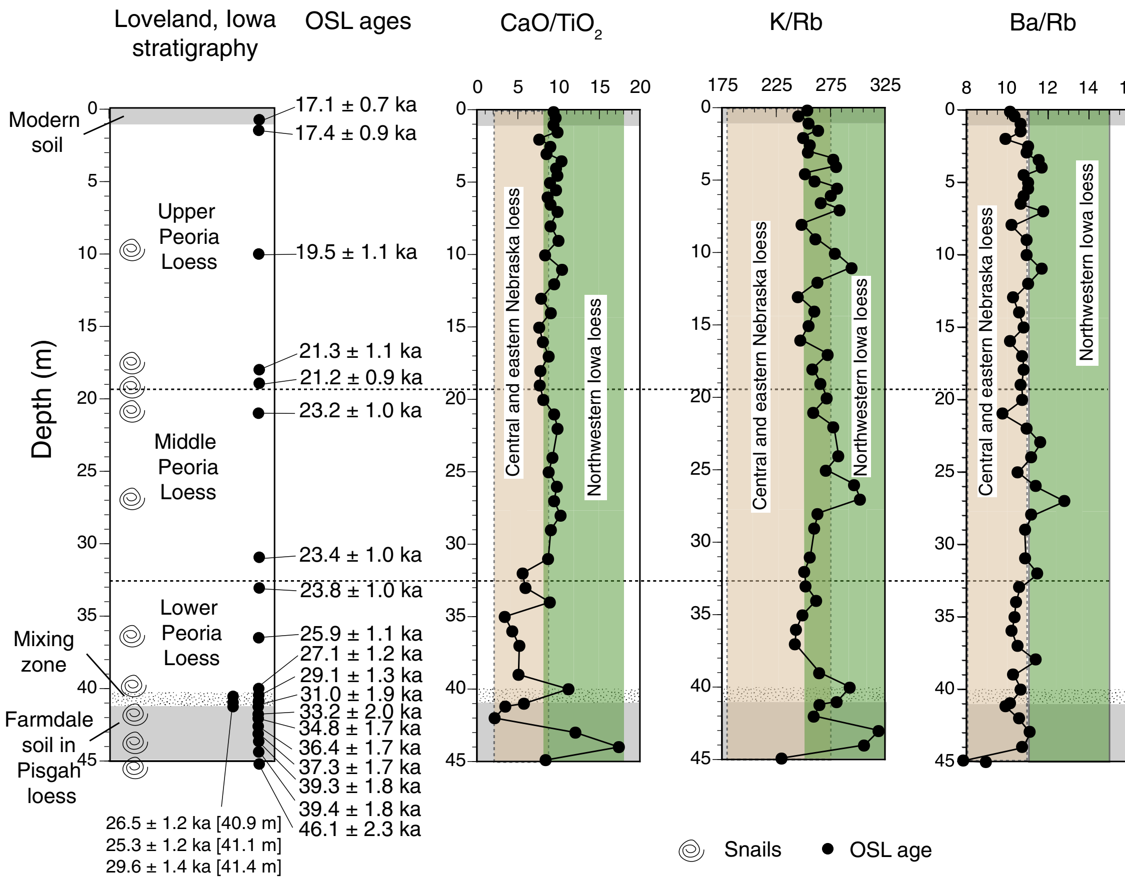

Figure 6. Stratigraphy, OSL ages, CaO/TiO_2, K/Rb, and Ba/Rb at Loveland, Iowa (all data from this study). Also shown are the ranges of element ratios in Peoria Loess from central and eastern Nebraska and northwestern Iowa (data from Muhs et al., 2008); single Nebraska loess sample with anomalously high K/Rb (cf. Fig. 5) not included in range.

fine silt increases in the same direction (Fig. 7). These trends indicate that regardless of whether or not there was more than one source, loess was derived from the west.

