2013

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Quaternary Science Reviews 76 (2013) 114–128

Contents lists available at SciVerse ScienceDirect

Quaternary Science Reviews

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

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ARTICLE INFO

Article history:
Received 10 December 2012
Received in revised form
3 May 2013
Accepted 15 May 2013
Available online 7 August 2013

Keywords:
Snails
Eolian
Chronology
Dust
Paleoclimate

ABSTRACT

Constraining the ages and mass accumulation rates of late Quaternary loess deposits is often difficult because of the paucity of organic material typically available for ^{14}C dating and the inherent limitations of luminescence techniques. Radiocarbon dating of small terrestrial gastropod shells may provide an alternative to these methods as fossil shells are common in loess and contain ~12% carbon by weight. Terrestrial gastropod assemblages in loess have been used extensively to reconstruct past environmental conditions but have been largely ignored for dating purposes. Here, we present the results of a multi-faceted approach to understanding the potential for using small terrestrial gastropod shells to date loess deposits in North America. First, we compare highly resolved ^{14}C ages of well-preserved wood and gastropod shells (Succineidae) recovered from a Holocene loess section in Alaska. Radiocarbon ages derived from the shells are nearly identical to wood and plant macrofossil ages throughout the section, which suggests that the shells behaved as closed systems with respect to carbon for at least the last 10 ka (thousands of calibrated ^{14}C years before present). Second, we apply ^{14}C dating of gastropod shells to late Pleistocene loess deposits in the Great Plains using stratigraphy and independent chronologies for comparison. The new shell ages require less interpretation than humic acid radiocarbon ages that are commonly used in loess studies, provide additional stratigraphic coverage to previous dating efforts, and are in correct stratigraphic order more often than their luminescence counterparts. Third, we show that Succineidae shells recovered from historic loess in the Matanuska River Valley, Alaska captured the 20th century ^{14}C bomb spike, which suggests that the shells can be used to date late Holocene and historic-aged loess. Finally, results from Nebraska and western Iowa suggest that, similar to other materials, shell ages approaching ~40 ka should be viewed with caution as they may reflect trace amounts of contamination. In sum, our results show that small terrestrial gastropod shells, especially from the Succineidae family, provide reliable ages for late Quaternary loess deposits in North America.

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1. Introduction

In North America, loess deposits mantle large portions of the Great Plains, Mississippi River Valley and Snake River Plain, and lowlands in the Pacific Northwest and Alaska (Fig. 1). These deposits are an important terrestrial archive of past environmental and climate conditions, and are one of the few geologic deposits that contain primary information of past atmospheric circulation patterns and wind regimes (Bettis et al., 2003a,b; Muhs, 2013). Deciphering such information requires establishing strong chronologic frameworks for loess deposits at multiple sites, especially when attempting to understand past conditions over regional scales. Although loess has been studied intensively for decades, determining the ages and mass accumulation rates of loess deposits can be difficult because of the paucity of organic material typically available for radiocarbon dating and the inherent limitations of luminescence techniques.

Charcoal and plant macrofossils are occasionally found in loess and are ideally suited for radiocarbon dating (Trumbore, 2000). Charcoal is especially preferred because it is resistant to chemical degradation and can be treated aggressively to remove unwanted contaminants prior to ^{14}C analysis (Bird et al., 1999). Although researchers must be aware of potential complicating issues associated with reworking (ages would be too old) or dating charred roots (ages would be too young), in most cases charcoal and plant macrofossils yield reliable ^{14}C ages. However, it is rare to find enough of

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0277-3791/$ – see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.quascirev.2013.05.013

Fig. 1. Distribution of late Quaternary loess deposits in North America (after Bettis et al., 2003b and sources therein).

these materials to establish the chronology of an entire exposure of loess.

More common in loess deposits are humic substances that are formed during the biodegradation of organic matter. Humic acids are a principal component of humic substances, and are often targeted for ^{14}C dating (McGeehin et al., 2001). Especially common in soils, humic acids differ from charcoal and plant macrofossils in that they are composed of complex, amorphous mixtures of heterogenous molecules that do not have a common molecular structure (MacCarthy, 2001). If humic acids remain in situ following plant decay, a process referred to as “self-humification,” then they may yield reliable ^{14}C ages (Cohen-Ofri et al., 2006). However, humic acids are often soluble in ground water, can be mobile in natural environments, and therefore have the potential to act as contaminants. This makes it difficult to evaluate the veracity of ^{14}C dates derived from humic acids because determining whether the dated acids are the result of self-humification or contamination processes is not possible in most situations. Moreover, soils and sediments that contain abundant humic acids represent an integration of an unknown (and possibly significant) amount of time that elapsed while the organics became concentrated enough to be targeted for dating, which further complicates interpretation of their ages.

Loess is an eolian deposit and therefore may be suitable for dating by luminescence techniques (Roberts, 2008; Singhvi and Porat, 2008; Wintle, 2008). Various methods, including optically stimulated luminescence (OSL), infrared-stimulated luminescence (IRSL), and thermoluminescence (TL), have been applied successfully to loess deposits over the past few decades. Unlike radiocarbon dating, in which assumptions are required regarding the temporal relation between the material dated and the timing of sedimentation, luminescence ages directly date the time of deposition and burial. Luminescence dating can also reach back farther in time than radiocarbon, potentially reaching the Last Interglacial Period and beyond if conditions are favorable (e.g., Li and Li, 2012). On the down side, uncertainties associated with luminescence ages are generally on the order of ~10%, which means that most Quaternary luminescence-based loess chronologies can be resolved only to millennial timescales. Luminescence dating is also typically more time-consuming and expensive than radiocarbon and requires assumptions regarding moisture content that cannot be known *a priori*.

Radiocarbon dating of terrestrial gastropod shells may provide an alternative to these approaches for dating loess deposits. Fossil gastropod shells are relatively common in loess, and their assemblages have been studied extensively to reconstruct paleoenvironmental conditions in North America (e.g., Leonard and Frye, 1954, 1960; Wells and Stewart, 1986; Rousseau and Kukla, 1994), the Chinese loess plateau (e.g., Liu, 1985; Rousseau et al., 2000) and central Europe (e.g., Rousseau, 1991), among others. Terrestrial gastropods are composed of aragonite ($CaCO_3$) and therefore contain ~12% carbon by weight. Thus, for most taxa, only a few shells (or even single shells) are required for ^{14}C dating by accelerator mass spectrometry (AMS). In addition, the aragonitic shells of terrestrial gastropods allow for easy and inexpensive screening for recrystallization to calcite through X-ray diffraction (XRD) analysis.

Evaluating the reliability of gastropod shell ^{14}C ages is complicated by two issues: the "limestone problem" and open-system behavior. Terrestrial gastropods are known to scrape and ingest limestone or other carbonate rocks and use the old carbon when building their shells (Rubin et al., 1963; Evin et al., 1980; Goodfriend, 1987). The magnitude of this "limestone problem," a term coined by Goodfriend and Stipp (1983), is highly variable and can result in ^{14}C ages of gastropod shells that are up to ~3000 ^{14}C years too old. Although most studies documenting this phenomenon have focused on relatively large, robust shells, recent studies have shown that some small terrestrial gastropods do not ingest limestone even when living in environments in which carbonate rocks are readily available (Pigati et al., 2004, 2010). Among the taxa that apparently avoid the limestone problem are some of the most common terrestrial gastropods in North America, including members of the Succineidae family (genera: *Catinella*, *Oxyloma*, and *Succinea*), which are often found in loess deposits.

To yield reliable ^{14}C ages, shells of Succineidae and other gastropods that do not ingest limestone must also behave as closed systems with respect to carbon during burial. The introduction of secondary carbon, either through exchange or addition, can cause measured ^{14}C ages to be either too young or too old depending on the age of the contaminants. The issue of small terrestrial gastropod shells remaining closed systems over geologic timescales has been tested at only a handful of localities, largely because it is difficult to find suitable materials (e.g., charcoal or plant macrofossils) to independently date the strata that contain the fossil shells. One such test was conducted at a late Quaternary sedimentary sequence near Oxford, Ohio in which fossil shells of multiple taxa, including Succineidae, yielded ages identical to that of well-preserved plant macrofossils recovered from the same thin (3–5 cm) silt unit (Pigati et al., 2010). Both the plant macrofossils and gastropod shells dated to ~25 ka, which indicates that the small gastropod shells remained closed systems since at least the Last Glacial maximum. However, it is unclear if these results can be extrapolated to other localities and time periods because the data are limited to a single stratigraphic horizon at one site.

In a related study, Rech et al. (2011) measured the ^{14}C content of "infinitely aged" small gastropod shells (those beyond the limit of ^{14}C dating) recovered from proglacial silt deposits in Illinois and found that contamination was present in a few shells, but only in trace amounts. Additional tests of open-system behavior of small terrestrial gastropod shells have been conducted in paleowetland deposits in southern Arizona (Pigati et al., 2004), the Great Basin (Brennan and Quade, 1997), and the Mojave Desert (Pigati et al., 2011), but the independent ages in these studies were either poorly constrained or could only be obtained from bounding stratigraphic units. In sum, although there is evidence that small terrestrial gastropod shells remain closed systems with respect to carbon over geologic timescales, this has not been tested systematically in late Quaternary deposits over large areas and multiple timescales, and has not been tested at all in loess deposits.

Here, we describe the results of a multi-faceted approach to understanding the potential for using ^{14}C dating of terrestrial gastropod shells to constrain the ages and mass accumulation rates of loess in North America. First, we compare highly resolved ^{14}C ages of well-preserved wood and gastropod shells recovered from a Holocene loess section in Wrangell-St. Elias National Park near Chitina, Alaska to determine if the shells behaved as closed systems with respect to carbon. Second, we apply ^{14}C dating of small terrestrial gastropod shells to a number of well-studied loess sequences in the Great Plains using stratigraphy and existing chronologies for comparison. Finally, we explore the limits of using terrestrial gastropod shells to date late Quaternary loess deposits at high temporal resolution at a site near the Yukon River in central Alaska, in historic-aged loess in the Matanuska River Valley of southern Alaska, and in old (>40 ka) loess at sites in western Iowa.

2. Materials and methods

Fossil gastropod shells were collected either individually or in small sediment blocks from Holocene and late Pleistocene loess deposits at three sites in Alaska and from multiple loess units (from youngest to oldest: Bignell Loess, Peoria Loess, Gilman Canyon Formation, Pisgah Loess, and Loveland Loess) at seven sites in the North American midcontinent (Table 1). Loess deposits in the midcontinent have been the focus of numerous studies over the past century; see excellent reviews by Bettis et al. (2003b), Busacca et al. (2004), and Roberts et al. (2007) for detailed treatments of the loess stratigraphy.

In the laboratory, shells were separated from the host sediment, placed in a beaker of ASTM Type 1, 18.2 MΩ (ultrapure) water, and subjected to an ultrasonic bath for a few seconds. The shells were then repeatedly dunked in a second beaker of ultrapure water to remove material adhering to the shell surface or lodged within the shell itself, and the process was repeated until the shells were visibly clean. In most cases, shells were selectively dissolved or etched briefly using dilute HCl to remove secondary carbonate (dust) from primary shell material. The etched shells were then washed repeatedly in ultrapure water and dried in an oven overnight at ~70 °C.

The clean, dry shells were broken and examined under a dissecting microscope to ensure that the interior whorls were free of secondary carbonate and detritus. We selected several shells at random for XRD analysis to verify that only shell aragonite remained prior to preparation for ^{14}C analysis. None of the fossil shells that we analyzed contained measurable quantities of calcite. Fossil shells that were free of detritus were converted to CO_2 using

Table 1
Locations and units present at each site.

