Quaternary aminostratigraphy of Mississippi Valley loess

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ABSTRACT

Five Pleistocene loess units in the Mississippi Valley that contain terrestrial gastropod fossils are differentiated by amino acid ratios (aIle/Ile values) in the total acid hydrolysate of the fossil terrestrial gastropods *Hendersonia occulta*, *Catinella* and *Succinea*. Late Wisconsin Peoria Loess, which has been independently dated by radiocarbon and thermoluminescence methods, is identified by aIle/Ile values in fossil gastropods which progressively increase from northern Illinois to southern Louisiana. Early(?) to middle Wisconsin Roxana Silt is characterized by aIle/Ile values in *Hendersonia* only slightly greater, and values in *Catinella* and *Succinea* distinctly greater than those of the Peoria Loess. AIle/Ile values in *Hendersonia* suggest that the "Chinatown silt" (informal term) in Illinois and the Loveland Silt in Arkansas are the same age. Independent geologic evidence suggests that they predate the Sangamon (last interglacial). AIle/Ile values in *Hendersonia* from the "Sicily Island loess" (informal term) in Louisiana indicate that it is significantly older than the Loveland Silt and the "Chinatown silt." The oldest loess unit recognized by aIle/Ile values in *Hendersonia* from the Mississippi Valley is the "County Line silt" (informal term) in Illinois. The study shows that amino acid ratios in fossil gastropods from loess are an extremely valuable relative-age indicator and provide a means of long-distance correlation of midcontinent loess deposits.

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INTRODUCTION

Stratigraphic units of Pleistocene loess in the Mississippi Valley, derived by eolian deflation of exposed valley trains draining the Laurentide Ice Sheet margin, have traditionally been correlated with the glacial succession in central North America (Frye and others, 1968). Late Wisconsin (<25 ka) Peoria Loess in the Mississippi Valley is generally correlated through radiocarbon dating of fossil shells and wood collected from the sediment. Thermoluminescence (TL) ages and radiocarbon ages on Peoria Loess agree well, but TL dating of loess beyond the limit of ^{14}C dating apparently yields only minimum ages (Canfield and Pearson, 1985; Norton and Bradford, 1985; Canfield and Mickelson, 1986). Thus, correlation of pre–late Wisconsin loess units in the Mississippi Valley relies on stratigraphic position, color, mineralogy, and soil development (Wascher and others, 1948; McKay, 1979a; Follmer, 1983; Schumacher and others, 1987), and the numerical age of most units is uncertain. Correlation of loess over long distances using soil development is difficult, however, as rates of soil development vary geographically.

Studies of the extent of amino acid racemization (AAR) in mollusks hold the potential for improving the correlation and relative dating of pre–late Wisconsin loess units in the Mississippi Valley. Although reliable numerical ages remain elusive, these amino acid methods have been widely used in North America and Europe to differentiate and correlate terrestrial, lacustrine, and marine Pleistocene deposits (Mitterer, 1974; Wehmiller and Belknap, 1978, 1982; Miller and others, 1979; Nelson, 1982; Kennedy and others, 1982; Miller and Mangerud, 1985; Hearty and others, 1986; Miller and others, 1987; McCoy, 1987). We measured the extent of amino acid racemization in terrestrial gastropods collected from 16 exposures of Pleistocene loess in the Mississippi Valley along a transect from

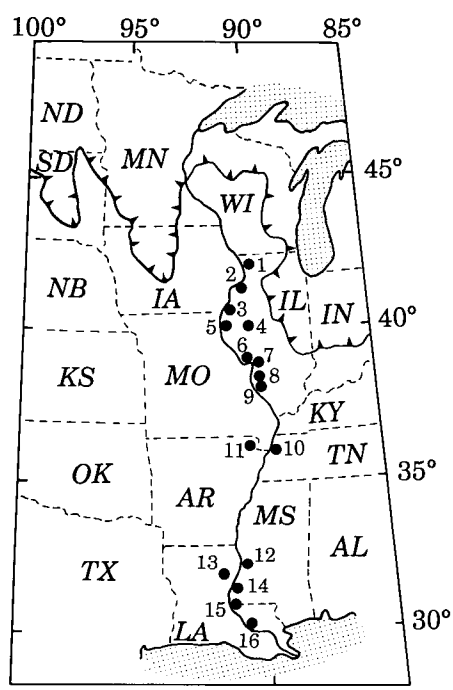

Figure 1. Location of sampled sites in the Mississippi Valley. Site numbers are listed in Table 1. Letters are abbreviations of state names. Stippled pattern shows the Great Lakes (to north) and Gulf of Mexico (to south). Barbed line is late Wisconsin limit of the Laurentide Ice Sheet.

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Illinois to Louisiana (Fig. 1). Here we evaluate these results and show that amino acid ratios in terrestrial gastropods can be used to differentiate loess deposits in the valley.

MISSISSIPPI VALLEY LOESS STRATIGRAPHY

Peoria Loess

The terms "Peoria Loess" and "Peorian" have been used in Illinois with several different meanings. The current meaning of Peoria Loess was defined in 1960 as surficial loess that occurs beyond the border of late Wisconsin till and overlies the Farmdale soil developed in Robein Silt or older deposits (Willman and Frye, 1970). Krinitzsky and Turnbull (1967) referred to equivalent-aged loess in the lower Mississippi Valley as "Vicksburg loess" (informal term). We follow recent workers who use the term "Peoria Loess" throughout the valley (Otvos, 1975, 1980; Miller and others, 1985), although some use local names in the lower valley (E. G. Otvos, Jr., 1984, written commun.).

Peoria Loess forms an essentially continuous sheet on the uplands adjacent to the Mississippi River from the state of Wisconsin south to southern Louisiana. Maximum loess thicknesses exceed 30 m along the bluffs of the valley (Smith, 1942; Krinitzsky and Turnbull, 1967; Snowden and Priddy, 1968); the loess thins with increasing distance from the flood plain of the river (Leighton and Willman, 1950; Ruhe, 1983). The lower part of the loess is generally calcareous and commonly fossiliferous where it is thicker than about 1 m within 30–50 km of the Mississippi River flood plain (Willman and Frye, 1970; Snowden and Priddy, 1968; McKay, 1979a). Fossils include a diverse assemblage of mollusks, mostly terrestrial gastropods (compare with Leonard and Frye, 1960; Leonard and others, 1971; Richards, 1938; Hubricht, 1962a, 1962b). The age of the base of Peoria Loess is about 25 ka in Illinois but it is younger downvalley (Snowden and Priddy, 1968; McKay, 1979b); deposition ended between 10 and 12.5 ka (McKay, 1979b).

