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# Radiocarbon dating loess deposits in the Mississippi Valley using terrestrial gastropod shells (Polygyridae, Helicinidae, and Discidae)

Jeffrey S. Pigati [a,*], John P. McGeehin [b], Daniel R. Muhs [a], David A. Grimley [c], Jeffrey C. Nekola [d]

[a] U.S. Geological Survey, Denver Federal Center, Box 25046, MS-980, Denver, CO 80225, USA
[b] U.S. Geological Survey, 12201 Sunrise Valley Drive, MS-926A, Reston, VA 20192, USA
[c] Illinois State Geological Survey, University of Illinois, 615 E Peabody Drive, Champaign, IL 61820, USA
[d] Department of Biology, University of New Mexico, Albuquerque, NM 87131, USA

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Small terrestrial gastropod shells (mainly Succineidae) have been used successfully to date late Quaternary loess deposits in Alaska and the Great Plains. However, Succineidae shells are less common in loess deposits in the Mississippi Valley compared to those of the Polygyridae, Helicinidae, and Discidae families. In this study, we conducted several tests to determine whether shells of these gastropods could provide reliable ages for loess deposits in the Mississippi Valley. Our results show that most of the taxa that we investigated incorporate small amounts (1–5%) of old carbon from limestone in their shells, meaning that they should yield ages that are accurate to within a few hundred years. In contrast, shells of the genus *Mesodon* (*Mesodon elevatus* and *Mesodon zaletus*) contain significant and variable amounts of old carbon, yielding ages that are up to a couple thousand $^{14}C$ years too old. Although terrestrial gastropod shells have tremendous potential for $^{14}C$ dating loess deposits throughout North America, we acknowledge that accuracy to within a few hundred years may not be sufficient for those interested in developing high-resolution loess chronologies. Even with this limitation, however, $^{14}C$ dating of terrestrial gastropod shells present in Mississippi Valley loess deposits may prove useful for researchers interested in processes that took place over multi-millennial timescales or in differentiating stratigraphic units that have significantly different ages but similar physical and geochemical properties. The results presented here may also be useful to researchers studying loess deposits outside North America that contain similar gastropod taxa.

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## 1. Introduction

Late Quaternary loess deposits blanket much of the upland areas immediately adjacent to the Mississippi Valley in Wisconsin, Iowa, Illinois, Missouri, Kentucky, Tennessee, Arkansas, Mississippi, and Louisiana (Fig. 1). The stratigraphy, age, and origin of these deposits have been the focus of studies for more than a century (Hilgard, 1879; Call, 1891; Mabry, 1898). One of the more challenging aspects of studying loess in the region has been to establish robust chronologies for the deposits. Charcoal and plant macrofossils are ideal for radiocarbon ($^{14}C$) dating, but are found in loess only occasionally, and rarely at multiple stratigraphic levels at a given site. Thus, researchers often must turn to less desirable materials for dating. Humic acids in soils developed in loess have been dated by $^{14}C$ at many localities in North America (e.g., Berg et al., 1985; Muhs et al., 1999; Mandel and Bettis, 2001; Muhs and Zárate, 2001; Bettis et al., 2003), but are limited to organic-rich strata and date the buildup of organic matter over time, rather than the act of loess deposition itself. Moreover, $^{14}C$ dates on bulk organic matter in loess represent some (unknown) duration of time that elapsed between loess deposition and when the organic material became concentrated enough to be targeted for dating. In most cases, the exact geochemical nature and origin of the carbon dated in bulk sediment samples are unknown, which further clouds interpretation of the resulting ages. Other chronometric techniques, including luminescence and amino-acid racemization (AAR), have been used previously to date loess deposits in the Mississippi Valley (Pye and Johnson, 1988; Clark et al., 1989; Forman et al., 1992; Rodbell et al., 1997; Markewich et al., 1998; Forman and Pierson, 2002). However, these techniques yield ages that are not as precise as $^{14}C$ ages, are relatively expensive and time consuming, and require assumptions regarding physical conditions (moisture content for luminescence) or climate parameters (variability in past temperatures for AAR) that cannot be known *a priori*.

* Corresponding author. Tel.: +1 303 236 7870; fax: +1 303 236 5349.
*E-mail address:* jpigati@usgs.gov (J.S. Pigati).

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Radiocarbon dating of terrestrial gastropod shells may provide a viable alternative to these techniques for researchers interested in constraining the age and mass accumulation rates of loess deposits in the Mississippi Valley. Recent work has shown that the shells of some gastropod families yield reliable $^{14}C$ ages for the late Pleistocene, regardless of the depositional context, local lithology, or climatic regime (Pigati et al., 2010). Many of the taxa that have been evaluated thus far are annuals or live only a few years, spending most of their time scavenging for food at or near the ground surface (Barker, 2001). The stratigraphic position of gastropod shells, therefore, should be temporally equivalent to the sediment deposited when the gastropods were alive, provided they did not burrow deeply below ground and die. Thus, if the shells yield reliable $^{14}C$ ages and assuming they are not reworked, they can be used to determine the timing of loess deposition fairly accurately.

Members of the Succineidae family (genera: *Catinella*, *Oxyloma*, and *Succinea*) have proven especially reliable for $^{14}C$ dating, yielding ages that are identical to wood, plant macrofossil, and luminescence ages in Holocene and late Pleistocene loess, wetland, and glacial deposits throughout North America (Pigati et al., 2010, 2013). However, although Succineidae shells are common in the Quaternary loess deposits of Alaska and the Great Plains, they are not as prevalent in loess that is proximal to the lower Mississippi Valley. In this area, terrestrial gastropods within the Polygyridae, Helicinidae, and Discidae families are fairly common in loess deposits and potentially could be targeted for dating purposes. It is likely that these taxa have been dated previously at loess sites in the Mississippi Valley (e.g., Snowden and Priddy, 1968; Pye and Johnson, 1988; McCraw and Autin, 1989; Markewich, 1993; Oches et al., 1996; Grimley et al., 1998), but most of these studies do not include specific taxonomic information and potential errors associated with the "limestone problem" are usually ignored.