Site name	Latitude (°N)	Longitude (°W)	Elevation (m)	Loess units present
Alaska				
Matanuska River Valley	61.631	149.119	163	–
Wrangell-St Elias NP	61.535	144.378	671	–
Yukon River Bridge	65.876	149.726	489	–
Midcontinent USA				
Beecher Island, CO	39.932	102.188	1119	MS, BL, BS, PL
Bignell Hill, NE	41.039	100.606	913	MS, BL, BS, PL, GCF
Council Bluffs, IA	41.257	95.840	339	MS, PL, PiL, LL
Devil's Den, NE	41.456	100.190	887	MS, HS, BL, BS, PL, GCF
Eustis, NE	40.649	100.071	822	MS, PL, GCF
Loveland, IA	41.500	95.880	349	MS, PL, FS, PiL
McCook, NE	40.200	100.645	779	MS, PL, GCF

Loess units: BL = Bignell Loess, PL = Peoria loess, GCF = Gilman Canyon Formation[1], PiL = Pisgah loess, LL = Loveland loess.
Soils: MS = Modern soil, HS = Holocene soil, BS = Brady soil, FS = Farmdale soil
[1]Includes two distinct soils and at least one, and possibly two, loess units.

A.C.S. reagent grade 85% H_3PO_4 under vacuum at 50 °C until the reaction was visibly complete (~1 h). The resulting CO_2 was split into two aliquots. One aliquot was converted to graphite using an iron catalyst and the standard hydrogen reduction process and submitted to either the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory or the NSF-Arizona AMS laboratory for AMS ^{14}C analysis. The second aliquot was submitted for $\delta^{13}C$ analysis in order to correct the measured ^{14}C activity of the shell carbonate for isotopic fractionation. All ^{14}C ages were calibrated using the IntCal09 dataset and CALIB 6.0 (Stuiver and

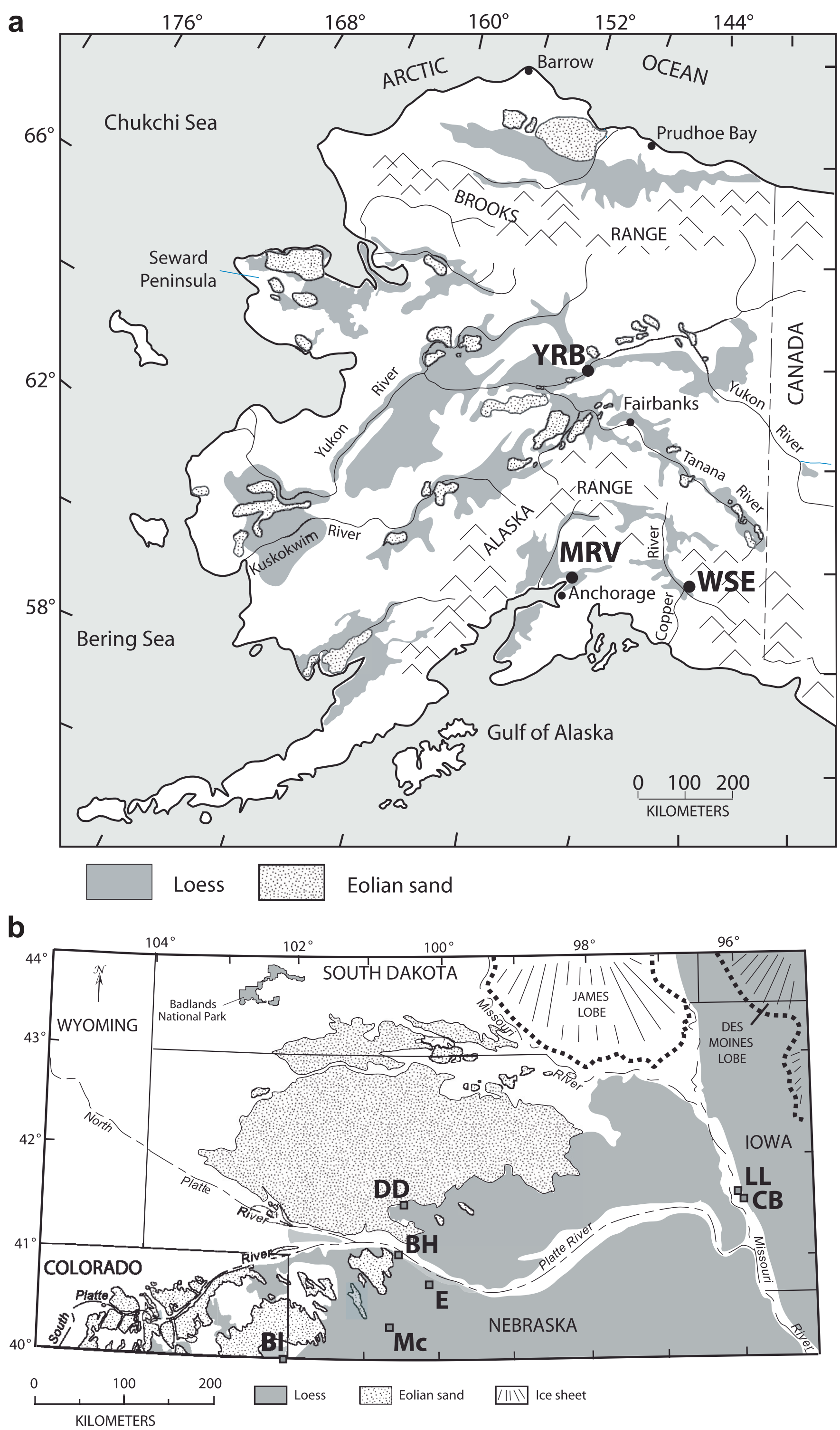

Fig. 2. (a). Study sites in Alaska. Site abbreviations: MRV = Matanuska River Valley; WSE = Wrangell-St. Elias National Park; YRB = Yukon River Bridge (loess distribution derived from sources in Muhs et al., 2004). (b). Study sites in the North American midcontinent. Site abbreviations: BH = Bignell Hill, NE; BI = Beecher Island, CO; CB = Council Bluffs, IA; DD = Devil's Den, NE; E = Eustis, NE; Mc = McCook, NE; LL = Loveland, IA (after Muhs et al., 2008).

Reimer, 1993; Reimer et al., 2009). Ages are presented in calibrated years BP (Before Present; 0 yr BP = 1950 A.D.) unless otherwise noted, and uncertainties are given at the 95% (2σ) confidence level. In the event that multiple ranges were permitted during calibration, ages that are discussed in the text are based on the mean of the ranges weighted by their probabilities as calculated by the CALIB program and are presented without uncertainties. For example, an age of a single calibrated range would be presented as 10.40 ± 0.16 ka, whereas it would be presented simply as 10.4 ka if multiple ranges were permitted.

3. Results and discussion

3.1. Comparison of shell ages to independent loess chronologies

We analyzed fossil gastropod shells recovered from late Quaternary loess deposits at Wrangell-St. Elias National Park in southern Alaska (Fig. 2a) and seven sites in the Great Plains (Fig. 2b). Previous work at the Wrangell section has shown the loess record spans nearly the entire Holocene (Muhs et al., 2013b) and therefore we should expect the shell ages to range from near modern to ~11 ka. At the Great Plains sections, the majority of the gastropod shells were recovered from Peoria Loess, which generally dates to between ~13 and 28 ka in the midcontinent (Bettis et al., 2003b; Muhs et al., 2008). Additional shells were collected from the younger (Holocene) Bignell Loess, as well as the older Pisgah Loess and Gilman Canyon Formation. Thus, in general we should expect the fossil gastropod shells recovered from the Great Plains sites to return ages that are between ~10 and 40 ka. Previous investigators have obtained independent ages for the loess sections using a number of different chronometric methods. We limit the discussion below to independent ages obtained using AMS ^{14}C, OSL, and IRSL techniques.

3.1.1. Wrangell–St. Elias National Park, Alaska

The Wrangell loess section is located along the banks of the Copper River in Wrangell-St. Elias National Park near the town of Chitina, Alaska. It is composed of ~9.5 m of organic-rich loess that overlies a diamicton that is presumably of glacial origin (Fig. 3). Unlike many loess deposits, the Wrangell section is filled with well-preserved tree stumps, logs, sticks and twigs that can often be identified to genus (Table 2). Independent ages ($n = 24$) derived from the fossil wood span nearly the entire Holocene, ranging from 0.9 ka at a depth of just under 1 m (depth referenced to the local ground surface) to 10.24 ± 0.03 ka near the base of the loess (Muhs et al., 2013b). The wood ages are in correct stratigraphic order and do not exhibit any significant reversals with depth.

Terrestrial gastropod shells, mostly Succineidae, are also abundant at the Wrangell loess section and are remarkably well preserved considering the amount of organic acids that are likely to have passed through the sediments. Similar to the wood results, the shell ages ($n = 19$) range from 1.0 to 10.40 ± 0.11 ka and are in correct stratigraphic order. With only a few exceptions, the shell ages are statistically indistinguishable from the wood ages at the same stratigraphic level (Figs. 3 and 4a). The discrepancies between the paired wood-shell ages are largely confined to the 1.5–4.0 m depth interval, and likely reflect stratigraphic complexities related to tree throw, mantling of tree stumps by loess, and other issues related to the uneven surface of forest floors rather than problems with the dated materials themselves. Although it is possible that the discrepancies may be due to contamination that would make the wood ages too young or the shell ages too old, we do not have independent evidence of either scenario. Preservation of the wood and plant macrofossils is

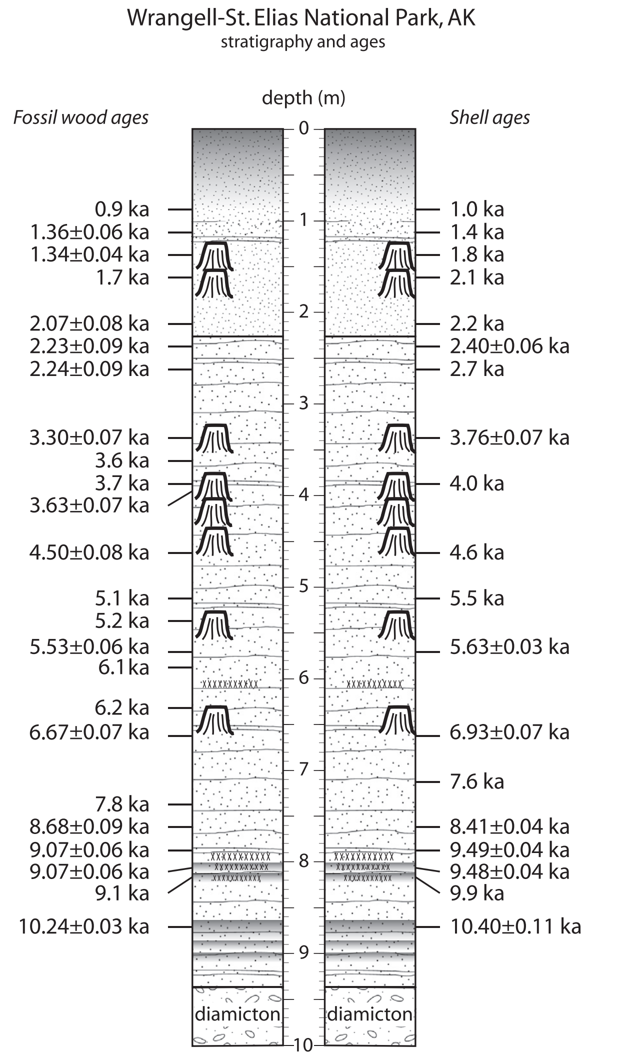

Fig. 3. Independent and gastropod shell ages from a Holocene loess section in Wrangell-St. Elias National Park near Chitina, AK. The independent ages consist of calibrated ^{14}C ages from well-preserved wood (Muhs et al., 2013b). The shell ages are from Succineidae shells.

remarkable throughout the Wrangell section, which argues against variable contamination of the organic material, and geochemical data show no relation between the amount of carbonate present in the loess and the deviation of the paired shell-wood ages (Fig. 4b). Taken as a whole, the chronologic data from the Wrangell section show that the gastropod shells behaved as closed systems with respect to carbon over the entire Holocene at this location.