Roxana Silt

Roxana Silt was established in 1960 as a lithostratigraphic unit (Willman and Frye, 1970) and has been interpreted as mostly loess that was deposited during the Altonian substage (early [?] or middle Wisconsin). It is found in the upper Mississippi Valley on the last interglacial Sangamon soil; its upper limit is stratigraphically bounded by the Peoria Loess, Morton Loess, or Robein Silt and is coincident with the top of the Farmdale soil. The extent of Roxana Silt south of Tennessee and Arkansas has been disputed (Miller and others, 1985; Winters and others, 1988). Radiocarbon ages on shells and wood from this unit range from 31,000 to 40,200 yr B.P. (Willman and Frye, 1970; McKay, 1979b).

Early Wisconsin (?) Loess

Recent studies have described a number of exposures with loesses thought to be of early Wisconsin (pre-Roxana) age. Miller and others (1985), Schumacher and others (1987) and Miller (in press) interpreted loess exposed below Peoria Loess at Sicily Island, Louisiana (unit defined informally as "Sicily Island loess" by Schumacher and others, 1987), as a pre-Roxana early Wisconsin unit. West and others (1980), Rutledge and others (1985), and Guccione and others (1986) correlated three loess units on Crowley's Ridge, Arkansas, with Peoria Loess, Roxana Silt, and Loveland Silt (the latter of Illinoian age, >125 ka). Rutledge and others (1985) interpreted the paleosol developed in the third loess on Crowley's Ridge as the Sangamon soil, of last interglacial age. Miller and others (1985), Schumacher and others (1987), and Miller (in press), however, correlated the third (Loveland) loess at Crowley's Ridge with the pre-Peoria loess at Sicily Island, Louisiana, and with a pre-Peoria loess at Vicksburg, Mississippi, which they interpret to be early Wisconsin based on TL ages (Pye and Johnson, 1988).

Pre-Wisconsin Loesses

Older pre-Wisconsin loess units have been well studied at only a few sites in the Mississippi Valley. Miller and others (1985), Schumacher and others (1987), and Miller (in press) correlated a fourth loess exposed at Crowley's Ridge (informally named "Crowley's Ridge loess" by Schumacher and others, 1987) with a third loess exposed at Vicksburg (compare with Krinitzsky and Turnbull, 1967). Schumacher and others (1987) and Miller (in press) correlated this fourth loess (Crowley's Ridge loess) with the pre-Wisconsin Loveland Silt identified elsewhere in the Midwest (Leighton and Willman, 1950; Daniels and Handy, 1959). As discussed above, however, West and others (1980), Rutledge and others (1985), and Guccione and others (1986) correlated the third loess on Crowley's Ridge with pre-Wisconsin Loveland Silt.

McKay (1979a, 1986) identified four pre-Wisconsin loess units in southwestern Illinois (informally named "Burdick silt," "Maryville silt," "Chinatown silt," and formally named Teneriffe Silt). A truncated soil is developed in the "Chinatown silt" at the Maryville section in Illinois, and an Illinoian till (informally named "Fort Russell till" by McKay, 1979a) with the Sangamon soil developed in it overlies the "Chinatown silt" at the Maryville and Powdermill Creek sections (McKay, 1986). McKay (1986) suggested that the "Chinatown silt" and "Fort Russell till" and their associated soils at the Maryville section record two glaciations and interglaciations, with the Sangamon Interglaciation represented by the Sangamon soil developed in the "Fort Russell till." McKay and Follmer (1985) and McKay (1986) correlated the "Chinatown silt" with Loveland Silt in Arkansas, arguing that the Loveland Silt there is "older than previously thought" (McKay and Follmer, 1985, p. 167).

AGES OF UNITS SAMPLED

We obtained terrestrial gastropod samples from 12 exposures of Peoria Loess (Fig. 1; Table 1). Shells and sediment from four of the sites in Illinois and one in Tennessee were dated by radiocarbon and TL methods, including two different horizons at the Beardstown, Illinois, site (the Cottonwood School Section; compare with Willman and Frye, 1970, p. 181–182). Samples from the three other sites in Illinois were collected from near the base of exposed Peoria Loess, but no independent dates were obtained from these sites. Our two samples from Vicksburg, Mississippi, are from the base of Peoria Loess at one of the best-dated sections in the Mississippi Valley (Snowden and Priddy, 1968; Johnson and others, 1984; Pye and Johnson, 1988). The sample from near the base of Peoria Loess at Natchez, Mississippi, was not independently dated. Shells from the same unit from which our samples were collected at a site northeast of Baton Rouge, Louisiana, have been ^{14}C dated (locality 16; Table 1).

Radiocarbon ages from our sampled sections are on gastropod shells, a material that may yield ^{14}C ages of which interpretation is uncertain. The greatest uncertainty in radiocarbon dating of terrestrial snails is in identifying the sources of shell carbonate and how these sources may influence the measured radiocarbon age (Goodfriend and Hood, 1983). One means of checking the reliability of shell ages is to cross-calibrate them with ages on wood or charcoal. Only a few examples exist where shell and wood have been dated from the same horizon in Peoria Loess (Willman and Frye, 1970; Coleman, 1972; Coleman and Liu, 1975). These paired analyses suggest that Pleistocene shell and wood ages from Peoria Loess disagree by < 10% (see also Rubin and others, 1963). TL ages also agree well with radiocarbon ages on shells from

the same units (Canfield and Pearson, 1985; Pye and Johnson, 1988).

TL dating of sediment is becoming a widely used method in Quaternary geochronology, and loess appears to be one of the most reliable materials for this type of dating (Wintle and Huntley, 1982; Berger, 1986). Canfield and Pearson (1985) and Pye and Johnson (1988) demonstrated the potential of TL dating for the younger loess record (<30 ka) of the Mississippi Valley, and our results from Illinois agree well with the radiocarbon chronology. Several workers (Johnson and others, 1984; Norton and Bradford, 1985; Canfield and Mickelson, 1986; Pye and Johnson, 1988) have published TL ages for older loess units which are younger than expected, although Miller and others (1985), Schumacher and others (1987), and Miller (in press) have accepted them.