Values of K/Rb and Ba/Rb in this transect show ranges similar to those found in middle and upper Peoria Loess at Loveland, spanning the K/Rb and Ba/Rb fields defined by Nebraska loess and northwestern Iowa loess (Figs. 5D, 8). Thus, dual sources of Peoria Loess are confirmed for southwestern Iowa, over a distance of at least 60–70 km east of the Missouri River. We note, however, that for K/Rb, the only localities that fall within the range of a Missouri River source are those situated within ~8 km of the river, with decreasing K/Rb eastward. This observation implies that although the flux of loess from the Missouri River might be high, there is a very rapid decrease in the influence of this source moving eastward. In contrast, Ba/Rb shows a Missouri River influence at slightly more than half the localities along the transect, including one that is more than ~60 km east of the Missouri River. Unlike K/Rb, however, Ba/Rb shows no systematic geographic trend.

Discussion

Chronology of loess deposition

Interpretations of previous age determinations of Peoria Loess in southwestern Iowa are limited by a number of issues, including a lack of suitable materials for radiocarbon dating, contamination of disseminated organic matter by younger carbon, and stratigraphic reversals in some luminescence age estimates. Here we compare our ages with previous estimates that we consider to be reliable based on the materials dated and stratigraphic consistency. Our oldest (35–50 μm quartz [post-IR] OSL SAR) age, from the base of the Pisgah loess at a depth of 45.5 m, is 46.1 ± 2.3 ka. This is in excellent agreement with a 4–11 μm, polymineral, IRSL MAAD age from about the same depth of 46.3 ± 3.9 ka, reported by Forman and Pierson (2002). Our ages of Pisgah loess somewhat higher in the section, at depths of 42.63 m and 42.12 m, are 36.4 ± 1.7 ka and 34.8 ± 1.7 ka, respectively, in good agreement with Forman and Pierson's (2002) IRSL age of 35.1 ± 3.1 ka from a similar depth. Forman et al. (1992) report a number of radiocarbon ages from the Loveland section. Most of these are on disseminated organic material of uncertain provenance, but two ages are on land snails, reported to be *Succinea* sp. Studies by Pigati et al. (2004, 2010) show that shells of this genus are suitable for radiocarbon dating. Forman et al.'s (1992) shell ages are ~39,300 cal yr BP for a sample near the base of the Pisgah loess and ~24,500 cal yr BP for a sample ~7.5 m above the contact of the Pisgah loess and Peoria Loess. Our OSL ages from similar depths are in good agreement with these ages.

The OSL ages at Loveland are also in good agreement with some of the previous radiocarbon ages for Peoria Loess conducted elsewhere in Iowa. Although none of his ages come from the Loveland section, Ruhe (1983; his Fig. 6-2 and Table 6-1) summarizes what radiocarbon ages from southwestern Iowa loess were available up to the early 1980's. The most reliable ages, on wood, suggest that lowermost (leached) Peoria Loess was deposited after ~29,400 cal yr BP at one locality in southwestern Iowa and after ~28,700 cal yr BP at another locality. We are not aware of any radiocarbon ages on wood or charcoal from within Peoria Loess or at its top from any localities in southwestern Iowa. However, in central Iowa, till of the Des Moines lobe of the Laurentide ice sheet (Figs. 1, 2) is found above Peoria Loess and younger loess does not overlie this till, based on hundreds of soil cores we have examined. A boreal forest with *Picea*, *Abies*, *Tsuga*, and *Larix* was

