DIVISION S-5—PEDOLOGY

Impact of Climate and Parent Material on Chemical Weathering in Loess-derived Soils of the Mississippi River Valley

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ABSTRACT

Peoria Loess-derived soils on uplands east of the Mississippi River valley were studied from Louisiana to Iowa, along a south-to-north gradient of decreasing precipitation and temperature. Major element analyses of deep loess in Mississippi and Illinois show that the composition of the parent material is similar in the northern and southern parts of the valley. We hypothesized that in the warmer, wetter parts of the transect, mineral weathering should be greater than in the cooler, drier parts of the transect. Profile average values of CaO/TiO_2, MgO/TiO_2, K_2O/TiO_2 and Na_2O/TiO_2, Sr/Zr, Ba/Zr, and Rb/Zr represent proxies for depletion of loess minerals such as calcite, dolomite, hornblende, mica, and plagioclase. All ratios show increases from south to north, supporting the hypothesis of greater chemical weathering in the southern part of the valley. An unexpected result is that profile average values of Al_2O_3/TiO_2 and Fe_2O_3/TiO_2 (proxies for the relative abundance of clay minerals) show increases from south to north. This finding, while contrary to the evidence of greater chemical weathering in the southern part of the transect, is consistent with an earlier study which showed higher clay contents in Bt horizons of loess-derived soils in the northern part of the transect. We hypothesize that soils in the northern part of the valley received fine-grained loess from sources to the west of the Mississippi River valley either late in the last glacial period, during the Holocene or both. In contrast, soils in the southern part of the valley were unaffected by such additions.

One of the most pressing issues in society today is the possibility of human-induced climate change. Addition of greenhouse gases to the atmosphere may result in global warming, based on atmospheric general circulation models (AGCMs) (Hansen et al., 1988). However, because AGCMs produce simplified forecasts of future climates, it is imperative that they undergo validation tests. An effective method for validation is to compare AGCM models of past climates with geologic data on past climates, particularly warm periods. A commonly studied, recent warm-climate interval is the last, or Sangamon, interglacial period that had its peak warming ~125 000 yr ago (Muhs and Szabo, 1994). The pedologic record potentially contains paleoclimatic information about the last interglacial period in the form of the Sangamon paleosol or its stratigraphic equivalent (e.g., the Eemian paleosol in Europe). There have been attempts to infer a longer, warmer, or wetter last interglacial period from studies of this soil or its equivalent in the midcontinent of North America (Ruhe, 1969; Hall and Anderson, 2000), Alaska (Muhs et al., 2001), and China (Maher et al., 1994). Critical to paleoclimatic interpretations, using paleosols, are reliable climofunctions for modern soils, which give an understanding of soil formation as a function of climate, all other factors being equal.

The importance of climate as a soil-forming factor has been appreciated by pedologists for more than 100 yr, starting with Dokuchaev (1883) and emphasized by Jenny (1941, p. 281) 60 yr ago. Since that time, there have been many soil climosequence studies. Much of the work of the past two decades has been summarized recently by Birkeland (1999, p. 430). One of the most commonly used geologic settings for soil climosequence studies is loess that covers a large region and spans gradients of temperature and precipitation. Such studies have been conducted in loess-dominated landscapes in China (Maher et al., 1994), Argentina (Alvarez and Lavado, 1998), and New Zealand (Webb et al., 1986). In the USA, soil climosequence studies have been made across the east-west precipitation gradient in the prairie-dominated loess belt (Jenny and Leonard, 1934; Wells and Riecken, 1969; Ruhe, 1984a) and across the north-south precipitation and temperature gradients in the forested loess uplands along the Mississippi River Valley (Torrent and Nettleton, 1979; Ruhe, 1984b,c). It is fortunate that many soil climosequences have been conducted in loess, as this is also the parent material for the Sangamon soil in much of the midcontinent of North America (Frye et al., 1968; Ruhe, 1969; Pye and Johnson, 1988; Rutledge et al., 1996; Markewich et al., 1998).

Several studies along the Mississippi River Valley suggest that significant chemical weathering of primary minerals has taken place in soils developed in last-glacial (Peoria) loess. Krinitzsky and Turnbull (1967), Snowden and Priddy (1968), Pye and Johnson (1988), and Markewich et al. (1998) all reported loss of both carbonate minerals and feldspars in soils derived from Peoria Loess in Mississippi and Arkansas. Beavers et al. (1963), Jones and Beavers (1966), Fehrenbacher et al. (1965), and Jones et al. (1967) reported alteration of silt-sized minerals and loss of soluble elements (Ca and K) relative to an insoluble element (Zr) in loess-derived soils in Illinois. These workers attributed the spatial variability in CaO/ZrO_2 and K_2O/ZrO_2 values in Illinois to distance from the loess source, with higher (less weathered)

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Abbreviations: AGCM, atmosphere general circulation models.

values close to the source and lower values distant from the source. Although this interpretation is certainly reasonable, it is difficult to decouple the parent material factor (loess-thinning) from the climate factor, because many of the transects studied in Illinois also span a precipitation gradient. For example, the lower CaO/ZrO_2 and K_2O/ZrO_2 values in southern Illinois that Jones and Beavers (1966) attribute to thinner loess also occur in a region of significantly higher precipitation than in northern Illinois, where CaO/ZrO_2 and K_2O/ZrO_2 values are higher.

By far the most comprehensive study of loess-derived soils in the Mississippi River Valley is a transect from southern Mississippi to southern Minnesota studied by Ruhe (1984b,c). Ruhe attempted to decouple loess sedimentation from climate variables by limiting his sample sites to areas immediately adjacent to the Mississippi River Valley, where presumably there would be a uniform parent material. He reported that soils in the northern part of the transect are thinner, less deeply leached, and have higher clay contents and base status than those in the southern part. Ruhe (1984c) attributed the differences in leaching depth and base status to climate; he felt the difference in clay content was because of local differences in loess sedimentation (Ruhe, 1984b). In contrast to other workers (Beavers et al., 1963; Fehrenbacher et al., 1965; Jones and Beavers, 1966; Jones et al., 1967; Krinitzsky and Turnbull, 1967; Snowden and Priddy, 1968; Pye and Johnson, 1988; Markewich et al., 1998), Ruhe thought that Mississippi River Valley loess-derived soils had experienced little chemical weathering and thought that the impact of climate was limited to the southward trend of decreasing base status. Nevertheless, evidence for chemical weathering of primary minerals reported by other workers (cited above), using either mineralogical or major element abundance data, suggests that a climate influence is detectable. Ruhe's (1984c) interpretations of moderate chemical weathering using only base status is debateable, because it is an indirect and partial indicator of primary mineral weathering. Furthermore, Ruhe's pedons were cultivated; base status could have been altered by fertilizer additions and soil amendments (e.g., liming).

We report results of a new soils study along the Mississippi River Valley, similar to Ruhe's (1984b,c) transect. Major element chemistry of bulk soil samples is used to assess degree of chemical weathering. New stratigraphic data and geochemical analyses of deep loess provide the baselines for comparison of soils with a similar parent material. Our major study goal is to assess which chemical parameters are most useful in inferring past climates from buried soils, particularly the Sangamon soil.