We analyzed shells from two pre-Peoria loess units which have been dated by TL: the third (Loveland) loess at the Wittsburg section on Crowley's Ridge, Arkansas, (Fig. 2) where Canfield (1985) reported a TL age of 85 ± 7 ka (Alpha-1226), and the "Chinatown silt" at the Powdermill Creek section, Illinois, (Fig. 2), where Canfield (1985) obtained a TL age of 77 ± 10 ka (Alpha-2067). We collected shells from "Sicily Island loess" at the Sicily Island section (Fig. 2) where Miller and others (1985) reported a ^{14}C age of 27,500 ± 1200 yr (GX-6483) on shells. Schumacher and others (1987) and Miller (in press) correlated "Sicily Island loess" with the second loess exposed at the Vicksburg section (Fig. 2), where Pye and Johnson (1988) reported TL ages ranging from 75–95 ka.

We analyzed shells from three other sections in the Mississippi Valley where pre-Peoria fossiliferous units are exposed (Fig. 2). At Collinsville, Illinois, we collected shells from the type section of the Roxana Silt (Pleasant Grove School section; Willman and Frye, 1970, p. 187), and from an exposure of Roxana Silt 1.5 km south of the Pleasant Grove section (the Drury Inn section). Finally, we analyzed shells from a pre-Peoria silt of unknown age which crops out near Lima, Illinois. This unit, referred to informally as the "County Line silt," is interpreted to be a loess.

TABLE 1. Alle/Ile RATIOS ON TERRESTRIAL GASTROPODS FROM MISSISSIPPI VALLEY LOESS

Lab. no.[a]	Locality[b]	Taxon	Alle/Ile[c]	Age[d] (yr)
		MODERN		
AAL-950[e]	Colorado	*Catinella vermeta*	0.011 ± 0.005 (5)	Modern
AAL-952[e]	Colorado	*Succinea concordialis*	0.008 (1)	Modern
		PEORIA LOESS		
AAL-4531, 4532	Savanna, IL (1)	*Catinella* sp.	0.11 ± 0.02 (10)	15,900 ± 1580 (Alpha-1934)
AAL-4249, 4250[f], 4668	Milan, IL (2)	*Catinella* sp.	0.10 ± 0.02 (20)	18,400 ± 360* (ISGS-1365)
AAL-4534	Lomax, IL (3)	*Succinea* sp.	0.096 ± 0.004 (5)	Late Wisconsin
AGL-525	Lomax, IL (3)	*Hendersonia occulta*	0.054 ± 0.011 (3)	Late Wisconsin
AAL-4377, 4378	Beardstown, IL (4)	*Succinea* sp.	0.10 ± 0.02 (6)	17,600 ± 320* (ISGS-1364)
AAL-4533	Beardstown, IL (4)	*Succinea* sp.	0.104 ± 0.008 (5)	19,400 ± 300* (ISGS-1363)
AAL-4248	Beardstown, IL (4)	*Vertigo* cf. *gouldi*	0.11 ± 0.02 (5)	19,400 ± 300* (ISGS-1363)
AGL-496	Beardstown, IL (4)	*Hendersonia occulta*	0.077 ± 0.012 (5)	19,400 ± 300* (ISGS-1363)
AGL-624	Alton, IL (6)	*Hendersonia occulta*	0.081 ± 0.004 (3)	Late Wisconsin
AAL-4535, 4536[g]	Collinsville, IL (7)	*Succinea* sp.	0.103 ± 0.013 (3)	15,190 ± 1520 (Alpha-1933)
AGL-526[g]	Collinsville, IL (7)	*Succinea* sp.	0.111 ± 0.011 (2)	Late Wisconsin
AAL-4537, 4538	Edgemont, IL (8)	*Succinea* sp.	0.113 ± 0.005 (4)	Late Wisconsin
AGL-522, 537, 538	Finley, TN (10)	*Hendersonia occulta*	0.089 ± 0.005 (6)	23,920 ± 400* (ISGS-1523)
AAL-4539, 4540	Vicksburg, MS (12)	*Helicina orbiculata*	0.142 ± 0.011 (10)	20,000[h]
DAN-244[i]	Vicksburg, MS (12)	cf. *Mesodon* sp.	0.123 ± 0.010 (3)	22,300[j]
AGL-498	Natchez, MS (14)	*Hendersonia occulta*	0.165 ± 0.013 (4)	20,000[k]
DAN-170[l]	Tunica, LA (15)	*Mesodon elevatus*	0.162 ± 0.007 (3)	20,690 ± 250 (UGa-836) 21,570 ± 310 (UGa-871)
DAN-225[m]	Wards Creek, LA (16)	cf. *Mesodon* sp.	0.16 ± 0.03 (3)	20,595 ± 225 (Beta-1854)
		ROXANA SILT		
	Collinsville, IL (7)[n]			
AGL-527, AGL-671	(Pleasant Grove School)	*Succinea* sp.	0.19 ± 0.01 (2)	35,200 ± 1000 (W-729)[o]
AGL-761	(Pleasant Grove School)	*Hendersonia* sp.	0.090 ± 0.003 (3)	
AGL-762	(Pleasant Grove School)	*Succinea* sp.	0.15 ± 0.02 (4)	
AGL-1001	(Drury Inn)	*Catinella* sp.	0.14 (1)	
AGL-1002	(Drury Inn)	*Succinea* sp.	0.12 ± 0.01 (2)	
AGL-1003	(Drury Inn)	*Hendersonia* sp.	0.105 (1)	
AGL-1074	(IGS Museum Collection)	*Hendersonia* sp.	0.089 ± 0.006 (3)	

AMINO ACID GEOCHRONOLOGY

Amino acid racemization is a time-, pH-, and temperature-dependent chemical reaction which is one of a series of complex reactions involving the degradation of protein preserved in carbonate fossils (Williams and Smith, 1977). The extent of racemization of an amino acid in the total acid hydrolysate of a carbonate shell is assumed to vary only with the integrated diagenetic temperature history of the shell and with age. Variation in the rate of racemization caused by differences in pH is thought to be insignificant because the buffering action of the shell carbonate keeps the pH constant (Wehmiller, 1977, 1982; Miller and Hare, 1980). Research has demonstrated the integrity of the carbonate matrix for excluding secondary amino acids (Miller and Hopkins, 1980; Miller and Hare, 1980), although diffusion and leaching of free amino acids can complicate the interpretation of amino acid ratios in older samples. Different amino acids in shells, however, racemize at different rates (Wehmiller and Belknap, 1978), and the same amino acid has been shown to racemize at different rates in different molluscan genera (Miller and Hare, 1975, 1980; Wehmiller and others, 1977; Lajoie and others, 1980; Miller and Mangerud, 1985).