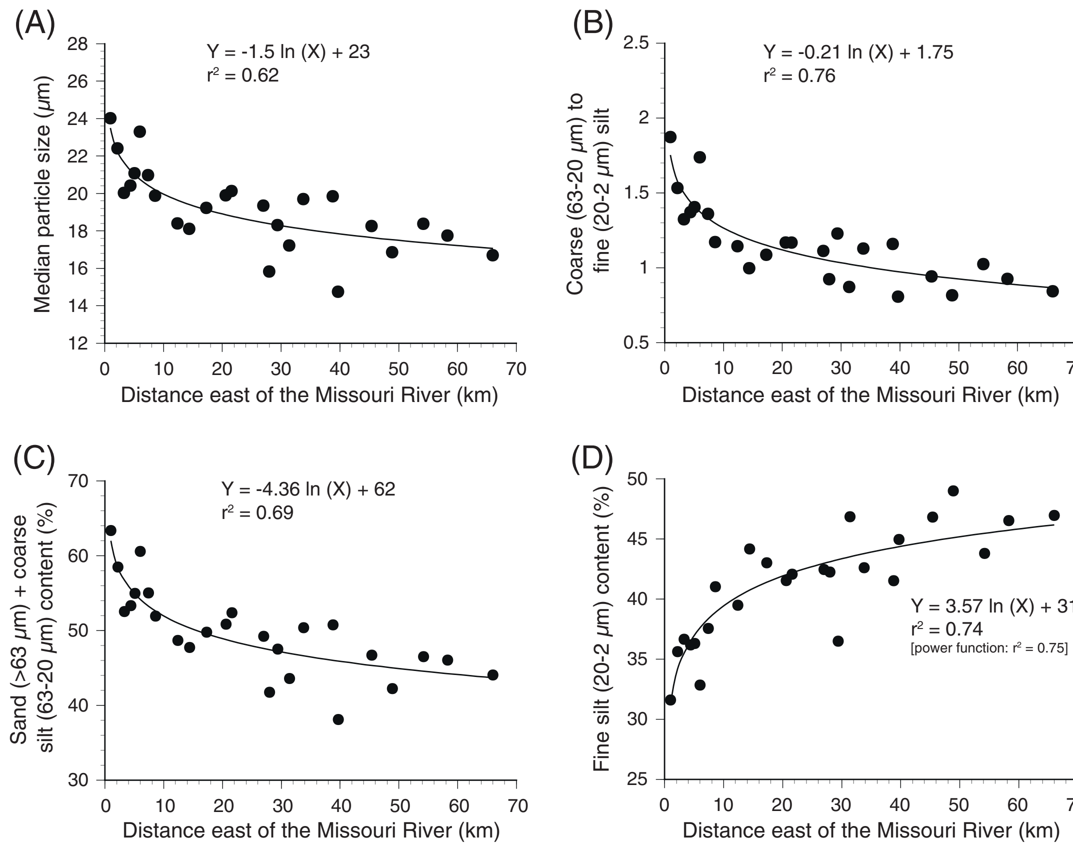

Figure 7. Particle size trends in Peoria Loess from southwestern Iowa (location shown in Fig. 2) shown as a function of distance east of the Missouri River. All data from this study.

growing in the loess of central Iowa and at least a minimally developed soil had formed when ice of the Des Moines lobe entered the region (Ruhe, 1969, 1983). Thus, at least in central Iowa, Peoria Loess deposition had ceased just before the advance of the Des Moines lobe.

A number of radiocarbon ages have been determined on wood from the upper part of Peoria Loess that hosted the boreal forest of central Iowa. Omitting those samples that have stratigraphic reversals or other problems (see notes in Bettis et al., 1996, their Table 1), wood samples in loess that are ~2–5 m below the contact with the overlying till have ages ranging from ~19,900 cal yr BP to ~17,500 cal yr BP. Wood in loess just below the contact with the till has ages that range from ~17,100 to ~16,300 cal yr BP. Because loess is absent from the surface of till of the Des Moines lobe, we infer that these radiocarbon ages provide reasonable estimates for the time of final loess deposition, although we caution that these are estimates from central Iowa only. Nevertheless, these radiocarbon ages are in excellent agreement with OSL ages obtained in this study from the uppermost Peoria Loess from Loveland (Table 1; Fig. 4). Overall, the new OSL ages we present here are in good agreement with the maximum-limiting and minimum-limiting ages of the time of Peoria Loess deposition, based on independent studies conducted previously in Iowa.