MATERIALS AND METHODS

We sampled soils from northern Louisiana to northern Iowa on well-drained but uneroded upland localities where deep Peoria Loess exists (Fig. 1). With the exception of pedons 3, 4, 5, 6, and 11, the soils were uncultivated. In the southern part of the transect, soils were described and sampled from hand-dug pits or deep roadcuts; in the northern part of the transect, soils were described and sampled from cores taken with a hydraulic drilling rig. Abbreviated soil descriptions and complete chemical data are given for all pedons in Table 1.

Pedons sampled in Louisiana, Mississippi, Tennessee, and Kentucky are in the Memphis series (fine-silty, mixed, active, thermic Typic Hapludalfs), those in southern Illinois are in the Alford series (fine-silty, mixed, superactive, mesic Ultic Hapludalfs), and those in northern Illinois and Iowa are in the Fayette series (fine-silty, mixed, superactive, mesic Typic Hapludalfs). All soils are Typic (Memphis and Fayette) or Ultic (Alford) Hapludalfs developed primarily under what was oak (*Quercus*)-hickory (*Carya*) deciduous forest in presettlement time (Kuchler, 1964). Past vegetation and climate differed from that of the present, but based on pollen studies, most of the region has probably been in mesic deciduous forest at least since about 9000 ^{14}C yr BP, with perhaps some mid-Holocene prairie occupation in parts of the northern Mississippi River Valley (Webb et al., 1993; Baker et al., 1996). In the southern portion of the transect, northern Louisiana, mean annual precipitation is ~1550 mm and mean January and July temperatures are 10°C and 28°C, respectively (based on 1961–1990 means for Baton Rouge, LA; all climatic data cited herein are from National Climatic Data Center, Asheville, NC, unpublished data, 1991). In northern Iowa, mean annual precipitation is as low as ~780 mm and mean January and July temperatures are -8°C and 23°C, respectively (based on 1961–1990 means for Prairie du Chien, WI, immediately east of our northernmost pedon). The southernmost part of the valley rarely has freezing temperatures, whereas the northern valley has 5 mo with mean daily minima below freezing (0°C). Precipitation has a winter maximum in the southern part of the valley, up to southern Illinois. From central to northern Illinois and Iowa, there is a very distinct summer maximum for precipitation. Ruhe (1984b,c) pointed out that effective moisture is greater in the southern valley not only because of greater overall precipitation, but also because maximum precipitation occurs during cooler months, when evapotranspiration is lower.

After description and sampling, total-soil splits from each horizon were pulverized in a shatterbox; major element chemistry was determined by wavelength-dispersive x-ray fluorescence and trace element chemistry was determined by energy-dispersive x-ray fluorescence. Abundances of soluble elements were normalized to relatively insoluble Ti and Zr to develop weathering ratios (Birkeland, 1999, p. 430). Profile average weathering ratios were determined by weighting all horizons in a pedon by horizon thicknesses and summing, similar to the approach used by Ruhe (1984b,c) for other parameters.

Major element composition of deep, unaltered loess was determined for samples obtained by drilling at two localities near Moline and Morrison (4 and 5 on Fig. 1) in northern Illinois, one locality (8 on Fig. 1) in southwestern Illnois, and published geochemical data from three localities at Natchez and Vicksburg, Mississippi (near pedons 21 and 22 on Fig. 1) reported by Pye and Johnson (1988). Pedon localities 5 and 4 correspond to the Rapids City B and Morrison sections originally described by Frye et al. (1968); loess geochemical data for these sections are in Muhs and Bettis (2000). Pedon 8 is at the Greenbay Hollow loess section described by Hajic (1990) and Grimley et al. (1998); geochemical data are reported here for the first time. Organic matter, charcoal, and conifer needle macrofossils from the Rapids City B loess were processed for accelerator mass spectometric radiocarbon dating at the USGS graphite extraction line laboratory in Reston, VA. After preparation at the USGS, abundances of ^{14}C in the Rapids City B samples were determined at the Lawrence Livermore National Laboratory.