Within a limited geographical area where the

TABLE 1. (*Continued*)

Lab. no.[a]	Locality[b]	Taxon	Alle/Ile[c]	Age[d] (yr)
		"CHINATOWN SILT"		
AGL-431[p]	Powdermill Creek, IL (9)	Hendersonia occulta	0.22 ± 0.02 (3)	
		LOVELAND SILT		
AAL-4541, 4542	Crowley's Ridge, AR (11)	Hendersonia occulta	0.27 ± 0.02 (7)	Pre-Wisconsin
		"SICILY ISLAND LOESS"		
AGL-497[q]	Sicily Island, LA (13)	Helicina orbiculata	0.44 ± 0.01 (4)	27,500 ± 1200 (GX-6483)
AAL-4392[r]	Sicily Island, LA (13)	Hendersonia occulta	0.458 ± 0.008 (3)	27,500 ± 1200 (GX-6483)
		"COUNTY LINE SILT"		
AGL-553[s]	Lima, IL (5)	Hendersonia occulta	0.62 ± 0.04 (6)	Pre-Wisconsin

[a]AAL—Amino Acid Geochronology Laboratory, INSTAAR, University of Colorado, Boulder.
DAN—Samples prepared by Nelson at INSTAAR, University of Colorado, Boulder.
AGL—Amino Acid Geochronology Laboratory, Department of Geology and Geography, University of Massachusetts, Amherst.
[b]Numbers in parentheses refer to site locations in Figure 1.
[c]Peak height ratio of D-alloisoleucine to L-isoleucine in the total amino acid hydrolysate (free and peptide-bound amino acids) measured as described by Miller and Hare (1980). Mean ratio with 1 standard deviation. Number in parentheses is number of separately prepared and analyzed samples, and each sample may be a single shell or, for smaller taxa, a few shells combined.
[d]Radiocarbon or TL age of dated material in same stratigraphic unit as analyzed shells, with laboratory numbers in parentheses. All radiocarbon ages are on gastropod shells. Asterisk indicates that the age was obtained on the same sample that was analyzed for amino acids. All TL ages are on loess.
[e]Samples provided by S. K. Wu, University of Colorado Museum, Boulder.
[f]AAL-4250, may be *Succinea* sp. Alle/Ile ratio for just AAL-4249 and 4668 is 0.091 ± 0.017 (12).
[g]Samples from same stratigraphic unit (Peoria Loess), but stratigraphic position of samples in relation to each other is uncertain.
[h]Age estimated based on position of sample in relation to radiocarbon dates from section (Mississippi Standard Loess Section; Snowden and Priddy [1968]). Collected by Clark from 0.3 m above base of unit (site 9, Miller and others, 1985, p. 108).
[i]Sample collected by J. J. Alford.
[j]Mean of three ^{14}C ages on wood and shells from near base of the Mississippi Standard Loess Section along Highway 61 (Snowden and Priddy, 1968, p. 120).
[k]Age estimated based on position of sample near base of section and ^{14}C ages of unit in this area.
[l]Sample collected by E. G. Otvos, Jr., site 2 in Tunica Bayou area (Otvos, 1980, p. 81).
[m]Sample collected by C. R. Kolb, J. J. Alford, and J. C. Holmes from surface of silt-clay at base of Peoria Loess.
[n]Samples AGL-527 and AGL-671 collected by Clark; samples AGL-761 and AGL-762 collected by Barry Miller. Samples from Drury Inn section collected by Miller. Drury Inn section is about 1.5 km south of Pleasant Grove School section. Sample AGL-1074 was originally collected from the Pleasant Grove School section.
[o]^{14}C age (from Willman and Frye, 1970, p. 187) on shell from Roxana Silt at Pleasant Grove School section, but stratigraphic position of our samples in relation to ^{14}C age is uncertain.
[p]Sample collected by D. McKay 3.7 m below top of "Chinatown silt."
[q]Sample collected by Clark from 3.2 m above base of exposed loess unit (site 7, Miller and others, 1985, p. 88).
[r]Sample collected by B. J. Miller from 1.8 m above base of exposed loess unit (site 7, Miller and others, 1985, p. 88).
[s]Sample collected by Barry B. Miller 1 m above base of unit.

TABLE 2. Alle/Ile PEAK-HEIGHT RATIOS ON TOTAL ACID HYDROLYSATE INTERLABORATORY COMPARISON (ILC) SAMPLES

	ILC-A powder	ILC-B powder	ILC-C powder
AAL (University of Colorado*)	0.157 ± 0.004	0.505 ± 0.029	1.08 ± 0.04
AGL (University of Massachusetts)	0.195 ± 0.003	0.58 ± 0.02	1.10 ± 0.03

*Data from Miller and Brigham-Grette (in press).

temperature history of all sites is the same, the extent of racemization (expressed as the ratio of D to L stereoisomers of a particular amino acid) should not vary for samples of equal age buried below the depth of significant seasonal temperature fluctuations (~2–3 m, depending on site conditions and climate) (Wehmiller, 1977; Miller and others, 1982). In such a region, D/L ratios may be used for correlation and for determining relative age (termed "aminostratigraphy" by Miller and Hare, 1980). Because the thermal histories of most sites are unknown, modern temperature data are used as a first approximation to define the geographic area over which amino acid ratios can be directly compared (Miller and Mangerud, 1985). Thus, this method assumes that present differences in MATs (mean annual temperatures) between sites closely approximate differences in EDTs (effective diagenetic temperature histories) of samples of the same age from those sites (Wehmiller, 1982).

Where independent dating control exists, the effect of different EDTs at different sites can be evaluated, and aminostratigraphic correlations can be made over a larger geographic area. Extensive studies of amino acid racemization in marine mollusks from Pleistocene deposits on the east and west coasts of the United States and in Europe have demonstrated that by using calibrated (independently dated) sites to estimate paleotemperature gradients during the Pleistocene, sites can be correlated over >20 degrees of latitude (Wehmiller and Belknap, 1978, 1982; Wehmiller and others, 1977; Kennedy and others, 1982; Miller and Mangerud, 1985; Hearty and others, 1986).