3.1.2. Beecher Island, Colorado

The stratigraphy at the Beecher Island section (from top to bottom) consists of a modern soil forming in Bignell Loess, unaltered Bignell Loess, the Brady Soil formed in Peoria Loess, and several meters of unaltered Peoria Loess (Fig. 5). Humic acids from the lower portion of the modern soil previously yielded an age of 10.41 ± 0.16 ka (Muhs et al., 1999). Humic acid ages of 12.94 ± 0.21 and 13.63 ± 0.18 ka were also obtained from the upper part of the Brady Soil at depths of 1.6 and 1.9 m, respectively (Muhs et al., 1999).

We collected and analyzed Succineidae shells from both Bignell Loess and the upper 4 m of unaltered Peoria Loess. Although Peoria

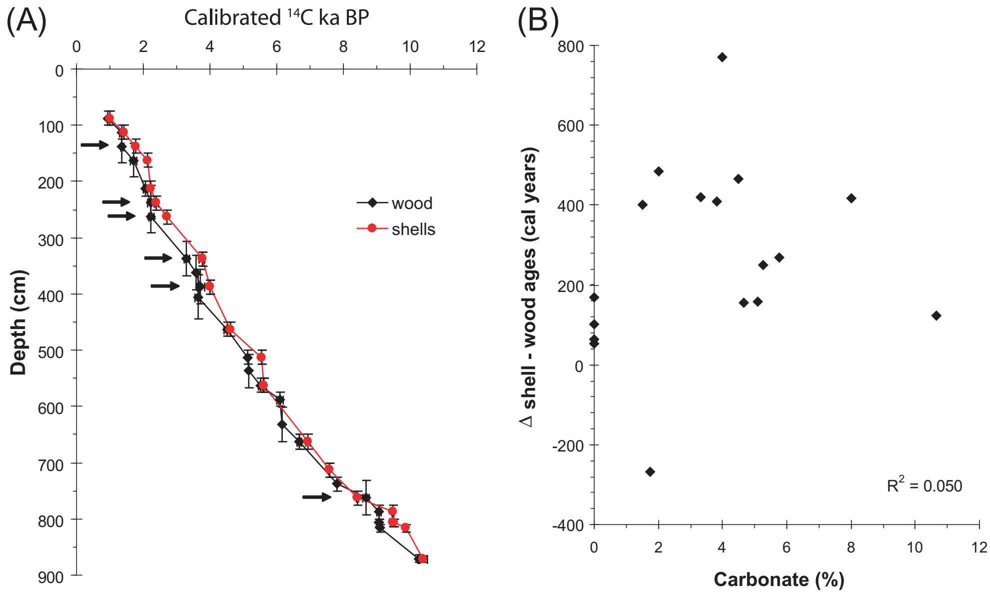

Fig. 4. (A) Depth versus age profile for wood and shell ages at the Wrangell section. Arrows indicate depths at which in situ tree stumps or large logs were sampled. (B) Deviations between the shell and organic ages (with shells ages being older) compared to the carbonate content of the host sediment. The lack of relation between the two parameters ($R^2 = 0.050$) suggests that carbonate intake by gastropods is unlikely to be the cause of the observed age discrepancies in the 1.5–4.0 m depth interval.

Loess actually extends to a depth of ~12 m at the Beecher Island site, we did not find any shells at depths below ~4 m. Calibrated shell ages ($n = 7$) for Bignell Loess range from 10.34 ± 0.13 to 12.4 ka, but are not in correct stratigraphic order, most likely because Bignell Loess is intensively bioturbated at this site. Thus, it is difficult to evaluate the veracity of these shell ages, other than to say that the overall range appears to be reasonable when compared to a single humic acid age from the lower part of the modern soil and independent ages of Bignell Loess at other sites (Mason et al., 2003). We obtained additional calibrated ages of ~15.3 and 15.8 ka for fossil shells recovered from Peoria Loess at depths of ~2.6 and 4.0 m, respectively. These ages are in good agreement with previous ages of the uppermost Peoria Loess elsewhere in the Great Plains (Bettis et al., 2003a). In all, ^{14}C dating of fossil shells has increased our knowledge of the loess chronology at the Beecher Island site to include Bignell Loess and an additional 2.5 m of Peoria Loess that were previously undated.

3.1.3. Bignell Hill, Nebraska

Peoria Loess at the Bignell Hill site is extremely thick and is exposed in two intervals, 2–16 m and 41–48 m below ground surface. The interval between 16 and 41 m is currently covered, but borehole data indicate that Peoria Loess is present continuously from 2 to 48 m depth (Bettis et al., 2003a). Thus, Bignell Hill may contain the thickest Last-Glacial-age loess deposit in the world. The stratigraphy at this section includes a modern soil forming in Bignell Loess, unaltered Bignell Loess, the Brady Soil formed in Peoria Loess, unaltered Peoria Loess that includes alternating massive and laminated strata, and the Gilman Canyon Formation, which here consists of two paleosols separated by 1–2 m of unaltered loess (Fig. 6).

Previous chronologic work on the upper exposure at Bignell Hill includes OSL dating of quartz ($n = 4$, Roberts et al., 2003) and ^{14}C dating of humic acids ($n = 2$, Muhs et al., 1999). Both sets of dates are in correct stratigraphic order and range from 9.4 ± 0.6 ka (1.9 m) to 16.6 ± 0.8 ka (14.1 m). New Succineidae shell ages ($n = 7$) for Peoria Loess in the upper exposure at Bignell Hill are also in correct stratigraphic order and range from 16.92 ± 0.19 ka (3.6 m) to 18.2 ka (13.6 m).

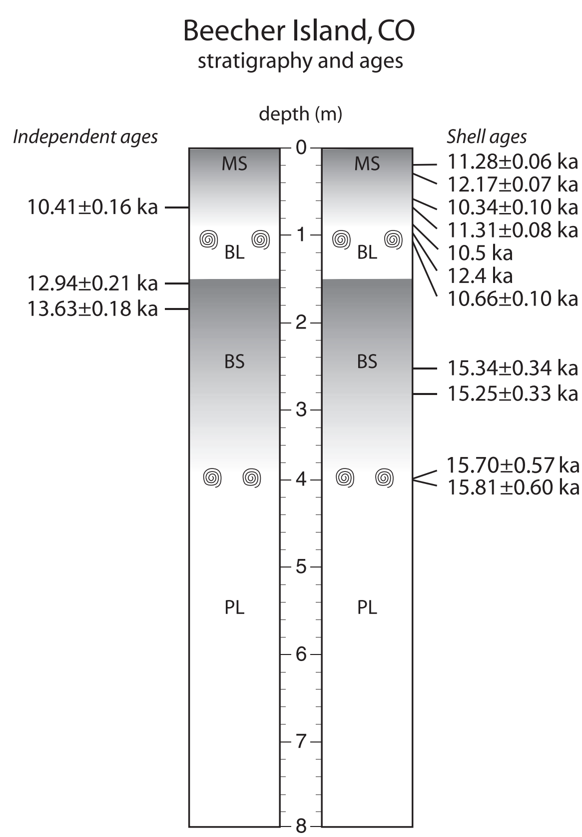

Fig. 5. Independent and gastropod shell ages at Beecher Island, CO. The three independent ages are all calibrated humic acid ages (Muhs et al., 1999). The shell ages are from Succineidae shells. Note that the modern soil is heavily bioturbated at this site, which is reflected in the shell ages. Stratigraphic units: MS = modern soil, BL = Bignell Loess, BS = Brady Soil, PL = Peoria Loess.

Table 2
Summary of sample information, carbon-14 ages, and calibrated ages for all sites.