The limestone problem (or limestone effect) refers to the fact that terrestrial gastropods often consume limestone or other carbonate rocks and incorporate the old ($^{14}C$-dead) carbon when building their shells (Goodfriend and Stipp, 1983). The amount of dead carbon in a particular shell can be highly variable, ranging from negligible to ~30% of the total, which would cause the ages to be up to ~3000 $^{14}C$ years too old (Goodfriend and Stipp, 1983; Pigati et al., 2004, 2010; Rakovan et al., 2010). Thus, $^{14}C$ ages derived from unidentified or mixed assemblages of gastropod shells, as has been the case in most Mississippi Valley loess studies, should be viewed with caution because of potential contamination issues stemming from the presence of carbonate sediments in the

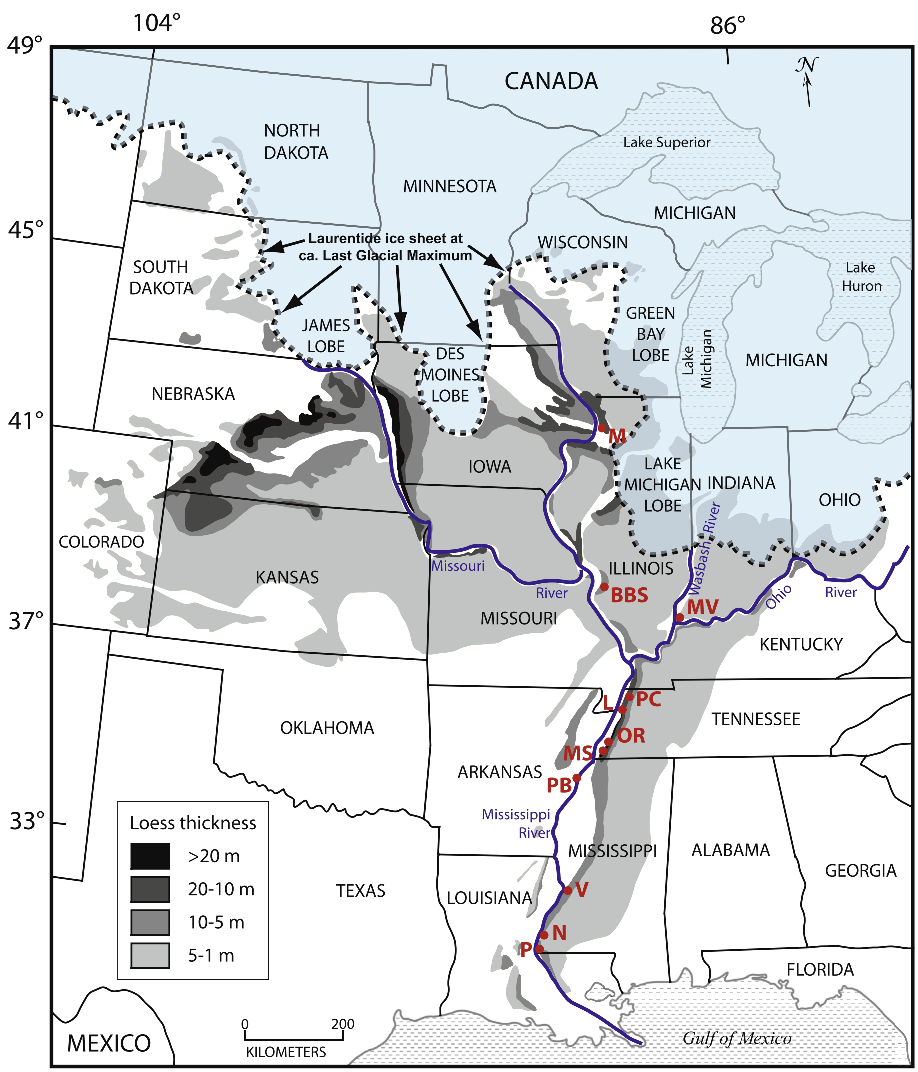


**Fig. 1.** Distribution and thickness of loess in the midcontinent of North America showing the maximum extent of the Laurentide ice sheet during the Last Glacial Maximum and our study sites in the Mississippi Valley (after Bettis et al., 2003, and references therein). Site abbreviations: M = Morrison, IL; BBS = Burdick Branch Section, IL; MV = Mount Vernon, IN; PC = Paw Paw Creek, TN; L = Lenox, TN; OR = Old River Section, TN; MS = Meeman-Shelby Forest State Park, TN; PB = Phillips Bayou, AR; V = Vicksburg, MS; N = Natchez, MS; and P = Pond, MS.

region. If loess chronologies based on gastropod shell ages are to be considered reliable, then the shells must be identified prior to analysis and the magnitude of the limestone problem should be quantified for the taxon of interest whenever possible.

Ideally, two criteria should be evaluated to determine if a particular type of gastropod is suitable for $^{14}C$ dating. First, modern specimens living in environments similar to those represented in the geologic record should be evaluated to determine the magnitude of the limestone problem. If a gastropod does not ingest limestone, then the $^{14}C$ activity of its shell carbonate will be identical to the atmosphere during the time in which it was alive (after correcting for isotopic fractionation). Second, fossil shell ages should be compared to independent ages, preferably $^{14}C$ ages of charcoal or plant macrofossils, to determine if the shells remained closed systems during burial. Shells that exhibit open-system behavior typically yield apparent ages that are too young and may contain measurable quantities of calcite that represent post-mortem alteration or secondary deposition (Rech et al., 2011). Few studies have addressed both issues simultaneously, however, because of the constraints imposed by the cost and time required for such analyses, as well as the difficulty of obtaining suitable material for establishing robust independent ages at multiple sites.

Here we report the results of a multi-faceted study that is somewhat less rigorous than this ideal, two-step approach, but one that still provides critical information for those interested in using gastropod shells to date loess deposits in the Mississippi Valley and elsewhere. First, we measured the $^{14}C$ activity of live-collected specimens of *Hendersonia occulta*, a common gastropod in loess deposits within the valley, to determine the potential magnitude of the limestone problem for specimens living in the region. Modern specimens of a few other taxa common to Mississippi Valley loess deposits, including *Discus macklintockii*, have been evaluated previously (Pigati et al., 2010). Second, we compared ages from fossil shells of the genera *Anguispira*, *Hendersonia*, *Inflectarius*, and *Triodopsis* with $^{14}C$ ages derived from Succineidae shells recovered from loess deposits at sites in Illinois and Indiana to determine if the shells remained closed systems with respect to carbon during burial. Finally, we compared shell ages derived from the genera *Anguispira*, *Haplotrema*, *Hendersonia*, *Inflectarius*, *Mesodon*, *Neohelix*, and *Zolotrema* recovered from Mississippi Valley loess against ages of known stratigraphic boundaries, including the basal contact of Peoria Loess, as well as to each other, to evaluate the accuracy, stratigraphic integrity, and internal consistency of the shell ages.