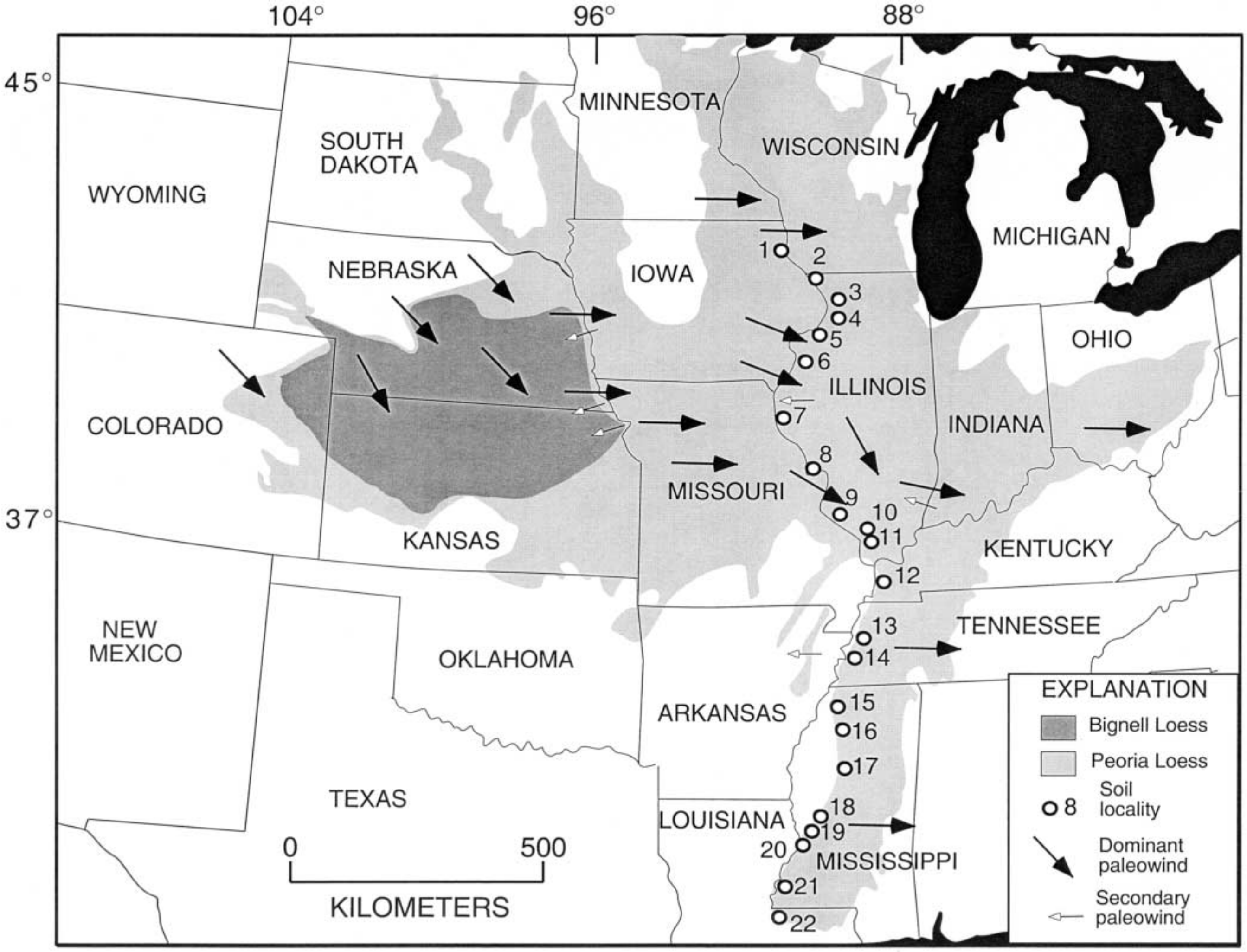

Fig. 1. Map showing the distribution of loess in the central USA, location of pedons sampled, and last-glacial paleowinds (Muhs and Bettis, 2000). Peoria Loess distribution slightly modified from Thorp and Smith (1952); Bignell Loess distribution compiled by the authors using data from Caspall (1972), Martin (1993), Johnson (1993), Kuzila (1995), Pye et al. (1995), and Muhs et al. (1999).

RESULTS

Loess Stratigraphy and Geochemistry

Loess stratigraphy and new radiocarbon ages agree well with previous studies of loess in the Mississippi River valley (Fig. 2 and 3). At the Rapids City B loess section in northern Illinois (Fig. 2), radiocarbon ages of the Farmdale soil, which underlies Peoria Loess, indicate that last-glacial loess deposition began sometime after ~23 000 ^{14}C yr BP and spruce (*Picea*) needles farther up in the section indicates Peoria Loess deposition was in progress by ~21 000 ^{14}C yr BP. Radiocarbon ages around clay-rich marker beds from a section ~37 km southwest of Greenbay Hollow reported by Grimley et al. (1998) indicate that Peoria Loess deposition was still in progress ~18 000 ^{14}C yr BP (Fig. 3). The youngest Peoria Loess deposition in Illinois may have occurred sometime after ~13 000 ^{14}C yr BP and could be as young as ~10 000 ^{14}C yr BP (Frye et al., 1968; Grimley et al., 1998; Wang et al., 2000). These ages are in reasonable agreement with ^{14}C and thermoluminescence ages of Peoria Loess reported from Tennessee, Arkansas, and Mississippi (Snowden and Priddy, 1968; Pye and Johnson, 1988; Oches et al., 1996; Rutledge et al., 1996; Rodbell et al., 1997; Markewich et al., 1998).

Comparison of deep, unweathered loess geochemistry in the Illinois sections with data reported by Pye and Johnson (1988) from localities in Mississippi shows that loess composition does not differ significantly in the northern and southern portions of the valley (Fig. 2, 3, and 4). Plots of individual samples of deep, unweathered loess show that concentrations of CaO, MgO, K_2O, Na_2O, Al_2O_3,and Fe_2O_3 in northern Mississippi Valley loesses (from Illinois) are similar to those in southern Mississippi Valley loesses, from sections at Vicksburg and Natchez (Fig. 4). Furthermore, both northern and southern Mississippi Valley loesses have distinctly different concentrations of CaO, MgO, Al_2O_3, and Fe_2O_3 than loesses found either to the west (Iowa) or the east (Indiana). Mean values and ranges for CaO/TiO_2, MgO/TiO_2, K_2O/TiO_2, Na_2O/TiO_2, Al_2O_3/TiO_2, and Fe_2O_3/TiO_2 are not significantly different among the northern Illinois (Rapids City B and Morrison) sections, the central Illinois (Greenbay Hollow) section, and the southern

Table 1. Morphology and major and trace element concentrations in Mississippi River valley loess-soil transect.†