Sources of loess in western Iowa

Simonson and Hutton (1954) considered the evidence for the Missouri River as the principal source for loess in southwestern Iowa to be "overwhelming." Subsequently, there have been challenges to this concept. As mentioned earlier, Ruhe (1983) recognized the importance of the Missouri River as a loess source, but pointed out that basal Peoria Loess (equivalent to "lower" Peoria Loess at Loveland) lacks carbonates at many locations. Ruhe (1983) noted that similar observations in loess of Kansas led Frye and Leonard (1951) to infer a lower rate of loess deposition in these zones, with syndepositional leaching explaining the lack of carbonates. He offered an alternative explanation, however, whereby non-glacial erosion of pre-Peoria, leached paleosols (presumably the Farmdale and Sangamon soils) could have generated particles that were transported to the drainage system, and then entrained as loess. Ruhe and Olson (1980) documented that such a process apparently took place in the time of early Peoria Loess deposition in Indiana. With regard to Peoria Loess higher in the section (and based primarily on grain size data), Muhs and Bettis (2000) hypothesized that lower Peoria Loess and middle Peoria Loess at Loveland were derived from the Missouri River and upper Peoria Loess could represent the distal component of nonglaciogenic loess from Nebraska. Thus, non-glacial sources have been proposed for two of the three Peoria Loess zones recognized at Loveland.

Geochemical data presented here lead us to conclude that glacial outwash from the Missouri River was not the only source of loess at Loveland. K/Rb and Ba/Rb values, which proxy for K-feldspar and micas from different loess sources, are distinctive for loess of central and eastern Nebraska, derived from non-glacial sources, and loess of northwestern Iowa, derived from glacial sources. Both sources appear to have been important contributors to loess at Loveland, in all three zones (lower, middle, upper), without either source dominating any of the three zones. We conclude, therefore, that distal loess from Nebraska probably was added to Missouri River-derived loess, throughout the last glacial period, not just during the time of upper Peoria Loess deposition, as hypothesized by Muhs and Bettis (2000).

If distal loess from Nebraska contributed eolian particles to deposits in western Iowa, there must be chronological evidence that this western source was available at the time of earliest loess deposition at Loveland. Radiocarbon and OSL ages of loess deposition in Nebraska permit such an interpretation. The oldest Peoria Loess at Loveland where both K/Rb and Ba/Rb imply a Nebraska-derived loess component is at

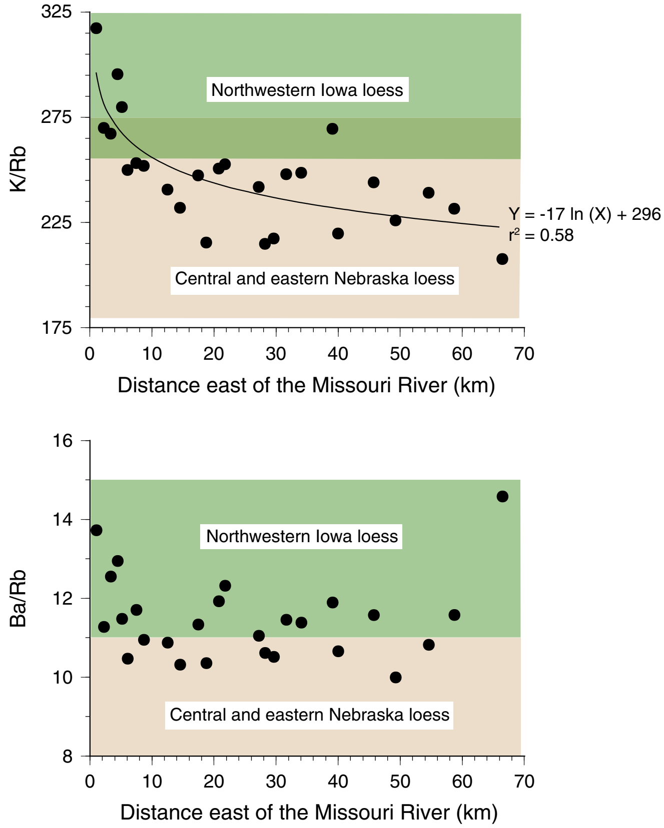

Figure 8. K/Rb and Ba/Rb in Peoria Loess from southwestern Iowa (location shown in Fig. 2) shown as a function of distance east of the Missouri River. Data are from this study. Also shown are the ranges of element ratios in Peoria Loess from central and eastern Nebraska and northwestern Iowa (data from Muhs et al., 2008); single Nebraska loess sample with anomalously high K/Rb (cf. Fig. 5) not included in range.