Sample #	Laboratory #[a]	AMS #	Source[b]	Material dated	Unit[c]	Depth (m)[d]	$\delta^{13}C$ (vpdb)[e]	^{14}C age (^{14}C ka BP)	Age (cal ka BP)[f]	P[g]
Alaska										
Wrangell-St Elias National Park										
AK-1704	WW-7766	CAMS-146787	2	Probable *Picea*	–	0.75–1.00	−26.7	1.00 ± 0.03	0.81 ± 0.01	0.06
									0.93 ± 0.03	0.74
AK-1704	WW-8406	CAMS-151339	1	Succineidae	–	0.75–1.00	−7.6	1.08 ± 0.03	0.97 ± 0.04	0.72
									1.04 ± 0.02	0.28
AK-1705	WW-7767	CAMS-146778	2	Probable *Picea*	–	1.00–1.25	−25.6	1.48 ± 0.04	1.36 ± 0.06	0.99
AK-1705	WW-8407	CAMS-151340	1	Succineidae	–	1.00–1.25	−7.3	1.53 ± 0.03	1.39 ± 0.04	0.70
									1.49 ± 0.03	0.27
AK-1706	WW-7768	CAMS-146779	2	Probable *Picea* stump	–	1.07–1.67	−28.4	1.45 ± 0.03	1.34 ± 0.04	1.00
AK-1706	WW-8284	CAMS-150894	1	Succineidae	–	1.25–1.50	−7.6	1.85 ± 0.03	1.77 ± 0.06	0.94
									1.85 ± 0.01	0.06
AK-1707	WW-7769	CAMS-146780	2	*Picea* stump	–	1.32–1.92	−26.6	1.77 ± 0.03	1.68 ± 0.07	0.88
									1.78 ± 0.03	0.12
AK-1707	WW-8408	CAMS-151341	1	Succineidae	–	1.50–1.75	−7.2	2.14 ± 0.04	2.09 ± 0.09	0.78
									2.27 ± 0.03	0.22
AK-1709	WW-7770	CAMS-146781	2	Cupressaceae?	–	2.00–2.25	−24.4	2.10 ± 0.03	2.07 ± 0.08	1.00
AK-1709	WW-8409	CAMS-151342	1	Succineidae	–	2.00–2.25	−7.9	2.19 ± 0.03	2.17 ± 0.04	0.40
									2.27 ± 0.04	0.60
AK-1710	WW-7771	CAMS-146782	2	Conifer wood (large)	–	2.07–2.67	−25.4	2.20 ± 0.03	2.23 ± 0.09	1.00
AK-1710	WW-8410	CAMS-151343	1	Succineidae	–	2.25–2.50	−7.0	2.37 ± 0.03	2.40 ± 0.06	1.00
AK-1711	WW-7772	CAMS-146783	2	*Picea or Larix (large)*	–	2.32–2.92	−25.5	2.21 ± 0.03	2.24 ± 0.09	1.00
AK-1711	WW-8411	CAMS-151344	1	Succineidae	–	2.50–2.75	−7.9	2.58 ± 0.03	2.63 ± 0.01	0.09
									2.73 ± 0.03	0.90
AK-1714	WW-7773	CAMS-146784	2	Probable *Picea* log	–	3.07–3.67	−25.2	3.08 ± 0.03	3.29 ± 0.07	1.00
AK-1714	WW-8412	CAMS-151345	1	Succineidae	–	3.25–3.50	−5.9	3.47 ± 0.03	3.76 ± 0.07	0.97
AK-1715	WW-7774	CAMS-146785	2	*Picea log*	–	3.32–3.92	−26.3	3.35 ± 0.03	3.51 ± 0.03	0.20
									3.60 ± 0.05	0.75
									3.67 ± 0.01	0.06
AK-1716	WW-7775	CAMS-146786	2	*Picea* stump	–	3.57–4.17	−25.4	3.44 ± 0.03	3.71 ± 0.07	0.83
									3.81 ± 0.02	0.17
AK-1716	WW-8413	CAMS-151346	1	Succineidae	–	3.75–4.00	−7.1	3.66 ± 0.03	3.96 ± 0.06	0.65
									4.06 ± 0.03	0.35
AK-1717	WW-7776	CAMS-146787	2	Probable *Picea* stump	–	3.65–4.45	−25.2	3.39 ± 0.03	3.63 ± 0.07	1.00
AK-1719	WW-7777	CAMS-146788	2	Probable *Picea*	–	4.50–4.75	−25.2	4.05 ± 0.03	4.50 ± 0.08	0.95
AK-1719	WW-8285	CAMS-150895	1	Succineidae	–	4.50–4.75	−7.4	4.09 ± 0.03	4.58 ± 0.06	0.74
									4.78 ± 0.02	0.20
AK-1721	WW-7778	CAMS-146790	2	Pinaceae	–	5.00–5.25	−29.3	4.43 ± 0.03	4.97 ± 0.10	0.76
									5.23 ± 0.05	0.22
									5.22 ± 0.06	0.51
AK-1721	WW-8414	CAMS-151347	1	Succineidae	–	5.00–5.25	−7.7	4.82 ± 0.03	5.51 ± 0.03	0.61
									5.59 ± 0.01	0.39
AK-1722	WW-7779	CAMS-146791	2	*Picea* stump	–	5.07–5.67	−25.7	4.51 ± 0.03	5.12 ± 0.08	0.66
									5.26 ± 0.04	0.34
AK-1723	WW-7780	CAMS-146792	2	*Picea*	–	5.50–5.75	−26.1	4.77 ± 0.03	5.53 ± 0.06	0.97
AK-1723	WW-8415	CAMS-151348	1	Succineidae	–	5.50–5.75	−7.7	4.92 ± 0.03	5.63 ± 0.03	0.94
									6.08 ± 0.10	0.09
AK-1725	WW-7781	CAMS-146793	2	Probable *Picea*	–	5.75–6.00	−26.1	5.28 ± 0.04	5.96 ± 0.02	0.91
									6.08 ± 0.10	0.90
AK-1726	WW-7782	CAMS-146794	2	*Picea* stump	–	6.02–6.62	−25.5	5.37 ± 0.03	6.05 ± 0.03	0.17
									6.13 ± 0.03	0.22
									6.23 ± 0.05	0.61
AK-1727	WW-7783	CAMS-146795	2	Probable conifer	–	6.50–6.75	−27.2	5.85 ± 0.03	6.67 ± 0.07	0.95
AK-1727	WW-8416	CAMS-151349	1	Succineidae	–	6.50–6.75	−7.2	6.07 ± 0.03	6.93 ± 0.07	0.98
AK-1729	WW-8417	CAMS-151350	1	Succineidae	–	7.00–7.25	−7.7	6.72 ± 0.03	7.53 ± 0.01	0.15
									7.59 ± 0.03	0.81
AK-1730	WW-7784	CAMS-146796	2	*Picea*	–	7.25–7.50	−26.8	6.97 ± 0.03	7.79 ± 0.08	0.93
									7.91 ± 0.01	0.07
AK-1731	WW-8342	CAMS-151127	2	Pinaceae (large)	–	7.32–7.92	−26.0	7.89 ± 0.03	8.68 ± 0.09	1.00
AK-1731	WW-8418	CAMS-151351	1	Succineidae	–	7.50–7.75	−7.9	7.62 ± 0.03	8.41 ± 0.04	0.99
AK-1732	WW-8343	CAMS-151128	2	Probable *Picea*	–	7.75–8.00	−24.3	8.15 ± 0.03	9.07 ± 0.06	0.96
AK-1732	WW-8419	CAMS-151352	1	Succineidae	–	7.75–8.00	−7.3	8.47 ± 0.03	9.49 ± 0.04	1.00
AK-1734	WW-8344	CAMS-151129	2	Unidentified wood	–	8.00–8.13	−25.0	8.14 ± 0.03	9.07 ± 0.06	1.00
AK-1734	WW-8280	CAMS-150890	1	Succineidae	–	8.00–8.13	−7.8	8.44 ± 0.03	9.48 ± 0.04	1.00
AK-1734b	WW-8281	CAMS-150891	1	Succineidae	–	8.00–8.13	−7.6	8.53 ± 0.03	9.51 ± 0.03	1.00
AK-1735	WW-8390	CAMS-151253	2	Unidentified wood	–	8.13–8.20	−27.6	8.15 ± 0.04	9.07 ± 0.07	0.85
									9.21 ± 0.04	0.15
AK-1735	WW-8282	CAMS-150892	1	Succineidae	–	8.13–8.20	−6.8	8.82 ± 0.03	9.83 ± 0.11	0.85
									10.09 ± 0.03	0.12
AK-1738	WW-8348	CAMS-151130	2	Unidentified wood	–	8.65–8.77	−27.4	9.10 ± 0.03	10.24 ± 0.03	1.00
AK-1738	WW-8283	CAMS-150893	1	Succineidae	–	8.65–8.77	−6.5	9.24 ± 0.03	10.40 ± 0.11	1.00
Yukon River bridge										
YRB-5a	WW-8913	CAMS-156093	1	Succineidae	–	0.55	−8.0	11.10 ± 0.03	12.96 ± 0.16	1.00

Table 2 (*continued*)

Sample #	Laboratory #[a]	AMS #	Source[b]	Material dated	Unit[c]	Depth (m)[d]	δ^{13}C (vpdb)[e]	^{14}C age (^{14}C ka BP)	Age (cal ka BP)[f]	P[g]
YRB-5b	WW-8914	CAMS-156094	1	Succineidae	–	0.61	−7.9	10.99 ± 0.03	12.83 ± 0.15	0.95
YRB-5c	WW-8915	CAMS-156095	1	Succineidae	–	0.63	−8.2	11.05 ± 0.03	12.92 ± 0.18	1.00
YRB-5e	WW-8916	CAMS-156096	1	Succineidae	–	0.68	−8.5	11.19 ± 0.03	13.06 ± 0.16	1.00
YRB-5f	WW-8917	CAMS-156097	1	Succineidae	–	0.69	−8.1	11.23 ± 0.03	13.17 ± 0.11	0.96
YRB-5g	WW-8918	CAMS-156098	1	Succineidae	–	0.72	−8.2	11.41 ± 0.03	13.28 ± 0.11	1.00
Midcontinental USA										
Beecher Island, CO										
BI-15	WW-8521	CAMS-151966	1	Succineidae	BL	0.2	−2.8	9.88 ± 0.03	11.28 ± 0.06	1.00
BI-16	WW-8522	CAMS-151967	1	Succineidae	BL	0.3	−4.5	10.38 ± 0.03	12.17 ± 0.07	0.47
BI-14	WW-8520	CAMS-151965	1	Succineidae	BL	0.6	−4.0	9.19 ± 0.04	12.31 ± 0.07	0.53
LI-204	NSFL-2754	CAMS-23131	3	Humic acids	MS	0.7	−17.8	9.25 ± 0.06	10.41 ± 0.16	1.00
BI-5	WW-8528	CAMS-151973	1	Succineidae	BL	0.7	*−8*	9.91 ± 0.04	10.47 ± 0.02	1.07
BI-13	WW-8519	CAMS-151964	1	Succineidae	BL	0.9	−5.2	9.33 ± 0.04	10.45 ± 0.03	0.12
									10.54 ± 0.06	0.81
									10.64 ± 0.02	0.07
BI-4	WW-8288	CAMS-150899	1	Succineidae	BL	1.0	−4.6	10.46 ± 0.03	12.25 ± 0.04	0.14
									12.47 ± 0.10	0.82
Bignell loess	WW-7321	CAMS-144497	1	Succineidae	BL	1.1	*−8*	9.42 ± 0.04	10.66 ± 0.10	1.00
LI-207	NSRL-2072	CAMS-17300	3	Humic acids	BS	1.6	*−25*	11.09 ± 0.07	12.94 ± 0.21	1.00
LI-208	NSRL-2073	CAMS-17297	3	Humic acids	BS	1.9	*−25*	11.81 ± 0.06	13.63 ± 0.18	1.00
BI-1	WW-8286	CAMS-150896	1	Succineidae	PL	2.6	−6.0	12.86 ± 0.03	15.34 ± 0.34	0.96
BI-2	WW-8287	CAMS-150898	1	Succineidae	PL	2.9	−5.9	12.79 ± 0.03	15.25 ± 0.33	1.00
Peoria loess	WW-7423	CAMS-144417	1	Succineidae	PL	3.9	−6.9	13.00 ± 0.04	15.70 ± 0.57	1.00
Peoria loess	WW-7320	CAMS-144496	1	Succineidae	PL	3.9	*−8*	13.07 ± 0.05	15.80 ± 0.60	1.00
Bignell Hill, NE										
BH-1	NSRL-2804	CAMS-24344	3	Humic acids	BS	1.94	*−25*	10.07 ± 0.08	11.64 ± 0.33	1.00
BH-2	NSRL-2805	CAMS-24345	3	Humic acids	BS	2.17	*−25*	10.49 ± 0.07	12.36 ± 0.23	1.00
BH-48.5-49.0	WW-8003	CAMS-148499	1	Succineidae	PL	3.4–3.9	*−8*	13.81 ± 0.07	16.92 ± 0.19	1.00
BH-49.0-49.5	WW-7322	CAMS-144498	1	Succineidae	PL	3.9–4.4	−8.5	14.00 ± 0.05	17.03 ± 0.22	0.96
BH-49.5-50.0	WW-7323	CAMS-144499	1	Succineidae	PL	4.4–4.9	−8.0	14.22 ± 0.05	17.29 ± 0.30	1.00
BH-50.5-51.0	WW-7324	CAMS-144500	1	Succineidae	PL	5.4–5.9	−9.1	13.99 ± 0.05	17.03 ± 0.22	0.97
BH-50.5-51.0 (r)	WW-7422	CAMS-144416	1	Succineidae	PL	5.4–5.9	−8.4	14.19 ± 0.05	17.27 ± 0.30	1.00
BH-52.5-53.0	WW-7327	CAMS-144502	1	Succineidae	PL	7.4–7.9	−7.7	14.32 ± 0.05	17.42 ± 0.33	1.00
BH-57.5-58.0	WW-7328	CAMS-144503	1	Succineidae	PL	13.4–13.9	−7.6	14.86 ± 0.05	17.98 ± 0.18	0.49
									18.37 ± 0.15	0.51
BH-7	NSRL-2956	CAMS-26401	3	Humic acids	GCS2	48.3	*−25*	30.77 ± 0.22	35.18 ± 0.43	0.76
									36.04 ± 0.21	0.24
BH-106	WW-8619	CAMS-153253	1	Succineidae	GCS2	48.6	*−8*	32.2 ± 1.3	37.4 ± 2.9	1.00
BH-3	NSRL-2806	CAMS-24346	3	Humic acids	GCS1	51.5	*−25*	40.6 ± 1.1	44.3 ± 1.6	1.00
Council Bluffs, IA										
Upper CB	WW-8526	CAMS-151971	1	Succineidae	LL	–	*−8*	51.4 ± 3.0	–	
Lower CB	WW-8527	CAMS-151972	1	Succineidae	LL	–	−4.8	45.4 ± 1.4	–	
Devil's Den, NE										
DD-2	WW-4054	CAMS-89225	4	Humic acids	BS	4.5	*−25*	10.11 ± 0.04	11.52 ± 0.04	0.09
									11.72 ± 0.12	0.72
									11.92 ± 0.05	0.15
DD-57	WW-8387	CAMS-151250	1	Succineidae	PL	15.0	−6.6	14.28 ± 0.04	17.35 ± 0.30	1.00
DD-34	WW-8386	CAMS-151249	1	Succineidae	PL	32.6	−5.8	18.98 ± 0.05	22.64 ± 0.34	0.93
									23.18 ± 0.06	0.07
DD-33	WW-8385	CAMS-151248	1	Succineidae	PL	33.3	−6.3	19.59 ± 0.05	23.38 ± 0.36	1.00
DD-3	WW-4055	AA-53370	4	Humic acids	GCS2	36.1	*−25*	22.68 ± 0.16	27.38 ± 0.56	1.00
DD-4	WW-4056	AA-53371	4	Humic acids	GCS1	36.8	*−25*	27.27 ± 0.27	31.57 ± 0.46	1.00
Eustis, NE										
–	–	–	5	*Vallonia gracilicosta*	PL	1.5	*−8*	13.84 ± 0.11	16.96 ± 0.25	1.00
Eustis-170-250	WW-7312	CAMS-144489	1	Succineidae	PL	1.7–2.5	*−8*	14.45 ± 0.05	17.55 ± 0.33	1.00
–	–	–	6	Humic acids	PL	2.1–2.3	*−25*	16.57 ± 0.08	19.74 ± 0.29	1.00
Eustis-350-550	WW-7313	CAMS-144490	1	Succineidae	PL	3.5–5.5	*−8*	15.40 ± 0.06	18.66 ± 0.14	1.00
Eustis-760-900	WW-7314	CAMS-144491	1	Succineidae	PL	7.6–9.0	*−8*	16.14 ± 0.07	19.06 ± 0.12	0.35
									19.32 ± 0.13	0.65
Eustis-900-975	WW-7315	CAMS-144492	1	Succineidae	PL	9.00–9.75	*−8*	16.62 ± 0.07	19.77 ± 0.30	1.00
Eustis 1265-1315	WW-8388	CAMS-151251	1	Succineidae	PL	12.65–13.15	−7.6	18.35 ± 0.05	21.88 ± 0.34	1.00
Eustis-1500-1650	WW-7317	CAMS-144493	1	Succineidae	PL	15.0–16.5	*−8*	18.91 ± 0.09	22.60 ± 0.37	0.95
Eustis 1	WW-4051	CAMS-89222	4	Humic acids	GCS2	16.1	*−25*	23.87 ± 0.10	28.75 ± 0.45	1.00
Eustis 2	WW-4052	CAMS-89223	4	Humic acids	GCS1	16.9	*−25*	28.10 ± 0.20	32.30 ± 0.68	1.00
Loveland, IA										
LP-A	WW-8002	CAMS-148498	1	Succineidae	PL	9.5	*−8*	16.38 ± 0.14	19.64 ± 0.39	0.98
LP-B	WW-7608	CAMS-145802	1	Succineidae	PL	18.5	*−8*	17.84 ± 0.06	21.29 ± 0.26	1.00
LP-C	WW-7605	CAMS-145799	1	Succineidae	PL	19.2	−7.1	17.95 ± 0.06	21.39 ± 0.21	1.00
LP-D	WW-7606	CAMS-145800	1	Succineidae	PL	19.4	−7.0	18.06 ± 0.06	21.59 ± 0.32	1.00
Loveland PL	–	AA-4828	7	Succineidae	PL	31.7	*−25*	20.54 ± 0.20	24.48 ± 0.52	1.00
LP-F	WW-7609	CAMS-145803	1	Succineidae	PL	36.0	*−8*	20.44 ± 0.08	24.27 ± 0.30	0.91
									24.69 ± 0.09	0.09
LP-G	WW-7610	CAMS-145804	1	Succineidae	PL	40.2	−6.2	25.18 ± 0.14	29.96 ± 0.39	1.00
LP-I	WW-7613	CAMS-145807	1	Charcoal	PiL	42.1	−23.5	34.33 ± 0.73	39.2 ± 1.8	1.00