			Color			Structure																			
Location	Horizon	Depth	moist	Texture	Grade	Size	Type	Bound	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	Fe_2O_3	MnO	TiO_2	P_2O_5	LOI	Rb	Sr	Y	Zr	Nb	Ba
		cm							%											Mg Kg^{-1}					
Pedon 22:	A	0–8	7.5YR 4/2	Sil	Mod	Med	Sbk	CS	80.6	6.34	0.36	0.24	0.63	1.63	2.29	0.17	0.692	0.13	5.7	55	88	41	627	15	574
St. Francisville, LA	E	8–24	7.5YR 5/4	Sil	Mod	Med	Sbk	CS	85	6.83	0.25	0.23	0.68	1.77	2.08	0.11	0.775	0.1	2.25	60	85	35	673	21	572
30°47.27′	Bt1	24–41	7.5YR 4/6	Sil	Mod	Med	Sbk	GS	76.3	10.7	0.25	0.64	0.57	1.99	4.2	0.08	0.771	0.2	3.6	88	84	31	507	18	589
91°22.44′	Bt2	41–72	7.5YR 4/4	Sicl	Mod	Med	Sbk	GS	74	12	0.25	0.79	0.58	1.85	5	0.1	0.787	0.21	4.7	82	84	27	462	35	544
	Bt3	72–104	7.5YR 4/4	Sicl	Mod	Med	Sbk		74.4	11.4	0.24	0.71	0.7	2.11	4.58	0.12	0.786	0.16	3.5	84	87	27	485	19	536
	Bt4	104–121	7.5YR 4/4	Sicl	Str	Fi	Sbk		74.6	11.1	0.27	0.7	0.8	2	4.43	0.1	0.786	0.15	4.2	83	101	28	490	25	554
Precipitation:	Bt5	121–145	7.5YR 5/4	Sil					76.4	11	0.29	0.71	0.87	2.04	4.49	0.08	0.82	0.14	3.2	77	102	31	508	24	571
1547 mm yr^{-1}	BC	145–157	7.5YR 5/4	Sil					75.6	10.9	0.3	0.68	0.91	2.13	4.25	0.07	0.792	0.13	3.05	83	106	32	502	22	554
Baton Rouge, LA	BC	157–176	7.5YR 4/3	Sil					76.6	10.8	0.35	0.68	1	1.88	4.25	0.07	0.797	0.12	3.3	69	116	29	509	33	532
	BC	176–185	7.5YR 4/3	Sil					76.5	10.5	0.39	0.66	1.09	2.13	4.03	0.07	0.773	0.12	2.55	74	117	29	507	18	532
	BC	185–198	7.5YR 4/3	Sil					76.8	10.4	0.42	0.66	1.09	2.03	4.16	0.07	0.783	0.11	3.55	78	123	27	509	24	549
	BC	198–208	7.5YR 4/3	Sil					77.8	10.4	0.45	0.65	1.14	1.88	4.14	0.07	0.795	0.11	2.4	68	134	29	508	18	533
	C	208–238	7.5YR 6/3	Sil					77.9	9.4	0.6	0.54	1.3	2.15	3.2	0.06	0.739	0.08	2.2	65	147	29	537	29	556
	C	238–268	7.5YR 4/4	Sil					79.6	9.17	0.59	0.54	1.18	2.03	3.2	0.06	0.707	0.08	2.1	69	141	26	504	15	525
Pedon 21:	A	0–5	10YR 3/2	Sil	Mod	Fi	Pl	AS	84.9	6.95	0.43	0.27	0.71	1.61	2.01	0.12	0.743	0.07	2.5	55	101	47	749	20	684
Natchez, MS	E	5–15	10YR 4/2	Sil	Mod	Med	Pl	CS	85.2	7.07	0.38	0.27	0.73	1.62	2.01	0.07	0.76	0.06	2.15	53	101	41	763	20	618
31°34.27′	BE	15–28	10YR 4/4	Sil	Mod	Med	Sbk	CS	79.7	9.3	0.39	0.43	0.67	1.79	3.19	0.05	0.773	0.08	3.8	76	98	30	615	23	606
91°18.97′	Bt1	28–52	7.5YR 4/6	Sil	Mod	Med	Pr	GS	76.5	10.8	0.4	0.65	0.66	1.78	4.04	0.06	0.752	0.1	3.35	71	99	24	483	21	631
	Bt2	52–85	7.5YR 4/6	Sicl	Mod	Med	Pr	GS	76.2	11.2	0.39	0.73	0.68	1.8	4.33	0.09	0.745	0.12	3.35	71	101	25	517	22	641
	Bt3	85–109	7.5YR 4/6	Sil	Mod	Co	Sbk	GS	75.5	11.5	0.4	0.8	0.81	1.82	4.55	0.12	0.723	0.12	3.3	81	105	24	464	22	630
Precipitation:	Bt4	109–132	7.5YR 4/6	Sil	Mod	Med	Sbk	GS	76.1	11.4	0.43	0.84	0.88	1.88	4.57	0.1	0.721	0.12	3.05	71	121	29	476	31	611
1537 mm yr^{-1}	BC	132–174	10YR 4/4	Sil	Wk	Co	Sbk	GS	74.2	10.7	0.45	0.78	0.98	2.12	4.27	0.13	0.707	0.11	4.15	81	119	31	461	19	592
Natchez, MS	BC	174–215	10YR 4/4	Sil	Wk	Co	Sbk	GS	76	10.4	0.51	0.77	1.08	2.02	4.27	0.09	0.729	0.11	3.65	75	126	32	473	28	611
	C	215–257	10YR 5/4	Sil	Ms				76	10.2	0.57	0.77	1.16	2.09	4.09	0.09	0.725	0.12	3.5	83	140	31	475	30	631
	C	257–300	10YR 5/4	Sil	Ms				78	9.74	0.67	0.71	1.21	2.05	4.16	0.09	0.746	0.14	2.3	64	140	37	498	25	603
Pedon 20:	A	0–1	10YR 3/2	Sil	Wk	Fi	Gr	AS	72.1	6.99	0.88	0.38	0.71	1.46	2.33	0.11	0.703	0.14	14.3	53	120	25	645	17	621
Vicksburg, MS	E	1–7	10YR 4/3	Sil	Wk	Fi	Sbk	CS	78.8	7.63	0.37	0.4	0.79	1.68	2.67	0.04	0.735	0.09	4.75	58	103	26	698	20	558