a depth of ~37 m, where we have an OSL age of ~25,900 yr (Fig. 6). An OSL age on basal Peoria Loess at Bignell Hill, Nebraska is also ~25,000 yr (Roberts et al., 2003) and charcoal from immediately below Peoria Loess at Bellevue, Nebraska, gives an age of ~30,500 cal yr BP (Muhs et al., 2008). Numerous other localities in Nebraska have humic acid radiocarbon ages (likely minima) that come from either lowermost Peoria Loess or immediately below it and range from ~31,000 to ~25,000 cal yr BP (Johnson et al., 2007; Muhs et al., 2008). These ages permit the inference that Peoria Loess deposition in Nebraska could have occurred approximately as early as that of the earliest Peoria Loess at Loveland.

K/Rb and Ba/Rb values in our western Iowa transect show that delivery of distal Nebraska loess was not limited to a narrow zone adjacent to the Missouri River. K/Rb data imply that distal Nebraska loess was added to localities as much as ~60 km east of the Missouri River and Ba/Rb values imply such inputs to localities at least 50 km east of the river. Mahowald et al. (2006) used the high mass accumulation rates for Peoria Loess in Nebraska given in Roberts et al. (2003), as well as other localities, to model a significant, fine-grained, last-glacial dust flux from this region far to the east. Although this a highly generalized model, the data presented here provide some of the first evidence that major river systems did not necessarily dominate or limit regional dust flux, in broad agreement with the modeling of Mahowald et al. (2006).

Paleoclimatic implications

While the field evidence and magnetic data indicate that loess accretion at Loveland was fairly steady throughout Peoria time, without major periods of pedogenesis, the OSL chronology shows that loess sedimentation rates were certainly not constant. We computed MARs over the period of Pisgah loess and Peoria Loess deposition at Loveland using the loess thicknesses between dated intervals, the OSL ages presented herein, and assuming a typical loess bulk density of ~1.45 g/cm^3 (e.g., Muhs et al., 2003). Results indicate that MARs in loess at Loveland could have varied over three orders of magnitude (Fig. 9). MARs were lowest during the period of Pisgah loess accumulation, with an average of ~370 g/m^2/yr between ~46 ka and ~31 ka. Such a low MAR is consistent with the field evidence of soil development through nearly all of the Pisgah loess and the magnetic record, which shows an enrichment of pedogenic magnetic minerals through much of the profile. Lower Peoria Loess has a much higher MAR than Pisgah loess, ~3075 g/m^2/yr (assuming an age of ~27.1 ka at 40.0 m and an age of 23.8 ka at 33 m). Despite the higher deposition rate during this time, the MAR was still low enough to allow some syndepositional leaching of carbonates, based on CaO/TiO_2 values (Fig. 6). An alternative interpretation, permitted by K/Rb and Ba/Rb values, is that much Peoria Loess in the lower zone might be derived from lower-carbonate, distal loess from Nebraska (Fig. 6). Loess in the middle Peoria zone, however, accumulated ~10 m of sediment in no more than ~2000 yr and possibly as short a period as ~200 yr. The latter time period yields an extraordinary MAR of 72,500 g/m^2/yr; assumption of a 2000-year-long period of deposition decreases this by an order of magnitude (Fig. 9). For the lower part of upper Peoria Loess (19.0–10.0 m), we calculate an MAR of ~7700 g/m^2/yr (from 21.2 ka to ~19.5 ka). For the upper part (10.0–1.3 m) of upper Peoria Loess, we derive an estimated MAR of ~6000 g/m^2/yr (from ~19.5 ka to ~17.4 ka). We note that all our MARs for Peoria Loess at Loveland, even the lowest ones, are higher than almost all MAR estimates for last-glacial loess from elsewhere in North America, South America, Asia, and Europe (see summary in Mahowald et al., 2006, their supplementary data files).