(*continued on next page*)

Table 2 (*continued*)

Sample #	Laboratory #[a]	AMS #	Source[b]	Material dated	Unit[c]	Depth (m)[d]	$\delta^{13}C$ (vpdb)[e]	^{14}C age (^{14}C ka BP)	Age (cal ka BP)[f]	P[g]
LP-J	WW-7611	CAMS-145805	1	Succineidae	PiL	44.1	−8.1	35.96 ± 0.51	41.0 ± 1.0	1.00
Loveland PiL	–	AA-4827	7	Succineidae	PiL	44.8	*−25*	34.40 ± 0.70	39.3 ± 1.8	1.00
LP-K	WW-7612	CAMS-145806	1	Succineidae	PiL	45.7	−9.4	36.52 ± 0.55	41.45 ± 0.91	1.00
LP-L	WW-7614	CAMS-145808	1	Charcoal	PiL	45.7	−24.4	41.6 ± 1.8	45.6 ± 3.2	1.00
McCook, NE										
McC-1	WW-8523	CAMS-151968	1	Succineidae	PL	3.0–3.5	−6.3	18.02 ± 0.06	21.50 ± 0.27	1.00
McC-2	WW-8524	CAMS-151969	1	Succineidae	PL	4.5–5.0	−6.7	18.38 ± 0.06	21.90 ± 0.36	1.00
McC-3	WW-8525	CAMS-151970	1	Succineidae	PL	5.0–5.5	−6.7	19.11 ± 0.06	22.73 ± 0.31	0.83
									23.18 ± 0.12	0.17
GCF-upper	WW-2743	CAMS-63616	4	Humic acids	GCF	9.6	*−25*	26.42 ± 0.20	30.98 ± 0.30	1.00
GCF-middle	WW-2744	CAMS-63617	4	Humic acids	GCF	9.8	*−25*	26.86 ± 0.21	31.26 ± 0.23	1.00
GCF-lower	WW-2745	CAMS-63618	4	Humic acids	GCF	9.9	*−25*	32.74 ± 0.25	37.41 ± 0.77	0.96

[a] WW = USGS radiocarbon laboratory in Reston, VA; CAMS = Lawrence Livermore National Laboratory; AA = NSF-Arizona AMS facility
[b] Source = (1) this study, (2) Muhs et al., 2013b, (3) Muhs et al., 1999, (4) Muhs et al., 2008, (5) Rousseau and Kukla, 1994, (6) Maat and Johnson, 1996, (7) Forman et al., 1992.
[c] BL = Bignell Loess, BS = Brady Soil, GCF = Gilman Canyon Formation, GCS = Gilman Canyon Soil, LL = Loveland Loess, PL = Peoria Loess, PiL = Pisgah Loess
[d] Depth below ground surface.
[e] Shell aliquots that did not contain enough material for stable isotope analyses were assigned $\delta^{13}C$ values of 8 ± 2‰ (italics). Similarly, small organic samples were assigned $\delta^{13}C$ values of −25‰.
[f] Calibrated ages were calculated using CALIB v. 6.0.0, IntCal09.14C dataset; limit 50.0 calendar ka B.P. Calibrated ages are reported as the midpoint of the calibrated range. Uncertainties are reported at the 2σ(95%) confidence level and are calculated as the difference between the midpoint and either the upper or lower limit of the calibrated age range, whichever is greater. Multiple ages are reported when the probability of a calibrated age range exceeds 0.05.
[g] P = probability of the calibrated age falling within the reported range as calculated by CALIB.

In the lower exposure, previous OSL ages range from 18.9 ± 0.9 ka (43.8 m) to 25.1 ± 1.1 ka (47.8 m) (Roberts et al., 2003). Unfortunately, we did not find any gastropod shells in Peoria Loess in this part of the section. Farther down in the section, one shell age, 37.4 ± 2.9 ka, obtained from the Gilman Canyon Formation is similar to a humic acid age (35.4 ka) at approximately the same depth (Muhs et al., 1999).

Two observations can be made regarding the new shell ages for Bignell Hill loess deposits. First, the shell ages establish new chronologic constraints for the 3–8 m depth interval, which demonstrates the utility of dating small terrestrial gastropod shells in loess deposits or strata that were previously undated. Second, the shell age of 18.2 ka that we obtained at a depth of ∼14 m is significantly older than the OSL age of 16.6 ± 0.8 ka at approximately the same depth. This represents the first in a series of discrepancies between our shell ages and corresponding OSL ages (with shell ages being consistently older) at loess sites in Nebraska.

3.1.4. Devil's Den, Nebraska

The Devil's Den section consists of a thick (∼38 m) section of loess that includes at least five soils (modern, Holocene, Brady, and two Gilman Canyon paleosols), unaltered Bignell Loess, a thick sequence of Peoria Loess that includes laminated and massive strata, and ∼1 m of bedded sand at a depth of ∼30 m (Fig. 7). The independent chronologic data for Peoria Loess are difficult to assess as OSL ages at depths of ∼7, 20, and 28 m are statistically indistinguishable from one another (Roberts et al., 2003). Humic acid ages of 27.38 ± 0.56 and 31.57 ± 0.46 ka obtained from the two Gilman Canyon paleosols are comparable to ages for this stratigraphic unit elsewhere (Johnson et al., 2007).

We obtained three new shell ages for Peoria Loess that are in correct stratigraphic order and range from 17.35 ± 0.30 ka (15 m) to 23.38 ± 0.36 ka (33 m). As above, calibrated shell ages near the base of Peoria Loess are ∼5 ka older than an OSL age ∼2 m *lower* in the section. The magnitude of this discrepancy is far greater than could be explained by the limestone problem or other contamination issues related to ^{14}C dating of Succineidae shells (Pigati et al., 2010). These results further demonstrate the utility of using ^{14}C dating of small terrestrial gastropod shells to date loess deposits, as the OSL ages at Devil's Den appear to be problematic.

3.1.5. Eustis, Nebraska

The uppermost part of the Eustis section is relatively simple in terms of its stratigraphy, consisting of a modern soil formed in Peoria Loess, ∼15 m of unaltered Peoria Loess, and ∼2 m of the Gilman Canyon Formation (Fig. 8). Five previous OSL ages range from 14.2 ± 0.6 ka (2.9 m) to 20.7 ± 0.9 ka (16.1 m) and are in correct stratigraphic order (Roberts et al., 2003). However, a humic acid age of 19.74 ± 0.29 ka at a depth of 2.2 m (Maat and Johnson, 1996) is more than 5 ka older than an OSL age of 14.2 ± 0.6 ka obtained ∼50 cm *lower* in the section. It is unclear if the humic acid age is anomalously old or if the OSL ages are too young as described above. Additional humic acid ages of 28.75 ± 0.45 and 32.30 ± 0.68 ka bracket the contact between Peoria Loess and Gilman Canyon Formation, similar to ages for this stratigraphic level observed elsewhere (Muhs et al., 2008).