The primary goals of this study were to determine whether $^{14}C$ ages derived from terrestrial gastropod shells that are common to the Mississippi Valley could be used to establish reliable chronologies for loess deposits in the region and, if so, to determine the practical limits of the technique. Understanding the practical limits is especially important because even if some gastropods incorporate small amounts of old carbon from limestone in their shells and are not able to provide ages that are accurate enough for high-resolution chronologies, they may still be useful for researchers studying events that occurred over longer timescales.

## 2. Materials and methods

Live gastropods were handpicked from forest litter near a loess outcrop at the Meeman-Shelby Forest State Park in western Tennessee (Table 1). Soft parts were removed with forceps and the shells were treated with 3% $H_2O_2$ for 18–24 h at room temperature to remove all remnants of organic matter prior to $^{14}C$ analysis by accelerator mass spectrometry (AMS) as described below.

Fossil gastropod shells were collected either individually or in small sediment blocks from late Pleistocene loess deposits at a total of 11 sites in Illinois, Indiana, Arkansas, Tennessee, and Mississippi (Table 1; Fig. 2). Many of these sites, most notably the Vicksburg and Natchez sites (Fig. 2g and h, respectively), have been the subject of sedimentologic, ecologic, and faunal studies for decades (Wascher et al., 1947; Leighton and Willman, 1950; Leonard and Frye, 1960; Hubricht, 1963; Krinitzsky and Turnbull, 1967; Snowden and Priddy, 1968; Ruhe, 1984a,b; Pye and Johnson, 1988; Clark et al., 1989; McCraw and Autin, 1989; Markewich, 1993, 1994; Mirecki and Miller, 1994; Oches et al., 1996; Rodbell et al., 1997; Markewich et al., 1998; Muhs et al., 2001; Oches and McCoy, 2001; Bettis et al., 2003).

**Table 1**
Site location information.

| Site name | Latitude (°N) | Longitude (°W) | Elevation (m) |
|---|---|---|---|
| Morrison, IL | 41.817 | 89.966 | 210 |
| Burdick Branch Section, IL[1] | 38.730 | 89.990 | 160 |
| Mt. Vernon, IN | 37.910 | 87.960 | 126 |
| Paw Paw Creek, TN | 36.304 | 89.357 | 79 |
| Lenox, TN | 36.072 | 89.496 | 143 |
| Old River Section, TN | 35.418 | 89.974 | 127 |
| Meeman-Shelby Forest State Park, TN | 35.262 | 90.063 | 68 |
| Philips Bayou, AR | 34.636 | 90.636 | 101 |
| Vicksburg, MS | 32.351 | 90.808 | 120 |
| Natchez, MS | 31.529 | 91.424 | 28 |
| Pond, MS | 31.081 | 91.522 | 125 |

[1] Also referred to as Site 51 in Leonard and Frye (1960) and Site 3 in the collection notes of A. Byron Leonard. Location given as NW 1/4, SW 1/4, Sec. 4, T3N, R8W, Madison County, IL.

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 immersed 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 treated with $H_2O_2$ as above and then 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 X-ray diffraction (XRD) analysis to verify that only primary shell aragonite remained prior to preparation for $^{14}C$ analysis. None of the fossil shells that we analyzed contained measurable quantities of calcite.

Clean modern and fossil shells were converted to $CO_2$ using ACS 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 the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Laboratory for $^{14}C$ 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. The resulting $^{14}C$ ages were calibrated using the IntCal13 dataset and CALIB 7.0 (Stuiver and Reimer, 1993; Reimer et al., 2013). Ages are presented in calibrated $^{14}C$ years BP (ka = thousands of years; BP = Before Present; 0 yr BP = 1950 A.D.) and uncertainties are given at the 95% ($2\sigma$) confidence level.

The magnitude of the limestone problem for various gastropod taxa was calculated in two ways. For live gastropods, we compared the measured $\Delta^{14}C$ values of the shells and modeled values for the $\Delta^{14}C$ of the gastropod diet following the methods described in detail in Pigati et al. (2010). If gastropods ate only live plants, then the $\Delta^{14}C$ of the gastropod diet could be determined using the