32°24.46′	BE	7–31	10YR 4/4	Sil	Wk	Med	Sbk	CS	80.9	8.08	0.33	0.41	0.77	1.86	2.75	0.06	0.74	0.1	2.8	70	95	28	675	18	611
90°49.30′	Bt1	31–53	7.5YR 4/4	Sil	Mod	Co/med	Sbk	GS	75	11.6	0.42	0.8	0.65	1.81	4.8	0.06	0.754	0.21	3.95	77	105	30	509	20	660
	Bt2	53–78	7.5YR 4/3	Sil	Mod	Med	Sbk	GS	73.1	11.9	0.46	0.81	0.73	1.84	5.01	0.1	0.728	0.22	4.05	68	107	25	456	41	606
	Bt3	78–94	7.5YR 4/3	Sil	Mod	Co/med	Sbk	GS	76	11.3	0.47	0.79	0.9	1.73	4.66	0.12	0.736	0.2	3.2	65	125	28	512	20	638
Precipitation:	Bt4	94–111	7.5YR 4/3	Sil	Mod	Med	Sbk	GS	74.5	11.1	0.44	0.79	0.98	1.94	4.27	0.09	0.725	0.15	3.2	70	121	26	481	22	621
1417 mm yr^{-1}	BC	111–127	10YR 5/4	Sil	Wk	Med	Sbk	GS	75.7	11.2	0.46	0.84	1.03	1.93	4.31	0.07	0.709	0.13	3	76	127	17	468	19	633
Vicksburg, MS	CB	127–161	10YR 4/3	Sil	Wk	Co	Sbk		76.4	11.3	0.5	0.85	1.1	1.95	4.17	0.09	0.703	0.13	3.05	67	133	31	455	20	707
	CB	161–195	10YR 4/3	Sil	Wk	Co	Sbk		77.1	10.8	0.6	0.85	1.17	1.85	4.03	0.09	0.692	0.11	2.65	67	154	34	478	19	713
	C	~350 cm	10YR 4/4	Sil					66.6	8.67	5.96	3.4	1.15	1.74	3.73	0.1	0.669	0.16	8.2	60	160	29	384	27	572
Pedon 19:	A	0–3	10YR 4/2	Sil	Wk	Fi	Gr	AS	82	5.95	0.55	0.22	0.74	1.54	1.73	0.06	0.738	0.08	6.45	48	106	27	852	27	547
Mechanicsville, MS	E	3–19	10YR 5/4	Sil	Wk	Med/fi	Pl	CW	85.1	6.44	0.33	0.25	0.73	1.6	1.88	0.04	0.748	0.07	2.45	57	101	29	837	21	552
32°38.88′	EB	19–25	10YR 4/4	Sil	Mod	Fi	Sbk	GS	81.3	9.08	0.29	0.45	0.69	1.63	3.01	0.03	0.743	0.12	3.15	61	97	30	645	20	614
90°31.54′	Bt1	25–42	7.5YR 5/4	Sil	Mod	Med/fi	Sbk	CS	79.6	10	0.31	0.55	0.66	1.61	3.5	0.05	0.735	0.14	3.2	66	99	31	591	19	607
	Bt2	42–66	7.5YR 4/4	Sil	Mod	Med	Pr	GS	73.2	12	0.39	0.77	0.73	1.81	4.8	0.07	0.735	0.19	3.8	74	108	26	475	21	630
	Bt3	66–95	7.5YR 4/4	Sil	Wk	Med	Pr	GS	75.6	11.5	0.45	0.81	0.9	1.94	4.47	0.1	0.734	0.17	3.45	68	123	28	483	18	650
Precipitation:	Bt4	95–122	7.5YR 3/3	Sil	Wk	Co	Sbk	GS	76.8	11	0.48	0.72	1.03	1.79	4.26	0.14	0.716	0.16	3.25	64	132	26	496	24	676
1475 mm yr^{-1}	BC	122–173	7.5YR 4/3	Sil	Wk	Co/med	Col	GS	76.1	10.3	0.59	0.7	1.16	1.94	3.96	0.13	0.708	0.13	2.75	67	151	32	521	21	703
Yazoo City, MS	C	173–230+	10YR 5/4	Sil	Ms				77.2	10.8	0.69	0.8	1.22	1.95	3.9	0.1	0.686	0.13	2.65	69	166	32	482	21	807
Pedon 18:	A	0–6	10YR 4/2	Sil	Wk	Med	Gr	CS	80.4	8	0.66	0.45	0.84	1.58	2.51	0.07	0.739	0.1	4.7	54	123	24	659	29	610
Yazoo County, MS	E	6–13	10YR 5/3	Sil	Mod	Med	Pl	CW	81.9	8	0.46	0.43	0.85	1.76	2.55	0.04	0.744	0.11	2.55	67	113	26	651	22	609
32°46.89′	Bt1	13–26	7.5YR 4/4	Sil	Mod	Med/fi	Sbk	GS	73	12.3	0.45	0.88	0.75	1.73	5.19	0.08	0.734	0.24	4.7	74	103	25	464	18	598
90°22.38′	Bt2	26–47	10YR 4/4	Sil	Mod	Med	Sbk	GS	74.6	11.7	0.44	0.81	0.9	1.85	4.91	0.1	0.727	0.22	3.8	84	112	24	490	22	605
	Bt3	47–66	10YR 4/4	Sil	Mod	Co	Sbk	GS	73.1	10.8	0.47	0.78	1.06	1.85	4.37	0.1	0.707	0.16	3.3	65	126	26	491	22	565
	Bt4	66–102	10YR 4/4	Sil	Mod	Co/med	Sbk	GS	76.4	11.1	0.54	0.87	1.16	1.84	4.2	0.07	0.7	0.13	2.95	70	139	30	485	19	657
Precipitation:	Bw	102–147	2.5YR 5/2	Sil	Mod	Co/med	Sbk	CS	77.3	10.6	0.73	0.84	1.28	1.82	3.88	0.08	0.704	0.12	2.65	64	161	35	491	27	747
1475 mm yr^{-1}	CB	147–170	10YR 4/3	Sil	Wk	Med	Sbk	CS	77.4	9.6	0.85	0.73	1.42	1.9	3.59	0.12	0.711	0.13	2.3	65	175	33	496	21	738
Yazoo City, MS	C	170–180+	10YR 4/4	Sil	Massive				76.8	10.5	0.94	0.88	1.35	1.77	4.32	0.11	0.687	0.15	2.7	60	177	33	452	18	761