New gastropod shell ages derived from shells of Succineidae ($n = 6$) and *Vallonia gracilicosta* ($n = 1$, Rousseau and Kukla, 1994) recovered from Peoria Loess range from 16.96 ± 0.25 ka (1.5 m) to 22.60 ± 0.37 ka (15.75 m). The shell ages are in correct stratigraphic order but are consistently 3–4 ka older than OSL ages at similar depths throughout the section. If this discrepancy was due entirely to the shells being too old because of the limestone problem, this would require 30–40% of the shell carbonate to be derived from limestone or other carbonate rocks. Although old carbon problems approaching these levels have been observed in large-shelled gastropods (Goodfriend and Stipp, 1983), the magnitude of contamination required to reconcile the OSL and shell ages at Eustis is well beyond what has been measured for members of the Succineidae family (Brennan and Quade, 1997; Pigati et al., 2010). As above, the results from Eustis show the utility of ^{14}C dating gastropod shells in loess deposits as the OSL ages here are apparently too young for reasons that are unknown.

3.1.6. McCook, Nebraska

The McCook loess section consists of a well-developed modern soil formed in Peoria Loess, ∼9.5 m of unaltered Peoria Loess, and the Gilman Canyon Formation (Fig. 9). Three previous humic acid ages from the soil in the Gilman Canyon Formation range from 30.87 ± 0.33 ka (9.5 m) to 37.41 ± 0.77 ka (10 m) (Muhs et al., 2008).

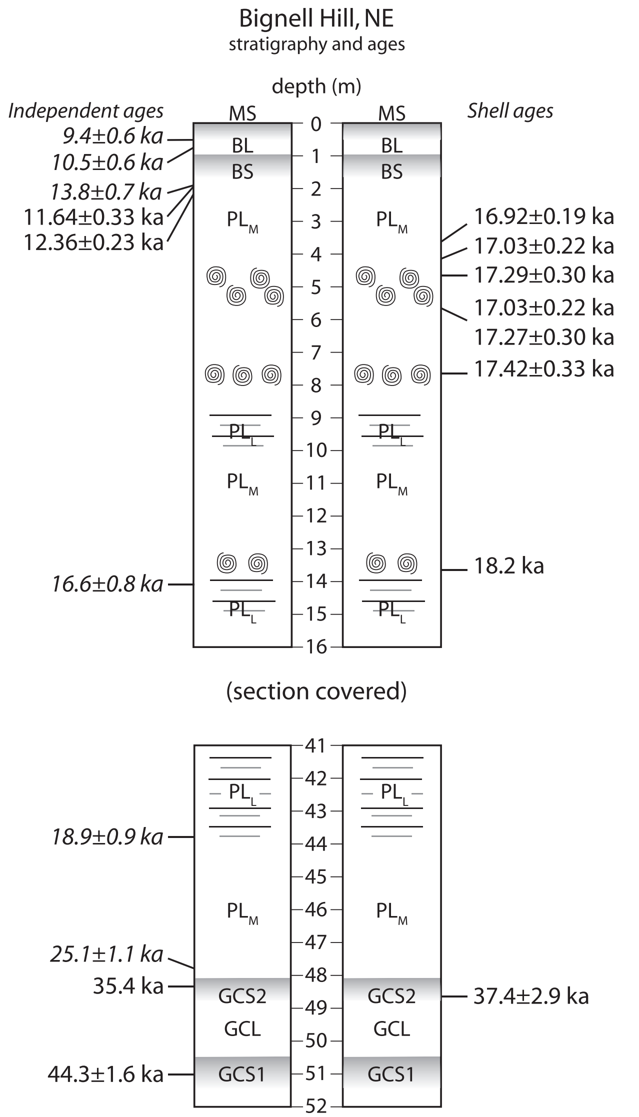

Fig. 6. Independent and gastropod shell ages at Bignell Hill, NE. The independent ages consist of calibrated humic acid ages (standard font) and OSL ages (italics) (Muhs et al., 1999; Mason et al., 2003; Roberts et al., 2003). The shell ages are from Succineidae shells. Stratigraphic units: MS = modern soil, BL = Bignell Loess, BS = Brady Soil, PL = Peoria Loess (subscripts: M = massive, L = laminated), GCS = Gilman Canyon Soil, GCL = Gilman Canyon Loess.

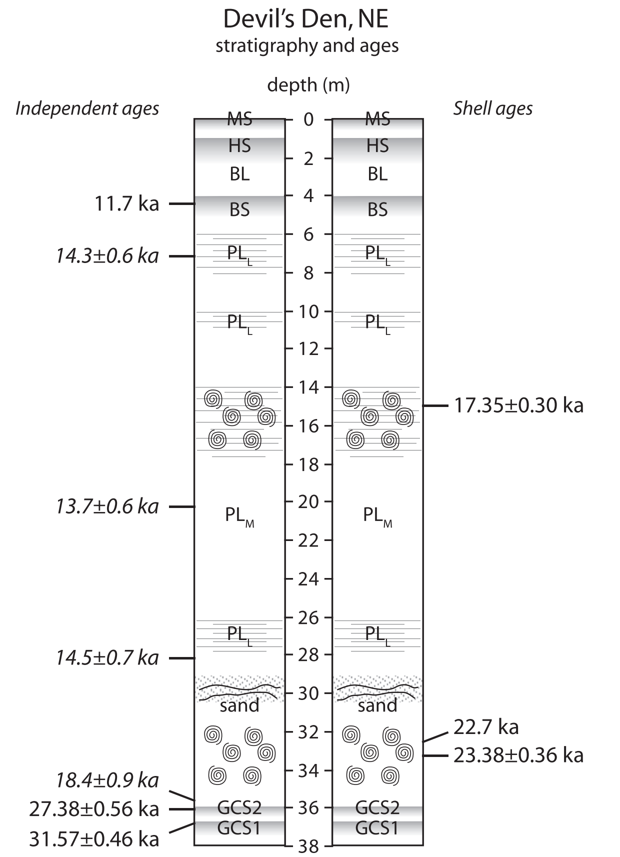

Fig. 7. Independent and gastropod shell ages at Devil's Den, NE. The independent ages consist of calibrated humic acid ages (standard font) and OSL ages (italics) (Roberts et al., 2003; Muhs et al., 2008). The shell ages are from Succineidae shells. Stratigraphic units: MS = modern soil, HS = Holocene soil, BL = Bignell Loess, BS = Brady Soil, PL = Peoria Loess (subscripts: M = massive, L = laminated), GCS = Gilman Canyon Soil.

Succineidae shells recovered from higher in the section yielded ages that range from 21.50 ± 0.27 ka (3.0–3.5 m) to 22.8 ka (5.0–5.5 m) and are in correct stratigraphic order. The shell ages establish new chronologic constraints for Peoria Loess at this location, which was previously undated.

3.1.7. Loveland, Iowa

The upper part of the loess section at Loveland, Iowa consists of a modern soil formed in Peoria Loess, ~41 m of Peoria Loess that can be separated into upper (0–19 m), middle (19–32 m), and lower (32–41 m) subunits based on sedimentological and geochemical properties (Muhs and Bettis, 2000), the Farmdale Soil formed in Pisgah Loess, and a few meters of unaltered Pisgah Loess (Fig. 10).

A new suite of high-resolution OSL ages obtained for Peoria Loess at the Loveland section are in correct stratigraphic order and range from 17.1 ± 1.3 ka (1.0 m) and 29.1 ± 1.7 ka (41 m) (Muhs et al., 2013a). Succineidae shell ages ($n = 7$) for the Peoria Loess are nearly identical to the luminescence ages at each sampled interval and

Table 3
Summary of new mass accumulation rates for Peoria loess.

Location	Chronology type	Loess deposition rate (m ka^{-1})	Mass accumulation rate (g m^{-2} yr^{-1})[a]	Time period (ka)
Beecher Island, CO	Independent	–	–	
	Shells	2.8	4010	15.3–15.8
Bignell Hill, NE (upper exposure)	Independent	4.4	6320	13.8–16.6
	Shells	7.6	11070	16.9–18.2
Bignell Hill, NE (lower exposure)	Independent	0.6	940	18.9-25.1
	Shells	–	–	
Devil's Den, NE	Independent	n/a[b]	n/a[b]	
	Shells	3.0	4400	17.4–23.4
Eustis, NE	Independent	2.0	2880	14.2–20.7
	Shells	2.5	3660	17.0–22.6
Loveland, IA (upper Peoria)	Independent	4.5	6540	17.1–21.2
	Shells	5.5	7990	19.6–21.4
Loveland, IA (middle Peoria)	Independent	–	–	
	Shells	4.3	6170	21.6–24.5
Loveland, IA (lower Peoria)	Independent	6.7	9750	23.3–24.4
	Shells	1.6	2250	24.5–30.0
McCook, NE	Independent	–	–	
	Shells	1.5	2230	21.5–22.8

[a] Mass accumulation rates calculated using bulk density of 1.45 g cm^{-3}.
[b] Independent ages do not maintain stratigraphic order.

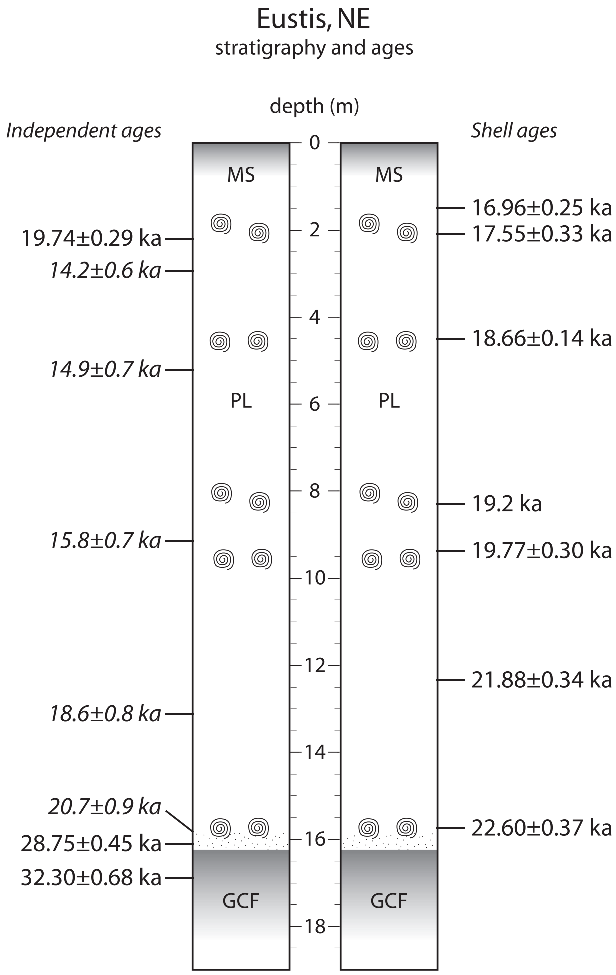

Fig. 8. Independent and gastropod shell ages at Eustis, NE. The independent ages consist of calibrated humic acid ages (standard font) and OSL ages (italics) (Maat and Johnson, 1996; Roberts et al., 2003; Muhs et al., 2008). The shell age of 16.96 ± 0.25 ka is based on a ^{14}C derived from *Vallonia gracilicosta* by Rousseau and Kukla (1994). All other shell ages are from Succineidae shells. Stratigraphic units: MS = modern soil, PL = Peoria Loess, GCF = Gilman Canyon Formation.