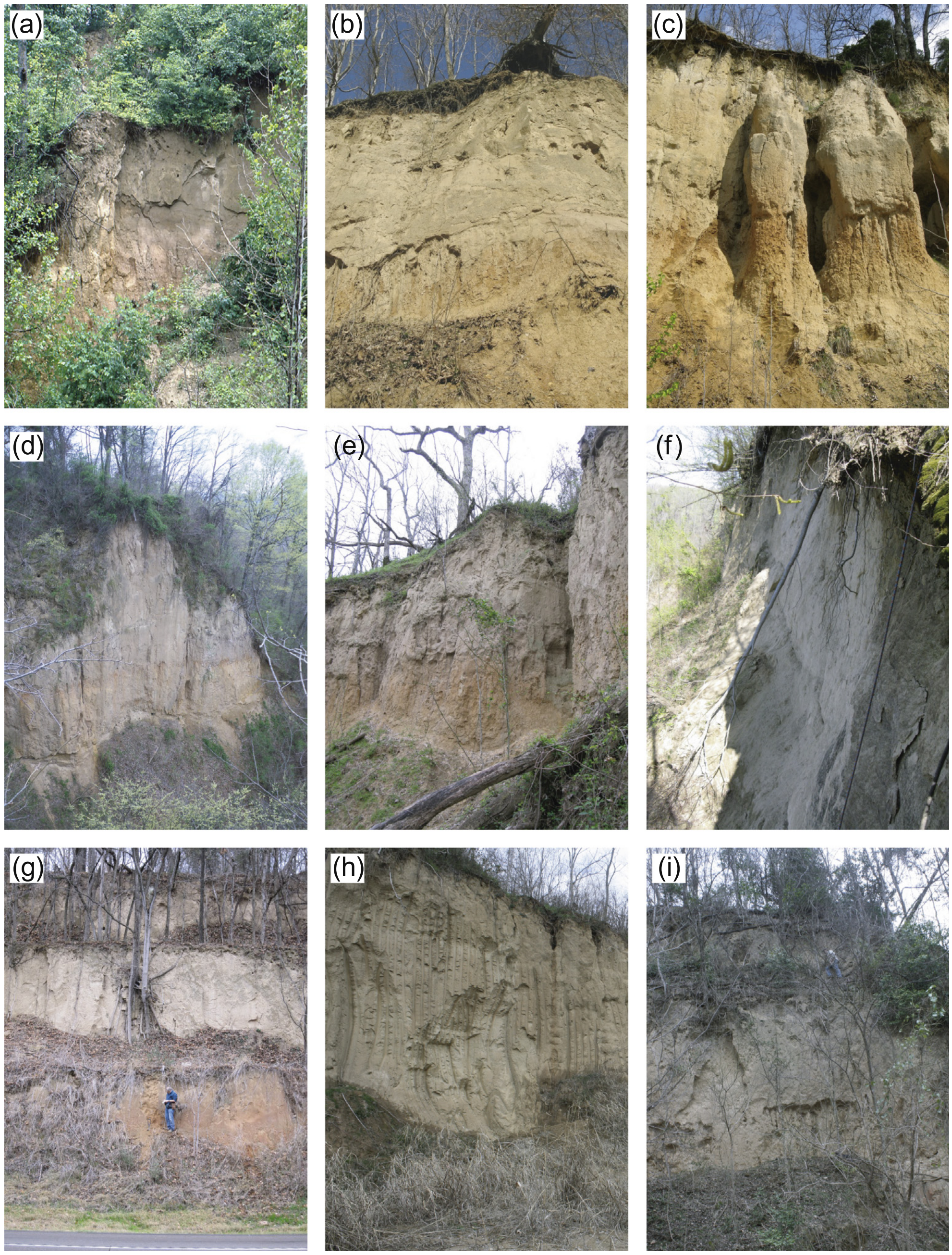


**Fig. 2.** Photographs of all study sections except the Morrison, IL and Burdick Branch Section, IL sites (from north to south; site abbreviations correspond to those presented in Fig. 1): (a) Mount Vernon, IN (MV); (b) Paw Paw Creek, TN (PC); (c) Lenox, TN (L); (d) Old River Section, TN (OR); (e) Meeman-Shelby Forest State Park, TN (MS); (f) Phillips Bayou, AR (PB); (g) Vicksburg, MS (V); (h) Natchez, MS (N); and (i) Pond, MS (P).

atmospheric $\Delta^{14}$C value for the year that the gastropod was collected alive and correcting for isotopic fractionation. However, gastropods consume both live and decaying organic matter, which complicates efforts to quantify their dietary isotopic value. The $\Delta^{14}$C values of decaying organic matter could be higher than modern values because of the $^{14}$C bomb spike effect (Hua and Barbetti, 2004), or lower than modern because of isotopic decay (Godwin, 1962). The impacts of these sources on the overall gastropod diet were determined using Monte Carlo simulation to encompass a reasonable range of carbon turnover rates in A-horizons of forest soils and ages of the organic matter consumed (Brovkin et al., 2008; Frank et al., 2012; McFarlane et al., 2013). Uncertainties associated with the modeled dietary values are relatively large, on the order of ~25‰, because of the large range of detritus $\Delta^{14}$C values that could be present at a given site. Thus, we cannot discern limestone effects that are less than ~250 years.

For fossil gastropod shells, limestone effects were determined using the difference between the apparent $^{14}$C ages of the shells and independent $^{14}$C ages from Succineidae shells, as well as independent ages of stratigraphic markers.

## 3. Results and discussion

Live terrestrial gastropods were collected from the forest floor at Meeman-Shelby Forest State Park in spring 2011 to determine if carbon in their aragonitic shells was in equilibrium with atmo-

**Table 2**
Limestone effect data for *Hendersonia occulta* collected live at Meeman-Shelby Forest State Park, TN.

| Sample # | Laboratory # | AMS # | $\delta^{13}C$ (vpdb) | Shell $\Delta^{14}C$ (‰) | Atmos $\Delta^{14}C$ (‰) | Diet $\Delta^{14}C$ (‰) | Limestone effect ($^{14}C$ years)[1] |
|---|---|---|---|---|---|---|---|
| MS-live-1 | WW-8787 | CAMS-155088 | −10.6 | −23.0 ± 2.8 | 44 ± 5 | 73 ± 20 | 810 ± 180 |
| MS-live-2 | WW-8788 | CAMS-155089 | −10.8 | 3.9 ± 3.3 | 44 ± 5 | 73 ± 20 | 580 ± 170 |

Uncertainties are given at the $2\sigma$ (95%) confidence level.
[1] Defined as the theoretical difference between the measured and theoretical $^{14}C$ activities for gastropods that incorporate the same amount of dead carbon in their shells as the aliquots measured here. These values are based on the difference between the dietary and shell carbonate $\Delta^{14}C$ values and converted into $^{14}C$ years (see Pigati et al., 2010 for details).

spheric $\Delta^{14}C$ concentrations at the time of collection. The measured $\Delta^{14}C$ values of two specimens of *H. occulta*, −23.0 ± 2.8 and 3.9 ± 3.3‰, are substantially lower than atmospheric values at that time (44 ± 5‰; Table 2).

For fossil gastropods, specimens that were collected and identified by A. Byron Leonard in the 1950s from Peoria Loess at the Burdick Branch Section in Madison County, IL included *Anguispira alternata*, *Catinella* '*gelida*', *H. occulta*, *Succinea* '*pleistocenica*', and *Triodopsis multilineata* (Leonard and Frye, 1960). [Note that *T. multilineata* = *Webbhelix multilineata* of Emberton (1988).] We obtained calibrated ages for these shells that range from 24.38 ± 0.26 to 20.17 ± 0.19 ka ($n = 6$; Table 3). Although sample depths were not recorded during collection, notes associated with the original collection indicate the shells were obtained from Peoria Loess.

Succineidae and other taxa recovered from Peoria Loess at several sites elsewhere in the Mississippi Valley yielded calibrated ages ranging from 30.33 ± 0.50 ka at Pond, MS to 18.76 ± 0.11 ka at Morrison, IL ($n = 35$; Table 3; Fig. 3), similar to ages for Peoria Loess determined elsewhere in North America (see Bettis et al., 2003 and references therein). Ages derived from shells of *H. occulta* and *M. elevatus* range from 41.2 ± 1.0 to 29.54 ± 0.48 ka for Roxana Silt at Lenox, TN ($n = 6$; Table 3; Fig. 3), which also fall within previously established boundaries for this pre-Peoria unit (Willman and Frye, 1970; McKay, 1979b; Follmer, 1983; Follmer et al., 1986; Grimley et al., 1998).