Continued next page.

Table 1. Continued.

Location	Horizon	Depth	Color moist	Texture	Grade	Structure Size	Type	Bound	SiO$_2$	Al$_2$O$_3$	CaO	MgO	Na$_2$O	K$_2$O	Fe$_2$O$_3$	MnO	TiO$_2$	P$_2$O$_5$	LOI	Rb	Sr	Y	Zr	Nb	Ba
		cm							%											Mg Kg^{-1}					
Pedon 17:	A	0–5	10YR 5/4	Sil	Wk	Fi	Gr	CS	72.2	7.8	0.54	0.47	0.64	1.48	3.12	0.08	0.756	0.13	12.9	58	103	27	663	23	540
Greenwood, MS	E	5–26	10YR 5/4	Sil	Mod	Med/fi	Sbk	CW	83.1	7.1	0.25	0.32	0.65	1.65	2.59	0.05	0.782	0.06	2.7	62	91	32	766	20	542
33°30.14′	BE	26–36	10YR 5/4	Sil	Mod	Med/fi	Sbk	CS	75.5	11.4	0.2	0.77	0.54	1.78	4.87	0.04	0.77	0.14	4.1	78	87	27	518	26	605
89°57.12′	Bt1	36–93	7.5YR 4/4	Sil	Mod	Med/fi	Abk	GS	74.4	12.2	0.22	0.89	0.66	1.83	5.27	0.07	0.766	0.16	3.95	79	96	29	451	21	536
	Bt2	93–123	7.5YR 4/4	Sil	Mod	Med	Sbk	GS	75.6	11.1	0.28	0.8	0.91	1.85	4.82	0.1	0.793	0.13	3.3	71	108	32	488	17	559
	Bt3	123–162	7.5YR 4/4	Sil	Mod	Co/med	Sbk	CS	76	10.8	0.32	0.78	0.96	1.87	4.67	0.11	0.802	0.12	3.1	70	118	32	494	22	642
Precipitation:	BC1	162–200	10YR 5/4	Sil	Wk	Co	Sbk	GS	77.7	10.4	0.42	0.71	1.09	1.87	4.32	0.06	0.8	0.1	2.5	75	122	34	510	19	570
1428 mm yr^{-1}	BC2	200–241	10YR 5/4	Sil	V. wk	Co	Sbk	GS	77.3	9.86	0.58	0.69	1.2	1.79	4.1	0.07	0.804	0.1	2.35	62	149	38	536	21	646
Winona, MS	C	241–270	10YR 5/4	Sil	Ms				77.9	10.1	0.73	0.7	1.26	1.79	4.1	0.07	0.787	0.11	2.1	60	160	37	516	20	676
	C	293–298	10YR 5/4	Sil	Ms				78.2	9.99	0.98	0.71	1.41	1.88	3.79	0.08	0.747	0.11	2.15	58	192	31	515	20	763
	C	310–320	10YR 5/4	Sil	Ms				77.2	9.59	1.06	0.69	1.41	1.95	3.59	0.08	0.706	0.12	2	59	187	27	510	23	709
Pedon 16:	A	0–7	10YR 3/2	Sil	Wk	Med	Gr	AS	82	7	0.41	0.23	0.72	1.52	1.97	0.25	0.778	0.09	5.15	53	105	49	669	28	749
Batesville, MS	E	7–24	10YR 4/4	Sil	Mod	Med/fi	Gr	CW	83.6	7.26	0.28	0.2	0.7	1.6	1.86	0.16	0.792	0.07	2.7	56	98	43	643	25	628
34°14.31′	BE	24–45	10YR 5/4	Sil	Mod	Fi	Sbk	CS	79	8.63	0.24	0.34	0.68	1.77	2.46	0.07	0.787	0.07	2.5	67	103	26	572	25	1180
89°56.29′	Bt1	45–59	10YR 5/4	Sil	Mod	Med/fi	Sbk	GS	77.7	10.6	0.24	0.61	0.65	1.83	3.73	0.1	0.8	0.1	3.3	72	96	23	505	27	667
	Bt2	59–87	10YR 4/4	Sil	Mod	Med	Sbk	GS	74.6	11.4	0.28	0.82	0.68	1.88	4.59	0.11	0.781	0.14	3.55	74	105	24	461	22	710
	Bt3	87–122	10YR 4/4	Sil	Mod	Med	Pr	GS	75.8	10.5	0.3	0.74	0.82	1.82	4.32	0.11	0.802	0.13	3.3	69	110	27	496	22	884
Precipitation:	BC	122–162	10YR 5/4	Sil	Mod	Co/med	Sbk	GS	75.5	10.8	0.34	0.77	0.9	1.86	4.64	0.14	0.803	0.13	2.95	70	111	28	490	21	706
1455 mm yr^{-1}	C	162–210+	10YR 4/4	Sil	Ms				76.7	10.5	0.53	0.72	1.15	1.91	4.41	0.09	0.814	0.11	2.75	75	138	34	499	20	557
Batesville, MS																									
Pedon 15:	A	0–3	10YR 3/2	Sil	Wk	Fi	Gr	AS	56.7	6.34	1.04	0.28	0.55	1.47	2.22	0.19	0.648	0.13	27.3	54	115	18	500	19	541
Senatobia, MS	E	3–35	10YR 5/4	Sil	Wk	Med/fi	Sbk	CW	81	7.42	0.29	0.31	0.75	1.76	2.52	0.06	0.805	0.07	3.85	67	94	35	768	26	531
34°37.22′	BE	35–47	10YR 5/4	Sil	Mod	Med/fi	Sbk	CS	75.7	10.9	0.2	0.64	0.59	1.77	4.18	0.04	0.794	0.12	4	74	83	34	513	21	667
90°04.03′	Bt1	47–79	10YR 5/4	Sil	Mod	Med	Sbk	GS	72.3	12.3	0.2	0.84	0.56	1.74	5.31	0.05	0.784	0.16	4.5	76	92	28	432	21	581
	Bt2	79–122	10YR 5/4	Sil	Mod	Med	Sbk	GS	72.1	11.3	0.25	0.81	0.75	1.75	5.05	0.09	0.806	0.12	3.55	66	101	32	472	23	676
	Bt3	122–154	10YR 4/4	Sil	Mod	Co	Pr	CS	75.5	11.2	0.34	0.82	0.95	1.97	4.89	0.18	0.803	0.13	3.35	66	119	37	499	20	600
Precipitation:	BC1	154–214	10YR 4/4	Sil	Wk	Med	Pr	GS	76.2	11	0.42	0.85	1.06	2.01	4.78	0.09	0.836	0.1	2.7	66	121	38	484	18	621
1350 mm yr^{-1}	BC2	214–260	10YR 5/6	Sil	Wk	Co	Sbk	GS	76.3	10.3	0.57	0.74	1.24	2.03	4.16	0.07	0.81	0.1	2.65	70	145	38	511	19	603
Hernando, MS	C	280	10YR 5/4	Sil	Ms				78	9.67	0.69	0.66	1.35	1.99	4.08	0.08	0.794	0.11	2.15	64	154	35	530	19	603
	C	330	10YR 5/4	Sil	Ms				77.9	9.99	0.81	0.71	1.36	2.02	4.23	0.09	0.783	0.12	2.25	61	176	38	538	19	606
Pedon 14:	A	0–8	10YR 3/2	Sil	Mod	Med/fi	Gr	CS	78.9	7.23	0.54	0.32	0.84	1.87	2.23	0.11	0.764	0.1	5.7	66	114	32	728	19	604
Millington, TN	E	8–18	10YR 5/3	Sil	Mod	Med	Pl	CW	84	7.01	0.41	0.28	0.91	1.66	2.07	0.16	0.801	0.08	2.75	58	116	41	810	20	638
35°25.73′	EB	18–38	10YR 5/4	Sil	Mod	Med	Sbk	CW	82.2	7.84	0.38	0.33	0.95	1.87	2.21	0.11	0.774	0.09	2.1	68	117	32	659	23	668
89°48.37′	Bt1	38–58	10YR 5/4	Sil	Mod	Med/fi	Sbk	GS	74.5	11.4	0.42	0.73	0.8	2.12	4.45	0.09	0.762	0.23	3.5	94	108	27	482	25	689
	Bt2	58–82	10YR 5/4	Sil	Mod	Fi	Sbk	GS	73.9	11.8	0.38	0.84	0.83	2.18	4.77	0.09	0.745	0.16	3.65	85	108	25	448	24	624
	Bt3	82–104	10YR 5/4	Sil	Wk	Co	Pr	CS	74.8	11.7	0.38	0.92	0.92	2.01	4.81	0.16	0.741	0.15	3.5	79	120	27	451	23	624
Precipitation:	BC1	104–159	10YR 5/4	Sil	Mod	Co	Pr	GS	75.6	11.3	0.42	0.9	1.02	1.93	4.72	0.16	0.755	0.15	3.2	73	129	29	460	23	632
1323 mm yr^{-1}	BC2	159–172	10YR 4/4	Sil	V. wk	Co	Pr		75.5	11.2	0.46	0.87	1.06	1.99	4.84	0.09	0.763	0.14	2.8	75	131	32	458	23	637
Memphis, TN	BC2	172–185	10YR 4/4	Sil	V. wk	Co	Pr	GS	74.3	10.9	0.49	0.84	1.13	2.16	4.63	0.09	0.747	0.13	2.8	77	132	31	456	20	657
	C	185–225+	10YR 5/4	Sil	Ms				75.8	10.5	0.55	0.77	1.12	2.07	4.57	0.11	0.79	0.14	2.9	70	135	36	496	19	650
Pedon 13:	A	0–7	10YR 3/2	Sil	Mod	Med	Gr	CS	74.5	7.43	1.45	0.37	0.97	1.74	2.22	0.13	0.692	0.12	10.7	58	199	33	616	20	959
Lauderdale County, TN	E	7–14	10YR 4/2	Sil	Wk	Med	Pl	CS	81.2	7.81	0.59	0.35	1.05	1.96	2.2	0.12	0.702	0.1	3.5	68	127	36	653	24	656
35°51.26′	EB	14–31	10YR 5/3	Sil	Wk	Med/fi	Sbk	CS	81.5	8.48	0.56	0.4	1.09	2.01	2.43	0.14	0.729	0.12	2.8	67	129	40	604	17	744
89°33.05′	Bw	31–51	10YR 4/4	Sil	Mod	Med/fi	Sbk	CS	76.1	11	0.6	0.75	0.93	2.03	4.19	0.09	0.731	0.2	3.6	74	125	34	516	19	708
	Bt1	51–76	10YR 4/3	Sil	Mod	Med	Pr	GS	74.2	11.3	0.63	0.79	0.99	2.05	4.69	0.13	0.694	0.22	3.4	80	136	29	473	18	675
	Bt2	76–96	10YR 4/3	Sil	Mod	Co	Sbk	GS	75.6	11.2	0.64	0.78	1.09	2.09	4.38	0.14	0.697	0.18	3	72	142	31	482	18	672
Precipitation:	Bt3	96–143	10YR 5/4	Sil	Mod	Co	Col	GS	75.8	11.2	0.64	0.84	1.13	2.04	4.25	0.12	0.69	0.15	2.9	78	154	32	464	20	729
1275 mm yr^{-1}	BC	143–192	10YR 5/4	Sil	Wk	Co	Sbk	GS	75.9	11.2	0.76	0.85	1.21	2.06	4.22	0.12	0.662	0.18	2.8	84	157	35	448	22	769
Blythville, AR	C	192–210+	10YR 5/3	Sil	Wk	Co	Col		74.5	11	0.75	0.9	1.19	2.27	4.35	0.13	0.691	0.19	2.85	82	155	36	455	16	744

Continued next page.