Measurement of Alle/Ile Ratios in Mississippi Valley Gastropods

In our samples, we measured the extent of epimerization (racemization about the alpha carbon atom in a molecule having more than one chiral carbon) of the single amino acid isoleucine. Over geological time, isoleucine epimerizes to its nonprotein diastereomer alloisoleucine, and the ratio between the two acids, expressed as alle/Ile, increases to an equilibrium value of 1.30 ± 0.05 (Williams and Smith, 1977; Miller and others, 1979). All of our samples were collected from >3 m depth. We used cation-exchange liquid chromatography (methods of Miller and Hare, 1980) to measure the alle/Ile ratio in the total acid hydrolysate (free and peptide-bound amino acids) of shells of six genera of gastropods. With the exception of a few samples (DAN-225, AAL-4284, AAL-4668, AAL-4532; Table 1), our samples meet the reliability criteria of Miller and Hare (1980) and Wehmiller (1982, 1984). Analytical variability of ratios from the same shell is <5%, and ratios from different shells in the same bed vary by <10%. The variability of ratios in samples with coefficient of variation >10% of the mean is most likely due to the small size of the shells analyzed, or to the limited number of preparations of some samples.

A comparison of the alle/Ile peak-height ratios from analyses of interlaboratory comparison (ILC) samples (Wehmiller, 1984) shows very little difference between those done at the University of Colorado laboratory (samples prefixed with AAL) and those done at the University of Massachusetts laboratory (samples with the AGL prefix) (Table 2). The only significant difference is in the ILC-A powder sample for which the University of Colorado laboratory found a significantly lower alle/Ile ratio in the total acid hydrolysate. A comparison of alle/Ile ratios from hydrolysates of *Succinea* from the Collinsville, Illinois, site shows a difference of <10% in the mean alle/Ile ratio determined at the two laboratories. It is concluded that, over-

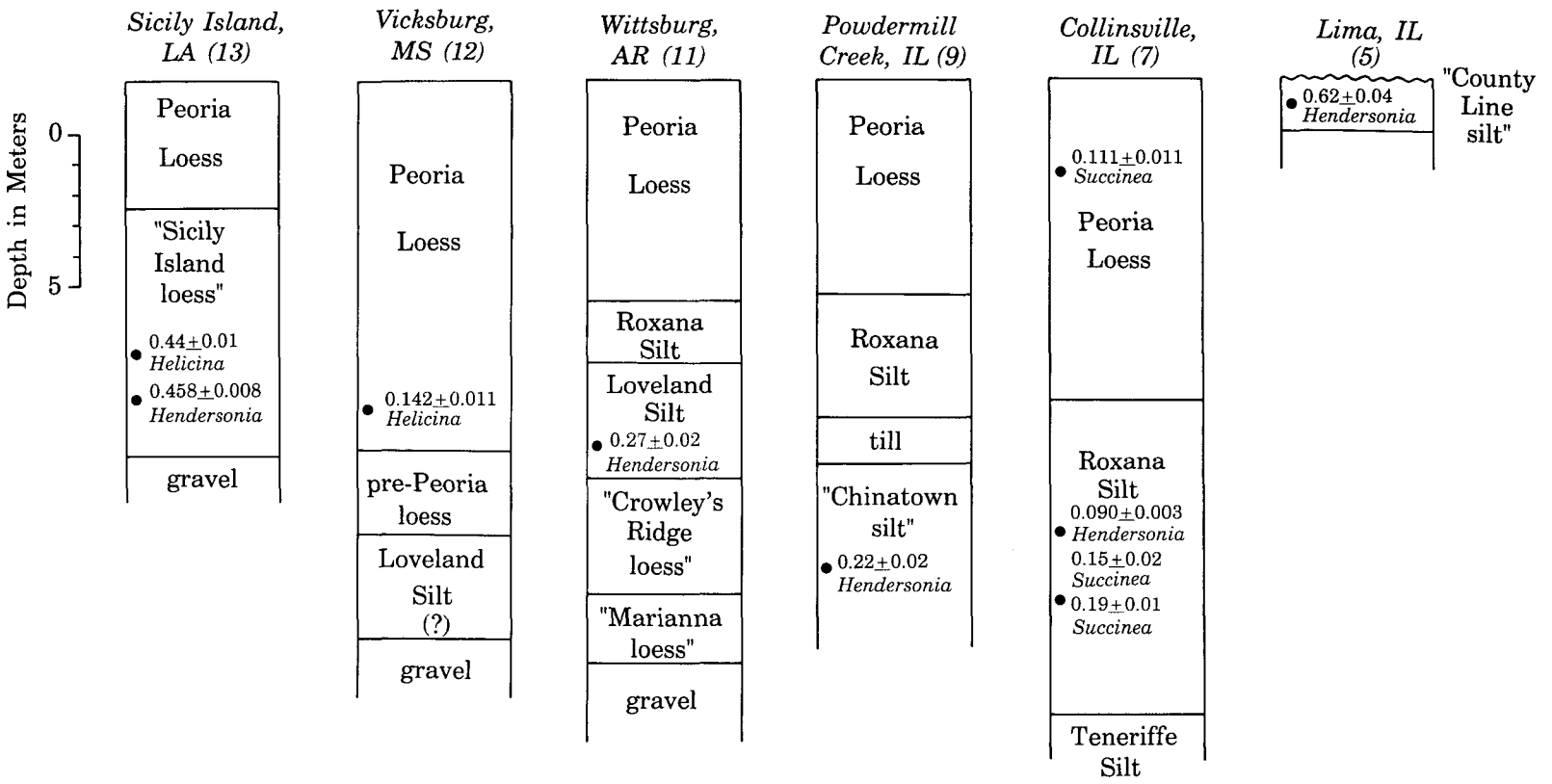

Figure 2. Stratigraphic sections in the Mississippi Valley that expose fossil-bearing pre–Peoria Loess units (localities from Fig. 1). Informal terms are identified in quotation marks. Locations of analyzed fossil gastropod genera with measured aIle/Ile ratios and one standard deviation are shown.

all, the differences in results between the two laboratories are relatively unimportant in this study.

Taxonomic Differences in Epimerization Rate

Correlation of units containing different types of mollusks is complicated by the fact that the rate of the isoleucine epimerization reaction has been shown to vary by as much as a factor of 2 from one mollusk genus to another (Miller and Hare, 1980). Detailed kinetic data for gastropods derived from laboratory studies and independently age-calibrated samples are available for only the fresh-water gastropod *Lymnaea* (McCoy, 1981) and the terrestrial genera *Vallonia* (Nelson and others, 1984), *Hendersonia*, and *Catinella* (McCoy, unpub. data). Preliminary data for 12 non-marine molluscan genera indicate that differences in apparent epimerization rates are generally <30% (Miller and Hare, 1980; Miller and others, 1982; W. D. McCoy and A. R. Nelson, unpub. data).