### 3.1. Test 1: Modern gastropods

The measured $\Delta^{14}C$ values of two specimens of *H. occulta* collected from the forest floor at Meeman-Shelby Forest State Park were substantially lower than atmospheric values at the time of collection, corresponding to a limestone effect of ~600–800 $^{14}C$ years. A previous study found a similar amount of old carbon in *H. occulta* shells collected live at sites in the Upper Midwest (Iowa, Minnesota, and Wisconsin), with calculated limestone effects ranging from negligible to ~1000 $^{14}C$ years and averaging ~450 years ($n = 13$; Pigati et al., 2010).

### 3.2. Test 2: Comparison against previously established ages for Peoria Loess

Calibrated ages for shells of five different taxa, including *A. alternata*, *C.* '*gelida*,' *H. occulta*, *S.* '*pleistocenica*', and *T. multilineata*, recovered from Peoria Loess at the Burdick Branch Section in Madison County, IL loess site, and Succineidae shells from Morrison, IL range from 24.38 ± 0.26 to 18.76 ± 0.11 ka (Table 3). Comparison with ages of Peoria Loess obtained elsewhere in Illinois, which range from ~29 to 13 ka (McKay, 1979a,b; Grimley et al., 1998; Wang et al., 2000; Muhs et al., 2001), shows that the shell ages fall within the accepted range.

### 3.3. Test 3: Internal consistency

Succineidae shell ages can be used as independent age control to compare with other shell ages based on their success in dating loess deposits throughout Alaska and the Great Plains (Pigati et al., 2013). At the Mount Vernon, IN loess section, for example, Succineidae shells recovered from Peoria Loess at a depth of 12.8 m yielded an age of 29.00 ± 0.45 ka (Table 3). Fossil shells of *H. occulta* and *Inflectarius inflectus* from the same stratigraphic level yielded ages of 28.49 ± 0.28 and 28.99 ± 0.33 ka, respectively. Both of these ages are statistically indistinguishable from the Succineidae ages.

Succineidae shells and other material (charcoal, plant macrofossils) that could be used for independent age control were not present at the other loess sites investigated here, so we can only use internal consistency as a check on the remaining shell ages. Most of the shells yielded ages that fall within the accepted range for Peoria Loess obtained elsewhere in North America and maintained stratigraphic order, with the notable exception of *Mesodon* (both *M. elevatus* and *M. zaletus*). Specimens of *Mesodon* were much larger than the other taxa studied here, averaging 2–3 cm in diameter and 1–2 cm in height. They also appear to contain more old carbon than any of the other taxa, as they often yielded ages that were older than other shells recovered from the same stratigraphic level. In the most extreme case, *M. zaletus* shells yielded ages that were a couple thousand years older than *H. occulta* at the same depth at the Pond, MS loess section. These results are similar to that of Rakovan et al. (2010), and show that *Mesodon* shells should be avoided for $^{14}C$ dating whenever possible as they often contain a significant, but variable, amount of old carbon in their shells. The remaining taxa investigated here appear to yield ages that are reasonable (i.e., accurate to within a few hundred years), although we note that determination of precise values for limestone effects was not usually possible because of the lack of robust independent age control.

### 3.4. Test 4: Basal contact of Peoria Loess

The contact between Peoria Loess and Roxana Silt in the Mississippi Valley generally dates to ~29 ka (Leigh and Knox, 1993; Markewich, 1993; Oches et al., 1996; Bettis et al., 2003). Succineidae shell ages from the Mount Vernon, IN section constrain the age of the basal contact to this time as well, with one Succineidae age of 29.00 ± 0.45 ka obtained from just above the contact and another of 30.69 ± 0.38 ka from just below (Table 3). We also obtained a number of ages from other gastropod taxa at sites in the Mississippi Valley that generally support these data, including shell ages from the lowermost part of Peoria Loess at Vicksburg, MS (*Neohelix albolabris*; 28.07 ± 0.29 ka), the Old River Section, TN (*H. occulta*; 28.19 ± 0.34 ka), Meeman-Shelby Forest State Park, TN (*H. occulta*; 29.95 ± 0.50 ka), and Paw Paw Creek, TN (*I. inflectus*; 30.12 ± 0.51 ka). *H. occulta* shells recovered from the uppermost