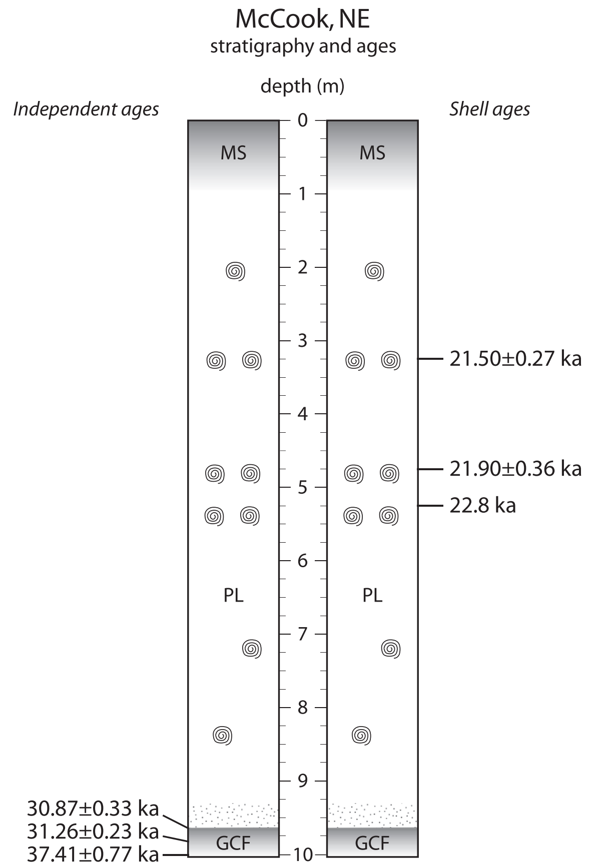

Fig. 9. Independent and gastropod shell ages at McCook, NE. The three independent ages are calibrated humic acid ages. The shell ages are from Succineidae shells. Stratigraphic units: MS = modern soil, PL = Peoria Loess, GCF = Gilman Canyon Formation.

range from 19.64 ± 0.39 ka (9.5 m) to 29.96 ± 0.39 ka (41 m). The shell ages are in correct stratigraphic order throughout the sequence with the exception of a *Succinea* shell collected by Forman et al. (1992) at a depth of ~36 m. This discrepancy may simply be due to differences in depth measurements as changes in surface morphology have certainly occurred in the intervening 20 years between the studies.

Lower in the Loveland section, we obtained two new charcoal ages, 39.2 ± 1.8 and 45.6 ± 3.2 ka, at depths of 42.1 and 45.7 m, respectively, and three new shell ages at depths ranging from 44 to 46 m for the Pisgah Loess. Additional luminescence ages for this portion of the Loveland section range from 27.1 ± 1.8 to 46.1 ± 3.7 ka (Forman et al., 1992; Muhs et al., 2013a). However, gastropod shells from this part of the Loveland section yielded ages that are all ~40 ka, which suggests they are probably beyond the limit of ^{14}C dating as their measured activities are very close to background levels. Thus, direct comparison of our shell ages and the luminescence ages at these depths is not warranted.

In all, the results from southern Alaska and the North American midcontinent show tremendous promise for using ^{14}C dating of small terrestrial gastropod shells to date late Quaternary loess deposits. In the absence of bioturbation, the new shell ages are consistently in stratigraphic order, agree with other ^{14}C-based ages, and allow chronologic constraints to be placed on units or strata that were previously either poorly dated or not dated at all. At Bignell Hill, Devil's Den, and Eustis (all Nebraska sites), the shell ages are several millennia older than OSL ages at similar depths. This suggests that the luminescence ages may underestimate the true ages of the loess deposits as the magnitude of this discrepancy is too large to be explained by limestone problems or other issues related to contamination of the shell material.

3.2. Mass accumulation rates

Loess mass accumulation rates (MARs) are important in modeling past global dust flux (Mahowald et al., 2006). Radiocarbon ages derived from humic acids provide only broad constraints for calculating MARs because the humic material accumulates primarily during times of soil formation rather than loess deposition. Moreover, as discussed above, some of the previous luminescence ages at the Nebraska sites appear to be too young based on the new shell chronologic data. Thus, shell ages can provide critical chronologic information for estimating mass accumulation or loess deposition rates for Peoria Loess in the Great Plains, including stratigraphic horizons that were previously undated. MARs based on the new shell chronologies range from 2230 g m^{-2} yr^{-1} (1.5 m ka^{-1}) at McCook, NE to 11,070 g m^{-2} yr^{-1} (7.6 m ka^{-1}) in the upper exposure at Bignell Hill, NE (Table 3). The new shell-based MAR estimates are higher than some previous OSL-based MAR estimates, cover more of the time represented by Peoria Loess, and do not show a statistically significant relation with either site location or age.

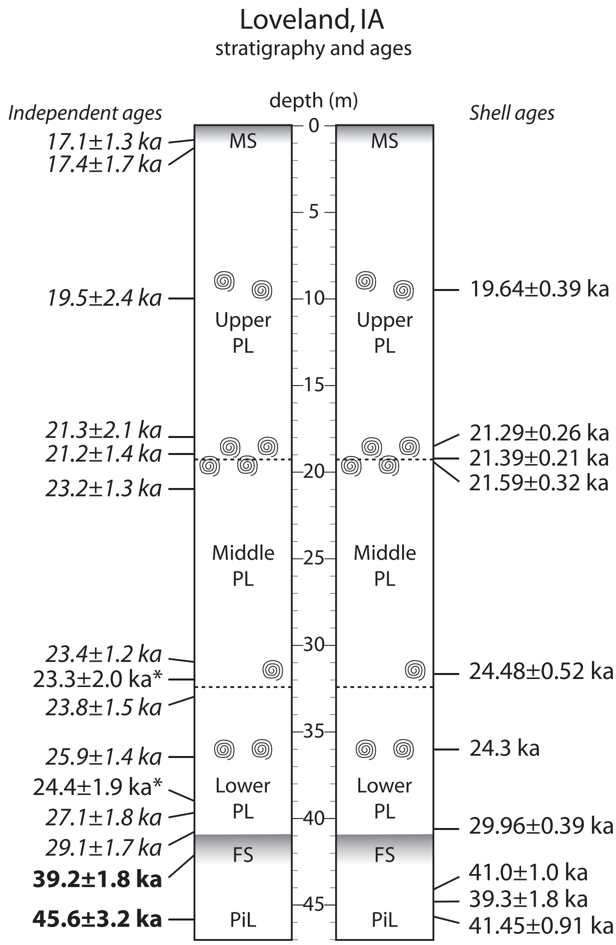

Fig. 10. Independent and gastropod shell ages at Loveland, IA. The independent ages consist of a suite of new OSL ages shown in italics (Muhs et al., 2013a), two IRSL ages marked by asterisks (Forman and Pierson, 2002), and two calibrated charcoal ages in bold font (this study). The shell ages of 24.48 ± 0.52 and 39.3 ± 1.8 ka are based on ^{14}C ages derived from *Succinea* sp. by Forman et al. (1992). All other shell ages are from Succineidae shells. Stratigraphic units: MS = modern soil, PL = Peoria Loess, FS = Farmdale Soil, PiL = Pisgah Loess.

3.3. *Limitations of the technique*

Despite the apparent success in using ^{14}C dating of gastropod shells to date North American loess deposits, the technique is not without its limitations. Bioturbation is clearly a factor that must be considered in all loess settings as gastropod shells can only provide reliable ages if they are found in their original stratigraphic positions. Below we discuss some additional limitations, including potential problems related to gastropod burrowing and issues related to dating gastropod shells near the upper and lower practical limits of the ^{14}C dating technique.

3.3.1. *Burrowing*

Terrestrial gastropods often burrow into the ground, particularly during dry or unusually warm or cold periods. If a gastropod burrowed into the subsurface and then died, its shell would yield an age that is younger than expected for that particular stratigraphic horizon. In wetland deposits in southeastern Arizona, Pigati et al. (2004) measured the ^{14}C content of multiple gastropod taxa at 10-cm intervals hypothesizing that if the snails burrowed more than this depth, the resulting ages would not be in correct stratigraphic order. Their results showed that burrowing was limited at that site and the shell ages can be resolved to at least decimeter scales.

Laminated loess deposits near a bridge spanning the Yukon River in central Alaska (YRB; Fig. 2a) provide an unusual opportunity to address potential problems related to terrestrial gastropods burrowing in loess. The YRB loess deposits exhibit distinct, millimeter-scale bedding planes and contain abundant Succineidae shells (Fig. 11a). We carefully examined the sediment surrounding the shells and did not observe any indication of burrowing. (Such a field test is usually not possible because of the massive nature of most loess deposits). Succineidae shells at the YRB section were large enough that we could obtain an AMS ^{14}C date on individual shells, which yielded ages that range from 12.83 ± 0.15 to 13.28 ± 0.11 ka (Table 2). Although the ages are statistically indistinguishable at the 95% (2σ) confidence level, all but the highest sample show a clear trend of increasing age with depth (Fig. 11b). Thus, we interpret these results to suggest that burrowing, if it occurred at all, was likely minimal and did not affect the stratigraphic integrity of the shell ages at the YRB section.

3.3.2. *Modern/historic shells*

Loess deposits exposed along the Matanuska River near Palmer, Alaska (MRV; Fig. 2a) have been described previously by Muhs et al. (2004). The Matanuska loess deposits contain abundant Succineidae shells, wood, and plant macrofossils, as well as anthropogenic garbage (Fig. 12a). This section provides an opportunity to test whether the shells can be used to date late Holocene and/or historic-aged loess deposits as we can directly compare measured $\Delta^{14}C$ values of the shells to known atmospheric values. If the shells are composed of carbon that is derived solely from the atmosphere (and not limestone) as the results above indicate, then shells recovered from the Matanuska loess section should record the late 20th century ^{14}C "bomb spike" (Manning et al., 1990; Meijer et al., 1995).

By definition, the $\Delta^{14}C$ value of the atmosphere in 1950 was 0‰ (Stuiver and Polach, 1977). Atmospheric $\Delta^{14}C$ values increased

Table 4
Summary of sample information and carbon-14 activity for the Matanuska River Valley samples.

Sample #	Laboratory #	AMS #	Material dated	Depth (cm)	$\delta^{13}C$ (vpdb)[a]	$\Delta^{14}C$ (per mil)
MV1-1	WW-9012	CAMS-156871	Succineidae	125	−7.7	−26.5 ± 2.8
MV1-3	WW-9013	CAMS-156872	Succineidae	130	−8.4	−22.8 ± 2.9
MV1-7	WW-9014	CAMS-156873	Succineidae	165	*−8*	−39.1 ± 3.3
MV1-8	WW-9015	CAMS-156874	Succineidae	173	−8.1	405.9 ± 4.1
MV1-9	WW-9016	CAMS-156875	Succineidae	182	−8.6	375.5 ± 4.2
MV1-10	WW-9017	CAMS-156876	Succineidae	190	−8.9	596.7 ± 5.0
MV1-14	WW-9018	CAMS-156877	Succineidae	198	−7.5	−39.0 ± 2.8
MV1-12	WW-9021	CAMS-156880	Wood	200	−24.8	−21.6 ± 2.8
MV1-15	WW-9019	CAMS-156878	Succineidae	215	−8.0	−35.6 ± 3.4
MV1-17	WW-9020	CAMS-156879	Succineidae	230	−6.8	−28.1 ± 2.8
MV1-18	WW-9022	CAMS-156881	Wood	230	−24.7	−58.7 ± 2.7

Assigned $\delta^{13}C$ value of 8 ± 2‰.
[a] Values in italics denote samples that did not contain enough material for stable isotope analyses.