Limited data for the six genera of gastropods we analyzed (Table 1) prevent a rigorous evaluation of generic differences in the rate of isoleucine epimerization. *Succinea* and *Catinella* samples of similar age from Illinois have similar ratios, suggesting similar epimerization rates at least to ratios of 0.11. Although shell characteristics are helpful (Burch, 1962), positive differentiation of these two genera is based on soft anatomy (Quick, 1935). *Vertigo* from Beardstown, Illinois, (AAL-4248) has ratios similar to those for *Succinea* and *Catinella*. *Hendersonia occulta* appears to racemize at a significantly lower rate than *Catinella*, *Succinea*, and *Vertigo* (AGL-496, AGL-525). At Vicksburg, Mississippi, on the basis of only three preparations, *Mesodon* ratios are slightly lower than those for *Helicina orbiculata*, but farther south, *Mesodon* ratios are the same as those for *Hendersonia occulta*. Much older samples of *Hendersonia occulta* and *Helicina orbiculata* from Sicily Island have the same ratios. At any single latitude, standard deviations of ratios overlap. We thus conclude that *Hendersonia occulta*, *Helicina*, and *Mesodon* racemize more slowly than do *Succinea*, *Catinella*, and *Vertigo*.

Aminostratigraphy

The aIle/Ile values from our 16 sites suggest that 5 loess units of differing relative age are represented in the Mississippi Valley (Figs. 3, 4; Table 1). Peoria Loess, which has been independently dated by radiocarbon and TL methods throughout the valley (Table 1), is identified by aIle/Ile values on fossil gastropods which increase progressively from northern Illinois (42°N) to southern Louisiana (30°25′N) (Fig. 3; Table 1). The two dashed curves in Figure 3a define an envelope of possible aIle/Ile values for *Hendersonia* (and the other "slow" epimerizers) from the Peoria Loess with an age range of 12,000 to 20,000 yr. The envelope provides a first approximation of the expected range of values and the expected latitudinal gradient assuming that the differences in EDTs between sites are the same as the differences in present-day MATs. Because the gradient of measured aIle/Ile values downvalley is less steep in the lower valley than the "expected" gradient suggests that late Pleistocene temperature depressions in the lower Mississippi Valley may have been larger than those in the north, and current MATs are not necessarily a good approximation of EDTs.

In any case, the increase in ratios from north to south reflects the different postdepositional temperature histories experienced by the samples. The gradient of the ratios down the valley serves as a useful measure of expected change in ratios on older samples. As discussed earlier, *Hendersonia* racemizes at a slower rate than *Catinella* or *Succinea*, resulting in lower aIle/Ile values for same-age samples (Fig. 3b). The scatter of aIle/Ile values from the northern to the southern sampled localities (Fig. 3) is due to real differences in age and diagenetic temperature of each sample, taxonomic differences in epimerization rate, and imprecision in measurement.

The samples from the Pleasant Grove section in Illinois (AGL-527, 671, 761, 762, and 1074) indicate that fossil gastropods from Roxana Silt are characterized by aIle/Ile values that are generally somewhat greater than those of the Peoria Loess. Other samples from nearby sites confirm this conclusion (AGL-1001, 1002, and 1003) (Table 1). In the case of AGL-527 and 671, aIle/Ile ratios in the hydrolysates of *Succinea* shells are as high as 0.19 ± 0.01. The large range in aIle/Ile ratios in shells from Roxana Silt may be due to the possible large range in age of sediments comprising the Roxana Silt as well as to a relatively low sedimentation rate that would allow some gastropod shells to remain near the surface for a relatively long period of time. Near-surface shells generally have higher mean aIle/Ile ratios and exhibit greater variance in aIle/Ile ratios compared to those buried more deeply (McCoy, 1981).

Because some of the shells from the Roxana Silt may be only a few thousand years older than some shells from the Peoria Loess, and because temperatures during those few thousand years may have been low relative to Holocene temperatures, it is not surprising that aIle/Ile ratios in those shells are only slightly greater than those from the Peoria Loess.

AIle/Ile values in samples collected from the "Chinatown silt" at the Powdermill Creek section, Illinois, do not differ significantly from values in samples collected from Loveland Silt at the Wittsburg section on Crowley's Ridge, Arkansas (Fig. 2). The two sites are 130 km apart, but the gradient of the line connecting the two samples is similar to the gradient of values from Peoria Loess over the same distance (Fig. 3a). We therefore suggest that Loveland Silt in Arkansas is correlated with "Chinatown silt" in Illinois, as previously reported by McKay and Follmer (1985) and McKay (1986).

AIle/Ile values in samples from "Sicily Island loess" at Sicily Island are considerably higher than values in shells from Loveland Silt on Crowley's Ridge and "Chinatown silt" in Illinois (Figs. 2, 3; Table 1). Because a line drawn between values in samples from "Sicily Island loess" and Loveland Silt is much steeper than the observed gradient of values on the Peoria Loess over the same interval (Fig. 3a), we suggest that the "Sicily Island loess" is significantly older than the Loveland Silt. Furthermore, the high aIle/Ile values from "Sicily Island loess" indicate that the finite ^{14}C age of 27,500 ± 1200 yr on shells from the unit (Miller and others, 1985; Table 1) should be interpreted as a minimum age.

The highest aIle/Ile values recorded in shells from the Mississippi Valley were measured on gastropods from the "County Line silt" (Figs. 2, 3; Table 1). Ratios are significantly higher than ratios from the "Sicily Island loess," and the sample locality is well north of Sicily Island (Fig. 3). The "County Line silt" is therefore the oldest loess recognized in the valley by aIle/Ile values.