Table 1. Continued.

Location	Horizon	Depth	Color moist	Texture	Grade	Structure Size	Type	Bound	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	Fe_2O_3	MnO	TiO_2	P_2O_5	LOI	Rb	Sr	Y	Zr	Nb	Ba
		cm							%											Mg Kg^{-1}					
Pedon 12:	A	0–7	10YR 4/2	Sil	Mod	Med	Gr	CS	75.4	7.82	0.68	0.43	0.83	1.92	2.58	0.12	0.717	0.12	7.8	74	114	26	586	18	603
Arlington, KY	E	7–18	10YR 4/3	Sil	Wk	Med	Pl	CW	80	9.14	0.36	0.47	0.87	1.95	2.96	0.1	0.766	0.09	3.3	73	100	33	595	20	607
36°46.93′	Bt1	18–42	10YR 5/4	Sil	Mod	Med/fi	Sbk	GS	75	11.8	0.34	0.85	0.75	1.94	4.68	0.08	0.772	0.13	3.7	78	106	30	453	21	638
89°02.57′	Bt2	42–63	10YR 5/4	Sil	Mod	Med	Pr	GS	73.5	11.5	0.31	0.86	0.86	2.09	4.7	0.11	0.745	0.13	3.6	84	97	25	434	19	570
	Bt3	63–85	10YR 5/4	Sil	Mod	Med	Pr	GS	74.8	11.4	0.33	0.87	0.91	1.98	4.81	0.1	0.768	0.13	3.2	77	106	27	438	17	606
	Bt4	85–128	10YR 5/4	Sil	Mod	Co	Pr	GS	76.1	11	0.38	0.87	1.03	1.89	4.91	0.12	0.795	0.13	2.9	68	123	29	489	21	568
Precipitation:	BC	128–169	10YR 5/4	Sil	Wk	Co	Pr		74.3	11.3	0.46	0.86	1.08	2	4.71	0.12	0.751	0.13	3.1	74	128	32	480	21	580
1234 mm yr^{-1}	BC	169–210	10YR 5/4	Sil	Wk	Co	Pr	GS	75.1	11.2	0.5	0.87	1.12	2.02	4.86	0.13	0.769	0.13	3.3	74	132	30	479	20	649
Charleston, MO	C	210–250+	10YR 5/4	Sil	Ms				78	9.78	0.61	0.7	1.2	2.01	4.29	0.07	0.815	0.12	2.6	62	149	38	555	20	574
Pedon 11:	Ap	0–14	10YR 4/4	Sil	Mod	Med	Sbk	AS	75.8	9.05	0.57	0.66	0.77	2.2	3.23	0.07	0.772	0.12	5.45	82	91	35	580	17	554
Anna, IL	AE	14–24	10YR 4/4	Sil	Mod	Med	Sbk	AS	76	9.02	0.61	0.67	0.76	1.98	3.24	0.08	0.778	0.12	4.85	80	93	34	575	17	576
37°22.50′	Bt1	24–31	10YR 4/4	Sicl	Mod	Med	Sbk	CS	70.8	11.8	0.57	0.92	0.71	2.32	4.67	0.07	0.767	0.13	5	92	89	29	408	18	551
89°07.50′	Bt2	31–42	10YR 4/4	Sicl	Mod	Med	Sbk	CS	71.3	12.3	0.57	1	0.71	2.08	5.1	0.08	0.77	0.14	4.75	90	93	29	388	15	554
	Bt3	42–60	10YR 4/6	Sicl	Mod	Med	Sbk	CS	70.4	12	0.5	1.01	0.82	2.32	5	0.11	0.763	0.13	4.6	89	101	29	396	17	534
	Bt4	60–80	10YR 4/6	Sicl	Mod	Med	Abk	CS	71.7	11.8	0.4	1.03	0.89	2.12	5.07	0.13	0.775	0.13	4.3	88	103	32	417	17	549
Precipitation:	Bt5	80–106	10YR 4/6	Sil	Mod	Med	Sbk	CS	73.6	11.5	0.36	0.99	1	2.28	4.62	0.15	0.786	0.12	3.4	88	117	31	447	19	588
1215 mm yr^{-1}	Bt6	106–127	10YR 4/6	Sil	Wk	Med	Abk	CS	73.2	11	0.37	0.95	1.07	2.4	4.44	0.11	0.797	0.11	3.55	85	117	31	446	16	562
Anna, IL	Bt7	127–160	10YR 4/6	Sil	Wk	Med	Abk		73.1	10.7	0.42	0.9	1.16	2.4	4.16	0.08	0.799	0.1	3.05	84	124	34	452	17	564
Pedon 10:	A	0–15	10YR 3/2	Sil	Str	Med/fi	Gr	GW	75.4	9.4	0.74	0.62	0.97	2.11	3.29	0.18	0.748	0.14	6.75	84	128	36	463	16	704
Murphysboro, IL	E	15–32	10YR 4/2	Sil	Str	Med	Gr	GW	77.3	8.87	0.56	0.56	1.07	2.47	2.62	0.18	0.751	0.12	4.5	82	123	37	474	17	705
37°46.44′	Bw	32–48	10YR 5/4	Sil	Mod	Med	Sbk	CS	74.3	10.7	0.48	0.8	0.94	2.42	3.71	0.11	0.755	0.17	4.25	96	116	30	422	18	681
89°21.52′	Bt1	48–66	10YR 5/6	Sicl	Str	Med	Sbk	GS	71.2	12.4	0.52	1.06	0.85	2.59	4.74	0.11	0.733	0.2	4.7	101	117	30	369	20	681
	Bt2	66–94	10YR 4/6	Sicl	Str	Co	Pr	GS	70.8	12.3	0.56	1.11	0.88	2.6	4.76	0.11	0.729	0.18	4.65	97	119	31	367	17	657
	Bt3	94–120	10YR 5/6	Sicl	Mod	Co	Pr	GS	71.8	12.2	0.55	1.07	0.94	2.26	4.8	0.11	0.742	0.17	4.35	93	124	34	390	17	615
Precipitation:	Bt4	120–136	10YR 5/6	Sicl	Mod	Co	Sbk	GS	71.8	12	0.55	1.05	1.01	2.53	4.62	0.18	0.744	0.15	4.3	92	128	34	398	16	627
1128 mm yr^{-1}	Bt5	136–170	10YR 5/6	Sicl	Mod	Co/med	Sbk		72.9	11.5	0.65	1.01	1.14	2.38	4.23	0.1	0.757	0.14	3.85	87	142	35	419	17	633
Carbondale, IL	BC	170–190	10YR 4/6	Sicl	Ms				73	11.4	0.73	1.01	1.2	2.37	4.3	0.09	0.752	0.14	3.9	84	153	36	409	15	746
	C	190–205	10YR 5/6	Sicl	Ms				74.5	11.1	0.84	0.92	1.28	2.21	4.09	0.09	0.752	0.14	3.45	84	156	34	434	14	590
	C	205–215	10YR 5/4	Sil	Ms				73.5	10.9	0.85	0.9	1.32	2.36	3.96	0.08	0.742	0.14	3.25	81	160	34	434	15	644
	C	215–225	10YR 5/4	Sil	Ms				74.4	10.8	0.89	0.88	1.34	2.35	3.92	0.09	0.743	0.13	3.2	87	162	30	438	14	606
	C	225–235	10YR 5/4	Sil	Ms				73.6	10.8	0.85	0.86	1.33	2.51	3.84	0.08	0.741	0.13	3.2	78	158	36	433	13	618
	C	235–245	10YR 5/4	Sil	Ms				76	10.9	0.89	0.89	1.33	2.27	3.97	0.09	0.759	0.13	3.25	80	159	34	439	14	627
Pedon 9:	A	0–5	10YR 3/2	Sil	Wk	Fi	Gr	GS	73.6	8.13	0.58	0.57	0.99	2.04	2.44	0.15	0.71	0.13	9.4	74	108	28	479	15	568
Ellis Grove, IL	AE	5–8	10YR 3/2	Sil	Wk	Fi	Pl	CS	78	9.07	0.35	0.63	1.06	2.11	2.83	0.09	0.745	0.1	4.65	80	111	30	487	19	597
38°00.79′	E	8–16	10YR 4/2	Sil	Wk	Fi	Pl	CS	81.5	8.14	0.3	0.48	1.05	2.03	2.33	0.14	0.737	0.07	2.85	77	106	31	522	17	610
89°54.48′	Bt1	16–40	10YR 5/4	Sicl	Str	Med	Pr	GS	79.6	9.03	0.28	0.62	1.02	2.37	2.7	0.07	0.744	0.07	2.95	82	107	30	480	19	595
	Bt2	40–55	10YR 5/6	Sicl	Str	Med	Pr		75.1	10.9	0.34	0.93	1	2.13	4.09	0.06	0.743	0.1	3.75	88	113	26	414	20	583
	Bt2	55–70	10YR 5/6	Sicl	Str	Med	Pr		69.3	12.6	0.5	1.16	0.99	2.23	5.31	0.05	0.709	0.12	4.9	91	113	25	349	18	527
Precipitation:	Bt3	70–85	10YR 5/6	Sicl	Str	Med	Pr		71.1	12.5	0.47	1.15	1.09	2.2	4.88	0.05	0.701	0.11	4.55	86	125	26	355	18	583
10.23 mm yr^{-1}	Bt3	85–100	10YR 5/6	Sicl	Str	Med	Pr		71.4	12.4	0.52	1.15	1.12	2.29	4.84	0.05	0.706	0.11	3.8	91	131	25	366	16	551
Red Bud, IL	Bt4	100–114	10YR 5/4	Sicl	Mod	Med	Sbk		70.2	11.9	0.61	1.09	1.24	2.38	4.57	0.06	0.7	0.1	4.2	80	144	28	386	18	588
	Bt5	114–125	10YR 5/4	Sicl	Mod	Med/fi	Sbk		72.1	12.1	0.68	1.16	1.27	2.08	4.76	0.06	0.708	0.1	4.6	82	156	28	401	17	738
	BC	125–138	10YR 5/4	Sicl	Wk	Fi	Sbk		72	11.3	0.85	1.1	1.42	2.3	4.14	0.14	0.721	0.12	3.65	81	173	32	411	15	794
	BC	138–148	10YR 5/4	Sicl	Mod/wk	Fi	Sbk		72.3	11.1	0.95	1.1	1.49	2.52	3.85	0.12	0.73	0.12	3.4	80	178	80	415	12	861
	C	148–160	10YR 5/4	Sil	Ms				73.6	10.9	0.98	1.08	1.51	2.39	3.82	0.1	0.729	0.13	3.25	81	176	41	423	15	798
	C	160–170	10YR 5/4	Sil	Ms				74.6	10.6	1.04	1.05	1.58	2.51	3.65	0.09	0.727	0.14	3.05	79	179	35	432	15	756
	C	170–180	10YR 5/4	Sil	Ms				73.6	10.5	1.09	1.03	1.59	2.49	3.61	0.09	0.722	0.15	2.8	77	181	36	437	15	684