**Table 3**
Summary of AMS sample information, carbon-14 ages, and calibrated ages for all fossil gastropod shells.

| Sample # | Laboratory # | AMS # | Material dated[1] | Gastropod family | Unit[2] | Depth (m)[3] | $\delta^{13}$C (vpdb)[4] | $^{14}$C age ($^{14}$C ka BP) | Calendar age (ka BP)[5] |
|---|---|---|---|---|---|---|---|---|---|
| Morrison, IL | | | | | | | | | |
| Morr 3.35 m | WW-6524 | CAMS-100000 | Succineidae | Succineidae | PL | 3.4 | −5.9 | 15.51 ± 0.04 | 18.76 ± 0.11 |
| IL-545 | WW-2155 | CAMS-100000 | humic acids | – | FS | 17.9 | *−25* | 31.86 ± 0.24 | 35.73 ± 0.54 |
| Burdick Branch Section, IL | | | | | | | | | |
| BBS3–3 | WW-9188 | CAMS-159697 | *Anguispira alternata* | Discidae | PL | Unknown | −7.2 | 18.09 ± 0.06 | 21.94 ± 0.24 |
| BBS3–2 | WW-9187 | CAMS-159696 | *Catinella 'gelida'* | Succineidae | PL | Unknown | −6.4 | 18.00 ± 0.06 | 21.79 ± 0.22 |
| BBS3–4 | WW-9189 | CAMS-159699 | *Hendersonia occulta* | Helicinidae | PL | Unknown | −5.9 | 17.07 ± 0.05 | 20.60 ± 0.18 |
| BBS3–6 | WW-9191 | CAMS-159701 | *Succinea 'pleistocenica'* | Succineidae | PL | Unknown | −7.4 | 17.38 ± 0.05 | 20.98 ± 0.22 |
| BBS3–1 | WW-9186 | CAMS-159695 | *Triodopsis multilineata* | Polygyridae | PL | Unknown | −8.6 | 16.72 ± 0.05 | 20.17 ± 0.19 |
| BBS3–5 | WW-9190 | CAMS-159700 | *Triodopsis multilineata* | Polygyridae | PL | Unknown | −7.9 | 20.32 ± 0.07 | 24.38 ± 0.26 |
| Mt. Vernon, IN | | | | | | | | | |
| MV-180 | WW-7116 | CAMS-141684 | Succineidae | Succineidae | PL | 3.3 | −5.6 | 19.80 ± 0.10 | 23.79 ± 0.28 |
| MV-185 | WW-7117 | CAMS-141685 | Succineidae | Succineidae | PL | 5.8 | *−5* | 19.34 ± 0.09 | 23.28 ± 0.29 |
| MV-1995b | WW-8515 | CAMS-151960 | *Hendersonia occulta* | Helicinidae | PL | 12.8 | −6.3 | 24.46 ± 0.11 | 28.49 ± 0.28 |
| MV-1995a | WW-8514 | CAMS-151959 | *Inflectarius inflectus* | Polygyridae | PL | 12.8 | −8.8 | 24.93 ± 0.12 | 28.99 ± 0.33 |
| MV-199S | WW-7318 | CAMS-144494 | Succineidae | Succineidae | PL | 12.8 | *−8* | 24.92 ± 0.20 | 29.00 ± 0.45 |
| MV-201/202 | WW-7319 | CAMS-144495 | Succineidae | Succineidae | UF | 13.5 | −10.6 | 26.48 ± 0.21 | 30.69 ± 0.38 |
| Paw Paw Creek, TN | | | | | | | | | |
| PC-2 | WW-8792 | CAMS-155093 | *Inflectarius inflectus* | Polygyridae | PL | 3.8 | −9.8 | 24.32 ± 0.13 | 28.35 ± 0.34 |
| PC-1 | WW-8791 | CAMS-155092 | *Inflectarius inflectus* | Polygyridae | PL | 5.1 | −9.8 | 25.89 ± 0.16 | 30.12 ± 0.51 |
| Lenox, TN | | | | | | | | | |
| L-1 | WW-8701 | CAMS-154074 | *Mesodon elevatus* | Polygyridae | RS | 1.5 | −9.6 | 25.99 ± 0.16 | 30.22 ± 0.50 |
| L-2 | WW-8702 | CAMS-154075 | *Hendersonia occulta* | Helicinidae | RS | 1.8 | −9.0 | 25.43 ± 0.15 | 29.54 ± 0.48 |
| L-3 | WW-8703 | CAMS-154076 | *Hendersonia occulta* | Helicinidae | RS | 2.0 | −8.5 | 26.89 ± 0.18 | 30.99 ± 0.24 |
| L-4 | WW-8704 | CAMS-154077 | *Mesodon elevatus* | Polygyridae | RS | 4.1 | −10.0 | 35.85 ± 0.51 | 40.4 ± 1.1 |
| L-5 | WW-8705 | CAMS-154078 | *Mesodon elevatus* | Polygyridae | RS | 5.2 | −10.5 | 36.81 ± 0.58 | 41.2 ± 1.0 |
| L-6 | WW-8706 | CAMS-154079 | *Mesodon elevatus* | Polygyridae | RS | 5.3 | −9.5 | 35.92 ± 0.52 | 40.5 ± 1.1 |
| Old River Section, TN | | | | | | | | | |
| OR-3 | WW-8709 | CAMS-154081 | *Hendersonia occulta* | Helicinidae | PL | 8.8 | −9.4 | 22.12 ± 0.10 | 26.34 ± 0.28 |
| OR-4 | WW-8710 | CAMS-154082 | *Hendersonia occulta* | Helicinidae | PL | 9.6 | −7.6 | 22.53 ± 0.10 | 26.85 ± 0.34 |
| OR-5 | WW-8711 | CAMS-154083 | *Hendersonia occulta* | Helicinidae | PL | 10.8 | −8.9 | 24.15 ± 0.13 | 28.19 ± 0.34 |
| OR-6 | WW-8712 | CAMS-154084 | *Hendersonia occulta* | Helicinidae | PL | 11.1 | −9.4 | 23.57 ± 0.12 | 27.69 ± 0.20 |
| Meeman-Shelby Forest State Park, TN | | | | | | | | | |
| MS-2 | WW-8786 | CAMS-155087 | *Hendersonia occulta* | Helicinidae | PL | 10.0 | −11.0 | 25.73 ± 0.16 | 29.95 ± 0.50 |
| Philips Bayou Quarry, AR | | | | | | | | | |
| PB-2 | WW-8790 | CAMS-155091 | *Inflectarius inflectus* | Polygyridae | PL | 6.3 | −10.9 | 21.89 ± 0.10 | 26.13 ± 0.24 |
| PB-1 | WW-8789 | CAMS-155090 | *Inflectarius inflectus* | Polygyridae | PL | 8.2 | −7.8 | 21.79 ± 0.09 | 26.02 ± 0.18 |
| Vicksburg, MS | | | | | | | | | |
| V-9 | WW-8749 | CAMS-154558 | *Neohelix albolabris* | Polygyridae | PL | 1.1 | −10.1 | 19.14 ± 0.06 | 23.10 ± 0.26 |
| V-7 | WW-8748 | CAMS-154557 | *Inflectarius inflectus* | Polygyridae | PL | 1.4 | −9.6 | 19.62 ± 0.06 | 23.64 ± 0.24 |
| V-2 | WW-8747 | CAMS-154556 | *Anguispira alternata* | Discidae | PL | 3.2 | −7.8 | 20.88 ± 0.07 | 25.22 ± 0.25 |
| V-12 | WW-8751 | CAMS-154560 | *Inflectarius inflectus* | Polygyridae | PL | 5.0 | −8.5 | 21.04 ± 0.07 | 25.39 ± 0.22 |
| V-13 | WW-8752 | CAMS-154561 | *Inflectarius inflectus* | Polygyridae | PL | 6.6 | −9.3 | 21.51 ± 0.07 | 25.81 ± 0.16 |
| V-18 | WW-8753 | CAMS-154562 | *Anguispira alternata* | Discidae | PL | 8.5 | −10.4 | 22.13 ± 0.08 | 26.34 ± 0.26 |
| V-20 | WW-8754 | CAMS-154563 | *Neohelix albolabris* | Polygyridae | PL | 9.7 | −8.5 | 24.02 ± 0.10 | 28.07 ± 0.29 |
| Natchez, MS | | | | | | | | | |
| N-23 | WW-8746 | CAMS-154555 | *Inflectarius inflectus* | Polygyridae | PL | 1.0 | −9.3 | 18.79 ± 0.05 | 22.65 ± 0.19 |
| N-15 | WW-8743 | CAMS-154551 | *Inflectarius inflectus* | Polygyridae | PL | 4.2 | −10.1 | 17.11 ± 0.05 | 20.64 ± 0.17 |
| N-10 | WW-8741 | CAMS-154550 | *Neohelix albolabris* | Polygyridae | PL | 5.5 | −9.8 | 19.16 ± 0.06 | 23.12 ± 0.26 |
| N-5 | WW-8740 | CAMS-154549 | *Inflectarius inflectus* | Polygyridae | PL | 7.0 | −10.1 | 19.08 ± 0.06 | 23.01 ± 0.27 |
| N-3 | WW-8739 | CAMS-154548 | *Haplotrema concavum* | Haplotrematidae | PL | 7.7 | −9.7 | 19.67 ± 0.06 | 23.70 ± 0.24 |
| N-21 | WW-8744 | CAMS-154552 | *Inflectarius inflectus* | Polygyridae | PL | 9.9 | −9.1 | 23.01 ± 0.09 | 27.33 ± 0.21 |