CONCLUSIONS

Five loess units in the Mississippi Valley containing terrestrial gastropod fossils can be differentiated by aIle/Ile values in the total acid

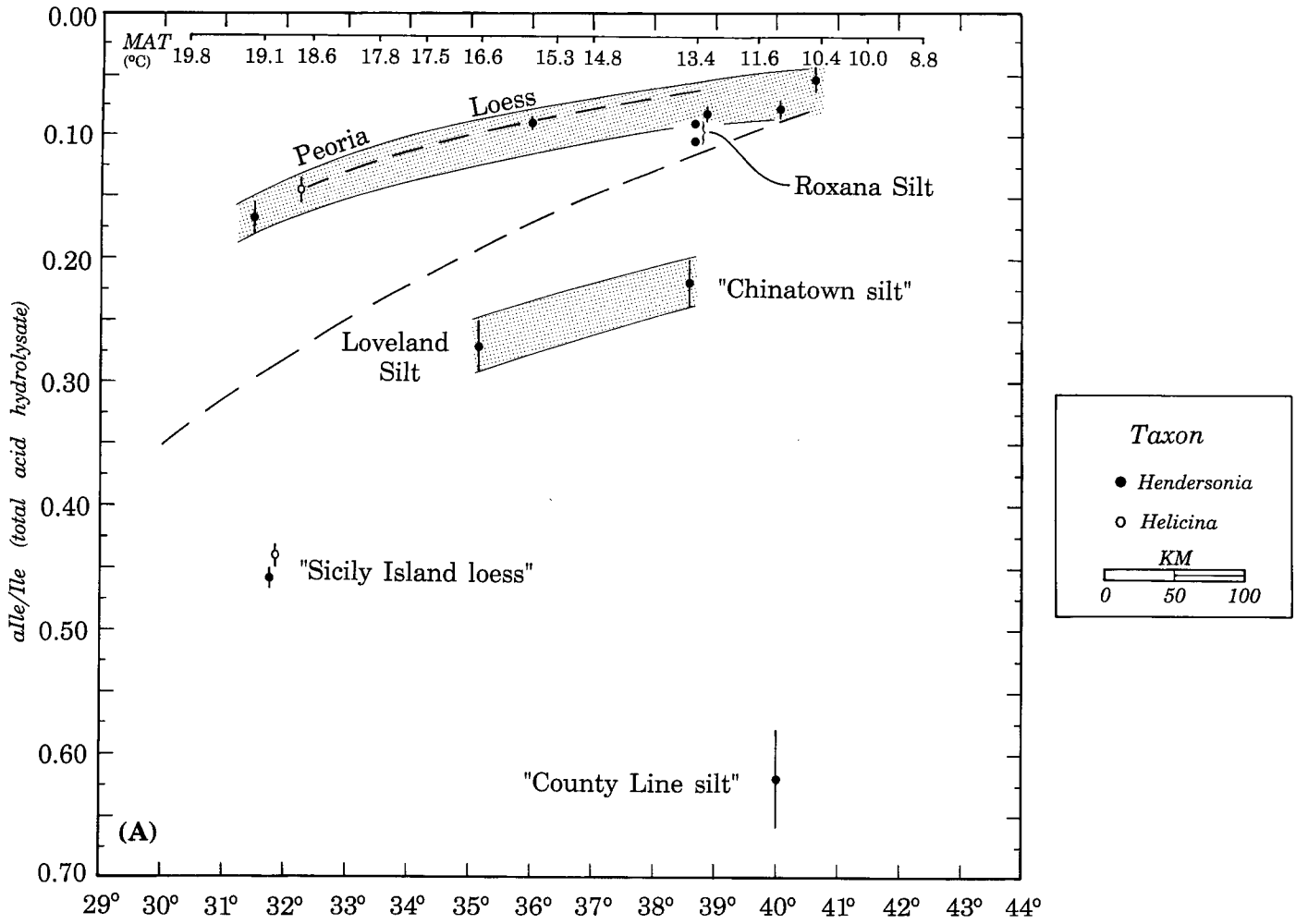

Figure 3. (A) Plot of aIle/Ile ratios (with one standard deviation) measured on *Hendersonia occulta* and *Helicina orbiculata* ("slow" epimerizers) against latitude. Localities from Figure 1. Stippled pattern identifies ratios on samples from the Peoria Loess and the suggested correlation of Loveland Loess with "Chinatown silt." Two dashed curves identify the upper and lower boundaries of an envelope of possible aIle/Ile ratios for *Hendersonia* (and other "slow" epimerizers) from the Peoria Loess with an age range of 12,000 to 20,000 yr given the expected latitudinal gradient assuming that the differences in EDTs between sites are the same as the differences in present-day mean annual temperatures (MATs from selected stations in the Mississippi Valley shown). See text for further discussion.

hydrolysate of fossil *Hendersonia occulta* and, to a lesser extent, *Catinella* and *Succinea* (Figs. 3, 4). Peoria Loess and Roxana Silt have been independently dated by radiocarbon and TL methods as late and middle to early(?) Wisconsin, respectively. Roxana Silt is differentiated from Peoria Loess on the basis of aIle/Ile values in *Hendersonia*, *Catinella*, and *Succinea* (Figs. 3, 4).

The next older unit is represented by the Loveland Silt in Arkansas and the "Chinatown silt" in Illinois. Schumacher and others (1987) and Miller (in press) correlated the Loveland Silt on Crowley's Ridge with a loess unit (pre-Peoria) exposed at the Vicksburg section (Fig. 2), which had been dated by TL at 75–95 ka (Johnson and others, 1984; Pye and Johnson, 1988). Schumacher and others (1987) and Miller (in press) accepted the TL ages and argued that Loveland Silt was a pre-Roxana, early Wisconsin unit. Rutledge and others (1985) argued that the soil developed in Loveland Silt on Crowley's Ridge is the Sangamon soil, and the Loveland Silt is thus pre-Sangamon. McKay and Follmer (1985) and McKay (1986) correlated the Loveland Silt with the "Chinatown silt." The "Chinatown silt" is overlain by late Illinoian "Fort Russell till," and the "Chinatown silt" was probably deposited during an early or middle Illinoian glaciation (McKay, 1986) (where late, middle, and early Illinoian are informal, relative terms).