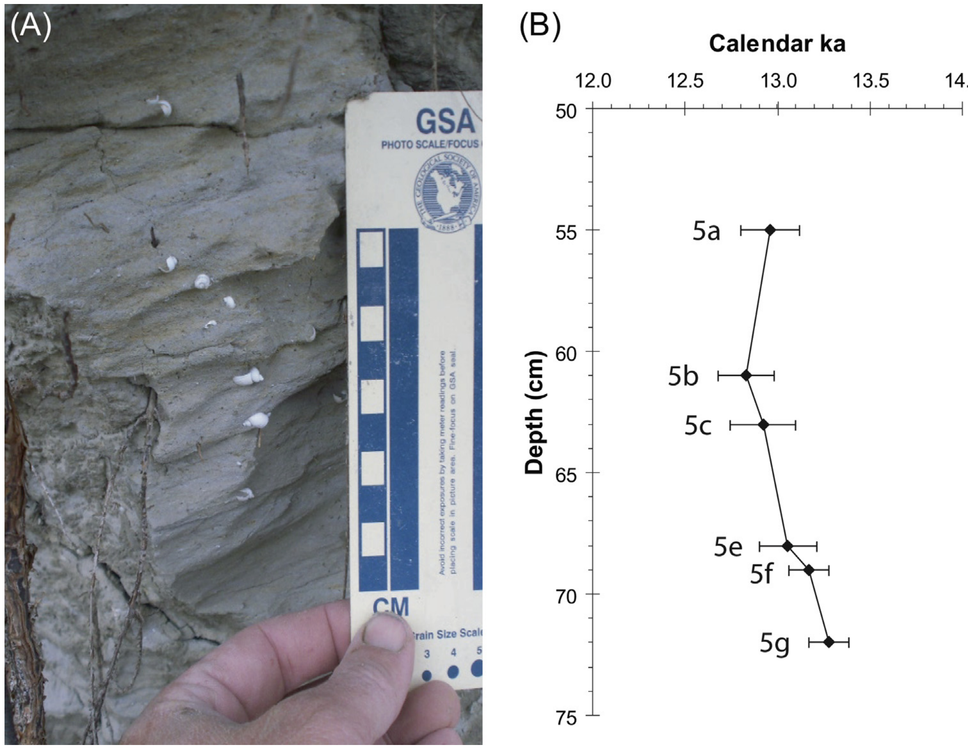

Fig. 11. (A) Photograph of in situ Succineidae shells in laminated loess deposits at the Yukon River Bridge section in central Alaska. (B) Age versus depth profile for six individual shells at this locality.

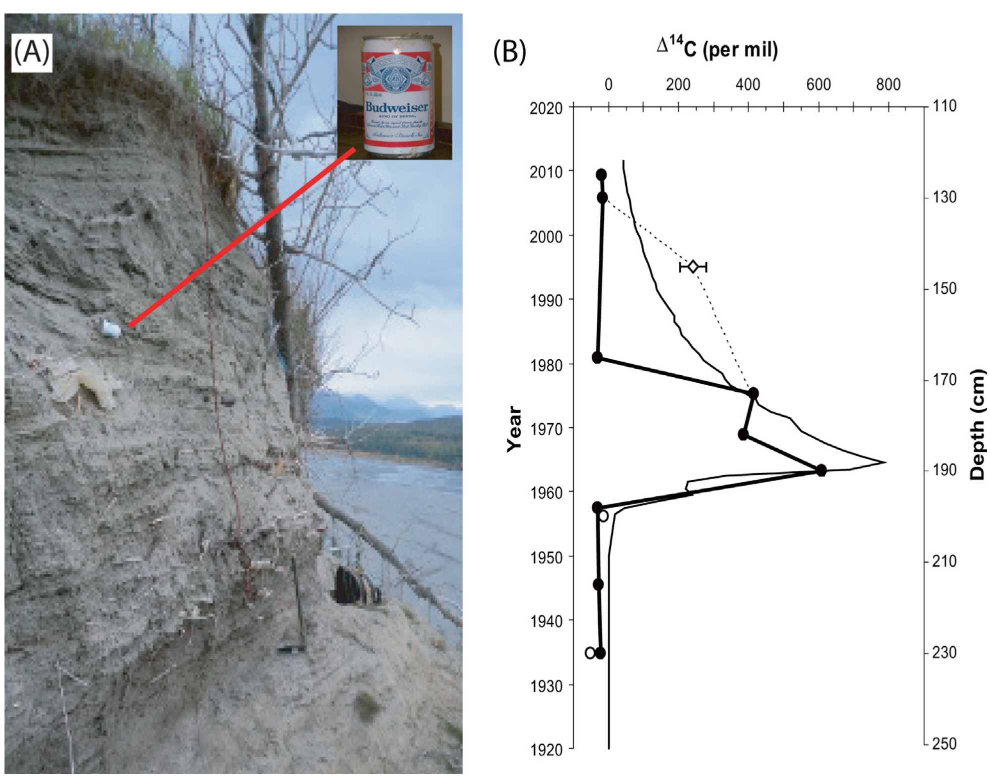

Fig. 12. (A) Photograph of the uppermost 3 m of loess at the Matanuska River Valley section, which included a beer can at a depth of 145 cm that was manufactured between 1980 and 1985 (Anheuser-Busch Companies, Inc., written pers. comm., 2011). (B) Comparison of $\Delta^{14}C$ values of Succineidae shells (filled circles) and wood (open circles) recovered from the MRV loess deposit with $\Delta^{14}C$ values of the "bomb spike" in the atmosphere (thin solid line) caused by above-ground testing of nuclear weapons as measured in the northern hemisphere (after Hua, 2004). Our preferred interpretation of the shell $\Delta^{14}C$ data (solid thick line) is that the shells are all in place and the beer can was deposited some time after its date of manufacture. An alternative interpretation (dashed line) is that the can is in place and the shell recovered from a depth of 165 cm was reworked from depths below the ^{14}C bomb spike interval.

dramatically between 1950 and 1963 because of above-ground testing of nuclear weapons, ultimately reaching ~800‰ at the time the Limited Test Ban Treaty was signed in October 1963 (Hua, 2004). Atmospheric $\Delta^{14}C$ values have declined exponentially since then as bomb ^{14}C has been incorporated into marine and terrestrial ecosystems.

At Matanuska, $\Delta^{14}C$ values for Succineidae shells were slightly lower than modern to depths of ~125 cm, then increased dramatically, reaching nearly 600‰ at depths between ~170 and 190 cm, before returning to values near zero below ~200 cm (Fig. 12c; Table 4). Although the peak values of the shells are slightly lower than peak atmospheric values in the early 1960s, it appears that the shells faithfully record at least most of the ^{14}C bomb spike. We note that a slight discrepancy exists with the stratigraphic position of the measured shells and a beer can in the section that was manufactured between 1980 and 1985 based on identifier markings and the UPC code (Anheuser-Busch Companies, Inc., pers. comm.). The can was found approximately 20 cm higher in the section than what would be predicted by the shell ^{14}C data alone (Fig. 12c), which means that either the can was deposited some time after its date of manufacture (our preferred interpretation) or the gastropod shell collected at a depth of 165 cm was reworked from older sediments (an alternative interpretation). In either case, our data show Succineidae shells can be used for creating a bomb profile in young sediments, and potentially may be used for ^{14}C dating loess of late Holocene and/or historic age if reworking can be excluded from consideration.

3.3.3. *Upper (older) practical limit of shell dating*

The impact of contamination by young carbon species increases with the sample age, and is especially pronounced when approaching the older limit of the ^{14}C dating method. The upper practical limit is set by two factors, analytical limitations and the integrity of the sample material itself. Significant strides have been made recently in designing and constructing ultra-low-blank ^{14}C extraction systems which, when combined with aggressive new pretreatment procedures, can yield reliable ^{14}C ages for charcoal of up to ~50 ka or more (Bird et al., 1999; Pigati et al., 2007; Higham, 2011).

In contrast to charcoal, gastropod shells rarely yield reliable ^{14}C ages beyond ~40 ka because of the influence of secondary carbonate. If calcite is precipitated on the shell surface or exchange between shell carbonate and groundwater bicarbonate occurs during burial, then the measured shell age may be far younger than the true age of the shell. For example, addition of only 1% modern carbon can cause shells that are >50 ka in age to yield apparent ^{14}C ages that fall in the 35–40 ka range. Whereas it is often possible to detect secondary calcite in the aragonitic shells, this becomes exceptionally difficult when calcite concentrations approach zero.

Shell ages from the Pisgah Loess at the Loveland section are indicative of what we might expect when reaching the practical limit of the technique. Three shell ages, 41.0 ± 1.0, 39.3 ± 1.8, and 41.45 ± 0.91 ka, were obtained from depths of 44.1, 44.8, and 45.7 m, respectively (Fig. 10). Although separated by ~1.5 m, the ages are statistically indistinguishable from one another and do not show a clear trend with depth, which indicates that the shells are likely beyond the limit of ^{14}C dating. Similarly, two aliquots of Succineidae shells recovered from the Loveland Loess at a section in Council Bluffs, Iowa yielded apparent ^{14}C ages in excess of 45 ka. However, because the Loveland Loess is pre-Sangamonian in age (i.e., >130 ka), the ^{14}C measured in the shells must be the byproduct of contamination. These results suggest that while we cannot place an absolute number to the upper practical limit, gastropod shell ages approaching or exceeding ~40 ka should be viewed with extreme caution.

4. Conclusions

In North America, loess deposits mantle large portions of the Great Plains, Mississippi River Valley and Snake River Plain, and lowlands in the Pacific Northwest and Alaska. These deposits contain primary information on atmospheric circulation patterns and wind regimes, which are critical to testing general circulation models. For such tests, it is imperative to establish strong chronologic control at multiple sites and timescales. The results of our study demonstrate that small terrestrial gastropod shells yield reliable ^{14}C ages for the late Quaternary and can be used to constrain the ages of loess deposits in North America.

Gastropod shells in loess have been used previously for estimating past environmental conditions, but have been largely ignored for ^{14}C dating. Our study is the first to systematically test whether small terrestrial gastropod shells remain closed systems with respect to carbon over geologic timescales in loess deposits at multiple localities. In a Holocene loess sequence in Alaska, shell ages (Succineidae) are indistinguishable from wood ages throughout the section. Gastropod shells recovered from a series of late Quaternary loess deposits in the North American midcontinent yield ages that either augment or improve upon existing chronologies. The new shell ages require less interpretation than humic acid ages commonly used in loess studies, provide additional stratigraphic coverage to previous dating efforts, are more precise and are in stratigraphic order more often than their luminescence counterparts, and allow for improved estimates of mass accumulation rates. In addition to North American loess studies, our results show that fossil Succineidae shells have tremendous potential for constraining the ages and mass accumulation rates of loess deposits in Europe and China, among others (e.g., Rousseau, 1991; Preece and Bridgland, 1999; Rousseau and Wu, 1999).

Potential problems related to gastropod burrowing appear to be relatively minor, as shell ages derived from a laminated loess unit in central Alaska show increasing age with depth on centimeter scales. Succineidae shells in the Matanuska River Valley of southern Alaska capture the 20th century ^{14}C bomb spike, which indicates that they can be used to date late Holocene and/or historic-aged loess. Finally, on the other end of the ^{14}C dating spectrum, results from loess deposits in Nebraska and western Iowa suggest that shell ages approaching ~40 ka should be viewed with caution as small amounts of contamination may cause the ages of "infinite" shells to appear much younger than their true ages.

Acknowledgments

We thank Zachary Muhs Rowland and Jossh Beann for field support in Alaska. We also thank Wrangell-St. Elias National Park and the Chitina Native Corporation for access. This manuscript benefited from constructive reviews from Buddy Schweig, Marith Reheis, and two anonymous reviewers. This project was funded by the U.S. Geological Survey's Climate and Land Use Change Research and Development Program.

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