(*continued on next page*)

**Table 3** (*continued*)

| Sample # | Laboratory # | AMS # | Material dated[1] | Gastropod family | Unit[2] | Depth (m)[3] | $\delta^{13}C$ (vpdb)[4] | $^{14}C$ age ($^{14}C$ ka BP) | Calendar age (ka BP)[5] |
|---|---|---|---|---|---|---|---|---|---|
| N-22 | WW-8745 | CAMS-154553 | *Zolotrema obstrictum* | Polygyridae | PL | 10.4 | −9.9 | 21.52 ± 0.07 | 25.82 ± 0.16 |
| Pond, MS | | | | | | | | | |
| P-7 | WW-8782 | CAMS-155083 | *Mesodon zaletus* | Polygyridae | PL | 7.2 | −8.0 | 22.88 ± 0.11 | 27.23 ± 0.26 |
| P-6 | WW-8781 | CAMS-155082 | *Mesodon zaletus* | Polygyridae | PL | 7.9 | −10.8 | 23.05 ± 0.12 | 27.36 ± 0.24 |
| P-5 | WW-8780 | CAMS-155081 | *Hendersonia occulta* | Helicinidae | PL | 8.7 | −8.7 | 21.57 ± 0.09 | 25.86 ± 0.18 |
| P-4 | WW-8779 | CAMS-155080 | *Mesodon zaletus* | Polygyridae | PL | 8.8 | −10.9 | 24.47 ± 0.13 | 28.49 ± 0.31 |
| P-2 | WW-8777 | CAMS-155078 | *Mesodon zaletus* | Polygyridae | PL | 8.9 | −10.0 | 25.49 ± 0.15 | 29.66 ± 0.49 |
| P-3 | WW-8778 | CAMS-155079 | *Mesodon zaletus* | Polygyridae | PL | 9.1 | −9.1 | 26.12 ± 0.18 | 30.33 ± 0.50 |

[1] Current taxonomic names of most specimens are identical to Hubricht (1985). Exceptions include (current names first) *Neohelix albolabris* = *Triodopsis albolabris*; *Zolotrema obstrictum* = *Triodopsis obstricta*; *Inflectarius inflectus* = *Mesodon inflectus*.
[2] Unit designations: PL = Peoria Loess, RS = Roxana Silt, UF = Upper Farmdale Soil; FS = Farmdale Soil.
[3] Depth from top of exposure.
[4] Carbon isotope ratios are measured against Vienna Pee Dee Belemnite (vpdb). Italicized numbers are estimates based on values obtained from other specimens at the same location. Values in italics are estimates.
[5] Calibrated ages were calculated using CALIB v. 7.0., IntCal13.14C dataset; limit 50.0 calendar ka B.P. Calibrated ages are reported as the midpoint of the calibrated range. Uncertainties are calculated as the difference between the midpoint and either the upper or lower limit of the calibrated age range, whichever is greater (reported at the 95% confidence level; 2$\sigma$). All ages reported include 100% of the 2$\sigma$ probability range as calculated by CALIB.

part of the Roxana Silt at the Lenox, TN site (see discussion below) yielded ages of 29.54 ± 0.48 and 30.99 ± 0.24 ka.

These data suggest the shells analyzed have behaved as largely closed systems with respect to carbon, although small amounts (1–5%) of contamination may be present given the spread of ages. Three issues limit our ability to quantify the presence/absence of open-system behavior when compared to the basal contact of Peoria Loess. First, many of the shells dated here were recovered from slightly above (or below) the contact and not at the contact itself. Therefore, they provide only minimum (or maximum) estimates for the basal contact age. Second, ages of most of the taxa analyzed should be corrected for the limestone effect by some amount; for example, based on the results of the live specimens, the *H. occulta* ages should be corrected by ~600–800 $^{14}C$ years. However, we did not make corrections to the data presented because we do not have sufficient data for most of the taxa analyzed. Finally, we are assuming that the Peoria/Roxana contact is not time-transgressive across the region, at least within the limits of the age uncertainties presented here. It is unclear if this is actually the case.

In sum, many of the taxa analyzed here probably incorporated at least some old carbon from limestone or other carbonate rocks in their shells, which precludes us from stating that the shell ages are accurate to within the analytical uncertainties reported in Table 3. Moreover, we are not able to constrain the age of the basal contact of Peoria Loess to the degree implied by the analytical uncertainties alone. However, the data presented here indicated that most of the shell ages (with the exception of *Mesodon*) are probably accurate to within a few hundred years or so, as they largely maintain stratigraphic order, are relatively consistent at a given depth in which we have multiple taxa analyzed, and appear to yield reasonable ages for the basal contact of the Peoria Loess at multiple sites in the valley (see Bettis et al., 2003 and references therein).

### 3.5. Test 5: Peoria or Roxana?

The section at the Lenox, TN site contains ~6 m of unaltered silt/loess that lies on top of the Sangamon Soil (Fig. 2c). The unaltered loess appears to be Peoria Loess, but it is missing the underlying Farmdale Soil–Roxana Silt sequence that is typically found between it and the Sangamon Soil. Thus, there are two potential scenarios that could explain the units observed. First, the unaltered loess is, in fact, Peoria Loess and the intervening Farmdale–Roxana package was either never present or was eroded before deposition of Peoria Loess occurred directly on top of the Sangamon Soil. Second, the unaltered loess is actually Roxana Silt lying on top of the Sangamon Soil and both the Farmdale Soil and overlying Peoria Loess have been eroded away. In most places in North America, the Roxana Silt is much thinner than the Peoria Loess, but in places it can be quite thick (Markewich, 1993). At the type section locality near Roxana, IL, for example, the Roxana Silt is as much as 16 m thick (Willman and Frye, 1970) and therefore, both scenarios are plausible.