The correlation of the "Chinatown silt" with the Loveland Silt, proposed by McKay and Follmer (1985) and McKay (1986) and supported in this study by aIle/Ile values in fossil *Hendersonia occulta* (Fig. 3), suggests that the Loveland Silt is pre-Sangamon. Because the "Chinatown silt" has a soil developed in it and is

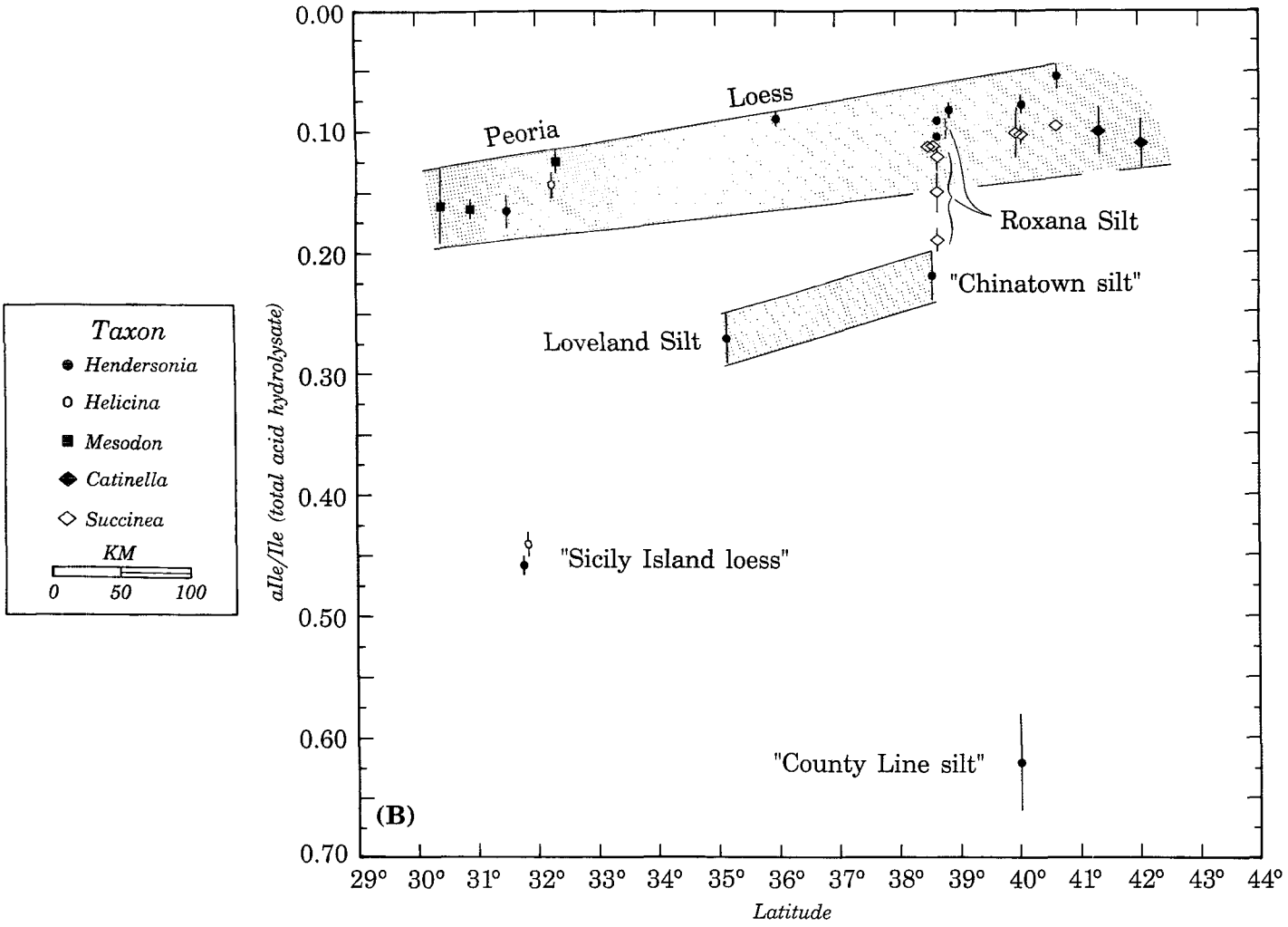

Figure 3. (*Continued*). (B) Plot of aIle/Ile ratios measured on fossil gastropod genera, including "slow" (*Hendersonia, Helicina, Mesodon*) and "fast" (*Succinea, Catinella*) epimerizers versus latitude. Stippled pattern identifies ratios from the Peoria Loess and the suggested correlation of Loveland Loess with "Chinatown silt." Overlapping ratios on samples from Roxana Silt with those from Peoria Loess are identified by brackets.

overlain by late Illinoian till, the correlative Loveland Silt on Crowley's Ridge may also predate the late Illinoian (McKay and Follmer, 1985). The soil developed in Loveland Silt would therefore be polygenetic, reflecting development during the Sangamon interglaciation as well as some period prior to that. Alternatively, the "Chinatown silt" may only correlate with the lower part of the Loveland Silt, and Loveland Silt may have continued to accumulate until the end of the Illinoian (Willman and Frye, 1970, Fig. 7). The soil developed in Loveland Silt is thus the Sangamon soil (Rutledge and others, 1985).

AIle/Ile values on fossil gastropods from the "Sicily Island loess" suggest that it is significantly older than Loveland Silt, rather than correlative with it as argued by Schumacher and others (1987) and Miller (in press). The oldest loess recognized by aIle/Ile values in the Mississippi Valley is the "County Line silt" in Illinois.

Peoria Loess
0.054-0.089 *(H.o.)*
0.096-0.113 *(Suc.)*
Roxana Silt
0.089-0.105 *(H.o.)*
0.12-0.19 *(Suc.)*
"Chinatown silt" Loveland Silt
0.22-0.27 *(H.o.)*
"Sicily Island loess"
0.458 *(H.o.)*
"County Line silt"
0.62 *(H.o.)*

Figure 4. Composite stratigraphic section of fossiliferous loess units in the Mississippi Valley. Relative ages are inferred from differences in mean ratios for all samples from units. Mean ratios shown are from analyses of *Hendersonia occulta* (*H.o.*) and *Succinea* (*Suc.*). Informal terms are shown in quotation marks.

Dating and correlation of the Pleistocene record in central North America has previously met with success primarily for events <50 ka, where deposits lie within the range of radiocarbon and TL methods. To a lesser degree, events >600 ka have been correlated and dated using paleomagnetic methods and fission track dating of volcanic ashes (Boellstorff, 1978; Easterbrook and Boellstorff, 1981; Baker and others, 1983; Hallberg, 1986). The results from this paper demonstrate that amino acid racemization in fossil gastropods offers a powerful dating method and correlation tool for mid-continent fossiliferous deposits that are >50 ka. The method circumvents problems associated with existing methods (lithology, soil development, stratigraphic position), and suggests that these deposits may be reliably differentiated and correlated over large regions.

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