We recognize that point-to-point computations of MARs in loess are dependent on the OSL ages with their analytical uncertainties. An alternative approach is to conduct a Bayesian reconstruction of the loess depositional history. Haslett and Parnell (2008) present the computational methods required for this approach, incorporated into the free R-software package Bchron, and Parnell et al. (2008) show how it can be applied to the chronology of sediments in lake cores. The advantage of a Bayesian approach is that it minimizes the dependence of the overall sedimentation rate history on individual ages and takes into account knowledge of the stratigraphic relationship between samples (i.e. the progression of ages with depth). Using this method (Haslett and Parnell, 2008), lower Peoria Loess has MARs of ~4700–5500 g/m^2/yr, middle Peoria Loess has rates of ~12,000–16,000 g/m^2/yr (in the main part of this section), and upper Peoria Loess has rates of ~1000–10,000 g/m^2/yr, with most depths showing rates of ~10,000 g/m^2/yr. Transitional periods between lower and middle Peoria Loess and between middle and upper Peoria Loess yield lower MARs. Thus, although Bayesian modeling generates a much more conservative estimate for MAR during middle Peoria time, this period still has the highest loess accumulation rates of the last glacial period at Loveland.

Variability in MARs implies variability over time in sediment availability, wind strength and duration, or some combination of these factors. Our K/Rb and Ba/Rb data, along with the zircon age distribution data of Aleinikoff et al. (2008), indicate that two loess sources for western Iowa apparently were able to supply sediment during the entire period of Peoria Loess deposition. Thus, sediment supplies do not appear to be lacking during any particular time over the last glacial period. A dual supply of source sediments may in fact help explain why overall, MARs at Loveland are very high. It follows, therefore, that wind strength is a more likely explanation of *variability* in MAR. A number of workers have used mean loess particle size as a wind strength indicator. For example, Porter and An (1995) consider the median diameter of loess quartz to be a proxy for the strength of the winter monsoon,