To test whether the large gastropod shells could be used to discern between Peoria Loess and Roxana Silt in the absence of a recognizable Farmdale Geosol or color change, we dated shells of *M. elevatus* and *H. occulta* throughout the sequence at the Lenox, TN site (Fig. 2c). Shell ages range from 41.2 ± 1.0 to 29.54 ± 0.48 ka ($n = 6$; Table 3). Although we have shown that *Mesodon* shells may yield ages that are too old and should be avoided for general dating purposes, the accuracy needed to answer the present question–is the unit Peoria Loess or Roxana Silt–is much less than that required for high-resolution chronologic questions. Shell ages from both taxa show that the unit at the Lenox site dates to > 30 ka, which implies the unit is indeed Roxana Silt. Similar applications of $^{14}C$ dating of gastropod shells may prove useful elsewhere in sit-

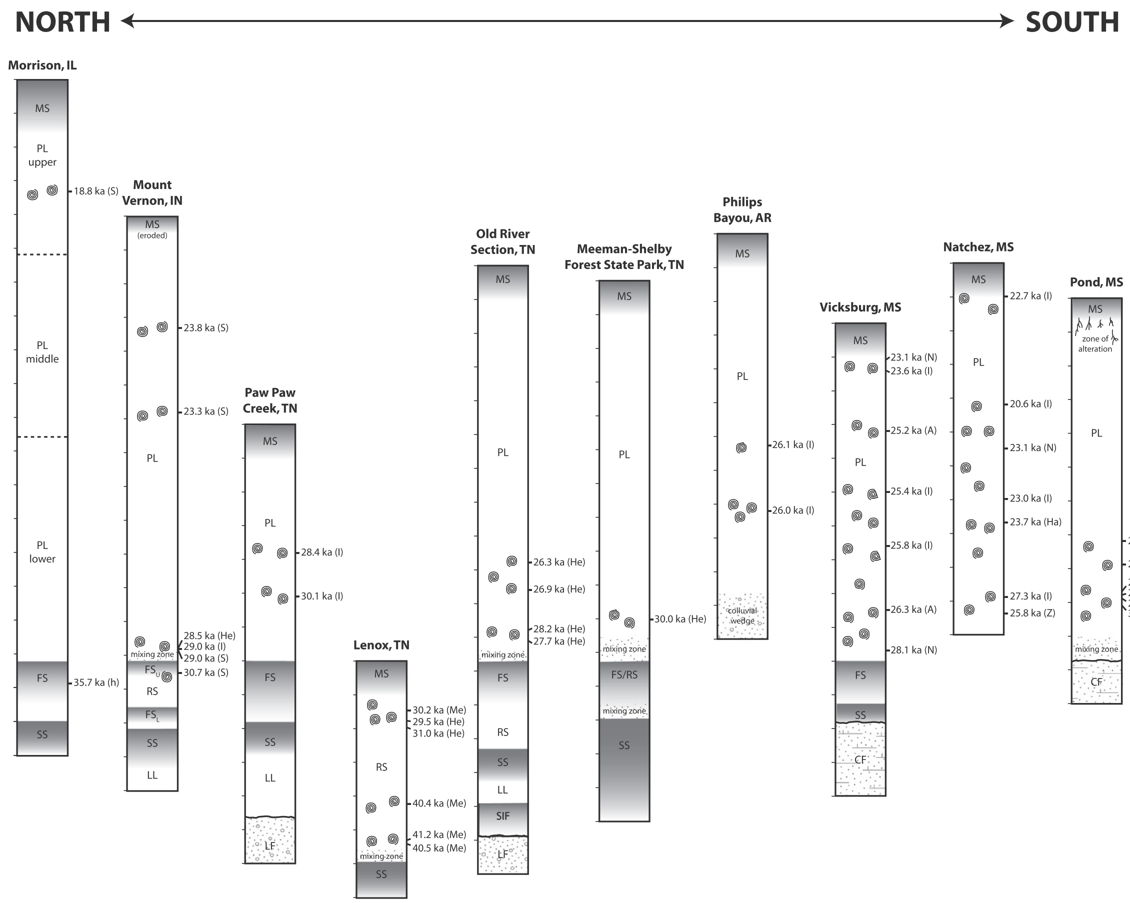


**Fig. 3.** Stratigraphic sections for all sites except the Burdick Branch Section, IL site. Sections are positioned using the base of the Peoria Loess as a common baseline. Tic marks on the left side of each section denote 1 m increments below the local ground surface; all sections are scaled equally. For simplicity, calibrated ages are shown without uncertainties and rounded to the nearest 0.1 ka (see Table 3 for complete ages). Abbreviations following ages denote taxa: A = *Anguispira alternata*, Ha = *Haplotrema concavum*, He = *Hendersonia occulta*, I = *Inflectarius inflectus*, Me = *Mesodon elevatus*, Mz = *Mesodon zaletus*, N = *Neohelix albolabris*, S = Succineidae, Z = *Zolotrema obstrictum*; h = humic acid age. Unit abbreviations: CF = Citronelle Formation; FS = Farmdale Soil; LF = Lafayette Formation; LL = Loveland Loess; MS = modern soil; PL = Peoria Loess; RS = Roxana Silt; SIF = Sicily Island Formation; SS = Sangamon Soil. Subscripts for Farmdale Soil: U = upper, L = lower.

uations where stratigraphic units have significantly different ages but similar physical and geochemical properties.

## 4. Conclusion

The data presented here show that fossil gastropods that are common to late Quaternary loess deposits in the Mississippi Valley, including *A. alternata*, *D. macclintockii*, *Haplotrema concavum*, *H. occulta*, *I. inflectus*, *N. albolabris*, *T. multilineata*, and *Zolotrema obstrictum*, incorporate at least some old carbon (∼1–5%) from limestone or other carbonate rocks in their shells. Although this causes the resulting shell ages to be slightly too old, they should be accurate to within a few hundred years or so. Thus, $^{14}C$ dating of terrestrial gastropod shells may be useful for those interested in studying processes that occurred over multi-millennial timescales at various localities in the Mississippi Valley and others outside North America where these taxa are found. It is imperative, however, that researchers bear in mind that the measured $^{14}C$ ages are probably not accurate to within the limits set by analytical uncertainties alone and the resulting data should not be over-interpreted beyond the limits set here.

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