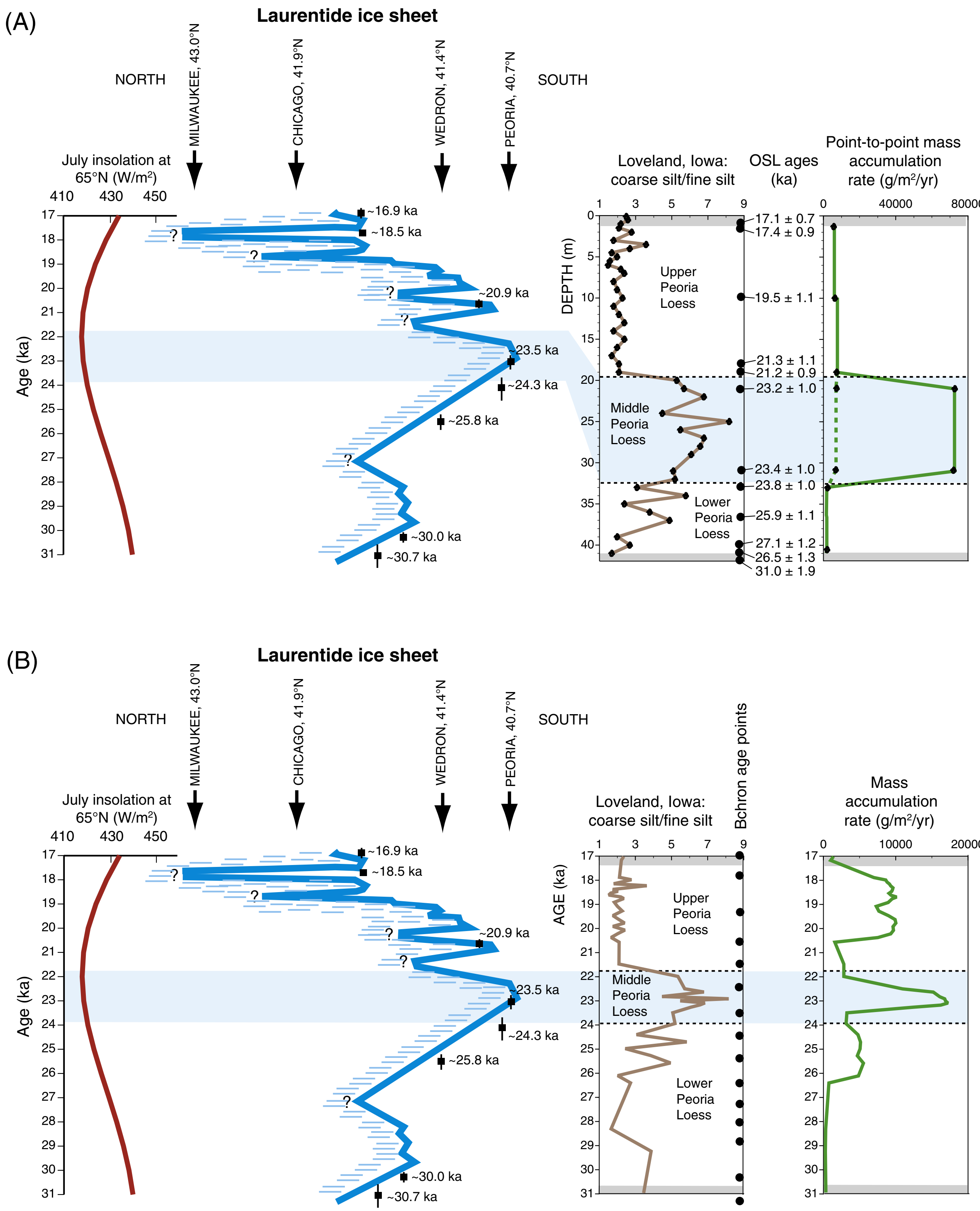

Figure 9. (A) Left to right: insolation from 31 ka to 17 ka at the top of the atmosphere at 65°N in July (from Berger and Loutre, 1991); time–distance diagram showing the southerly extent of the Laurentide ice sheet in the mid-continent of North America from ~31 cal ka BP to ~17 cal ka BP (redrawn from Johnson et al., 1997; their radiocarbon ages converted to calendar-year ages using Fairbanks et al. (2005)); stratigraphy, OSL ages, and coarse/fine silt ratios at Loveland, Iowa (OSL ages from this study; particle size data from Muhs and Bettis (2000)); and loess mass accumulation rates (green line) at Loveland, computed on a point-to-point basis (this study). Dashed green line shows the most conservative mass accumulation rate for Middle Peoria Loess, assuming ~2000 yr of deposition. (B) Same as in (A), except the vertical axes on the plots for loess at Loveland are ages (in ka) and mass accumulation rates are not computed point-to-point, but calculated using a Bayesian reconstruction of OSL ages (see text for discussion) based on the 15 points (solid circles) shown.

which, along with early spring, is the period of dust-transporting winds in China. Porter (2001) showed that the periods of greatest loess quartz diameter correlate with the periods of highest MARs in Chinese loess. Similarly, Antoine et al. (2009), studying last-glacial loess at Nussloch, along the Rhine Valley of Germany, considered high values of coarse silt to fine silt + clay to be indicators of greater wind strength.

At Loveland, the period of middle Peoria Loess deposition has both the highest MAR and the highest coarse silt/fine silt values (Fig. 9). We interpret this as the time of strongest winds in this part of central North America. This period, from ~24 ka to no later than ~21 ka, was also the period of minimum insolation at high latitudes in North American summers and was the time of maximum advance of the Laurentide ice sheet (Fig. 9). According to the McGee et al. (2010) "gustiness" model (with the reminder that their definition of "gustiness" differs from the WMO definition), this should be the period with the greatest latitudinal contrast in temperature, conditions that allow the strongest winds to be generated. Thus, the loess record at Loveland supports the general concept of McGee et al. (2010) that gustiness, generated by an enhanced meridional temperature contrast, may have been one of the primary drivers of LGM dustiness.

Geologic records from other regions do not all show maximum dustiness at exactly the same time within the last glacial period, however. For example, the time of maximum loess MAR at Loveland, Iowa differs from that for loess in central Nebraska. Roberts et al. (2003) reported that maximum MARs in Nebraska occurred during the *latest* period of Peoria Loess deposition, younger than the middle Peoria Loess section at Loveland. Carbonate content in Nebraska loess sections, interpreted to be an indicator of the degree of syndepositional leaching, is consistent with the late Peoria being the time of maximum MAR (Muhs et al., 2008). At Nussloch, Germany, there were several periods of exceptionally strong winds (based on coarse silt/fine silt + clay values) during the period between ~29.5 ka and ~18.7 ka (Antoine et al., 2009). The dust record from the NGRIP core of Greenland shows the maximum dust accumulation record somewhat earlier than that at Loveland, from ~26 ka to ~23 ka, although this overlaps the time of maximum MAR at Loveland (Ruth et al., 2007). We hypothesize that the differences in timing of maximum MAR and/or strongest winds (from grain size data) reflect variable regional controls on wind strength. In order to determine just how important these factors are, more loess studies with detailed geochronology are needed in widely separated regions. In North America, the best localities to seek high-resolution records would be immediately adjacent to major outwash-bearing drainages such as the Mississippi, Ohio, and Wabash rivers.

Conclusions

(1) Stratigraphic studies at Loveland, Iowa, supported by magnetic mineral analyses, show that relatively unaltered last-glacial (Peoria) loess accumulated one of the thickest deposits of this age in the world. Magnetic measurements show that paleosols that underlie Peoria Loess and a modern soil that caps the loess have enhanced maghemite and hematite contents. In contrast, Peoria Loess shows low values for these minerals, indicating more-or-less continuous sedimentation, uninterrupted by significant periods of pedogenesis.

(2) New OSL ages for the section at Loveland provide the first detailed chronology of Peoria Loess deposition during the last glacial period in western Iowa. OSL ages indicate that Peoria Loess deposition began around or shortly after ~27 ka and continued until ~17 ka. These ages are in good agreement with previous bracketing age estimates for loess deposition in Iowa, but more importantly, provide the first detailed chronology *within* the period of Peoria Loess deposition. Although magnetic data show no evidence of substantial depositional hiatuses within Peoria Loess below the modern soil, OSL ages indicate that rates of loess deposition were not constant during the last glacial period.

(3) K/Rb and Ba/Rb values, reflecting K-feldspar and mica compositions, are good indicators of loess sources. Based on these geochemical data, loess in western Iowa was derived not only from glaciogenic sources of the Missouri River, but also distal loess from non-glacial sources to the west. These provenance indicators show that despite large differences in particle size distributions between different stratigraphic zones within Peoria Loess, both sources contributed material throughout the thick section of loess at Loveland. K/Rb and Ba/Rb analyses indicate that distal Nebraska loess affected other localities in western Iowa as well.

(4) Mass accumulation rates (MARs) of loess at Loveland may have varied by as much as three orders of magnitude from ~46 ka to ~17 ka. Rates were lowest during the time of Pisgah loess accumulation. Within the period of Peoria Loess deposition, MARs were greatest during the period of middle Peoria Loess deposition around 23 ka, when ~10 m of loess accumulated in no more than ~2000 yr and possibly much less time. A conservative approach, using a Bayesian model of the chronology, still yields a maximum MAR during the period of middle Peoria Loess deposition. This time period coincides with the time of maximum grain size in Peoria Loess at Loveland; collectively, the coarse grain size and high MAR are interpreted to indicate exceptionally strong winds during this time period.

(5) The timing of inferred strong winds at Loveland coincides with a summer-insolation minimum at high latitudes in North America and the maximum southward extent of the Laurentide ice sheet, which grew at these high latitudes. These observations support a recently proposed model that last-glacial dustiness was driven largely by enhanced global gustiness, caused in large part by a steepened meridional temperature gradient during the last glacial period.

Acknowledgments

This work was supported in part by National Science Foundation Grant EAR-00-87572 (Bettis) and in part by the Climate and Land Use Change Program of the U.S. Geological Survey (Muhs). This is a contribution to the USGS project "Impacts of climate change on coastal and eolian landscapes." We thank Jeff Pigati, Dave Grimley, Mark Sweeney, Xiaoping Yang, and Derek Booth for helpful comments on an earlier draft of this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.yqres.2013.06.006.

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