Continued next page.

Table 1. Continued.

Location	Horizon	Depth	Color moist	Texture	Grade	Structure Size	Type	Bound	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	Fe_2O_3	MnO	TiO_2	P_2O_5	LOI	Rb	Sr	Y	Zr	Nb	Ba
		cm							%											Mg Kg^{-1}					
Pedon 8:	A1	0–5	10YR 3/3	Sil	Wk	Fi	Gr	C	79.1	7.97	0.85	0.37	1.33	2.12	2.23	0.09	0.76	0.19	4.5	62	151	27	620	17	580
Greenbay Hollow, IL	E	5–12	10YR 4/3	Sil	Mod	Fi	Pl	G	80.1	8.08	0.81	0.37	1.38	2.16	2.26	0.08	0.76	0.14	2.75	62	152	25	610	21	620
38°59.02′	EB	12–35	10YR 4/3,4/4	Sil	Wk	Med	Sbk	G	78.3	9.66	0.78	0.56	1.29	2.14	3.09	0.06	0.77	0.11	2.95	65	147	27	550	16	590
90°36.42′	Bt1	35–50	10YR 4/4,4/6	Sil	Mod	Med	Sbk	G	78.5	9.51	0.76	0.53	1.3	2.15	2.93	0.06	0.77	0.11	2.7	65	151	25	560	18	590
	Bt2	50–83	10YR 4/4	Sil	Mod	Med/fi	Abk	C	73.8	11.1	0.83	0.78	1.21	2.17	4.05	0.06	0.75	0.15	3.9	73	141	28	470	17	570
	Bt3	83–102	10YR 4/4	Sil	Mod	Med	Col	I	72.2	12.2	1	1	1.19	2.12	4.82	0.09	0.7	0.19	4.45	72	149	30	400	16	590
Precipitation:	Bt3	102–121	10YR 4/4	Sil	Mod	Med	Col	I	72.2	11.6	0.97	0.95	1.26	2.18	4.65	0.08	0.69	0.15	4.15	73	151	27	400	39	580
953 mm yr^{-1}	Bt4	121–141	10YR 4/6	Sil	Mod	Co	Col	G	72.5	11.3	0.96	0.97	1.26	2.34	4.64	0.08	0.69	0.14	4	74	150	30	400	24	570
St. Charles, MO	Bt4	141–172	10YR 4/6	Sil	Mod	Co	Col	G	74.5	10.8	1.03	0.89	1.31	2.38	4.6	0.09	0.67	0.19	3.3	71	150	33	410	14	570
	CB	172–200	10YR 5/4	Sil	Wk	Co/med	Sbk	G	75.5	10.5	1.1	0.86	1.35	2.13	4.56	0.1	0.7	0.18	3.25	70	153	32	410	16	580
	CB	200–230	10YR 5/4	Sil	Wk	Co/med	Sbk	G	75.3	9.39	2.05	1.37	1.34	2.27	3.93	0.09	0.67	0.14	3.45	63	165	29	420	14	480
	C1	230–260	10YR 5/4,6/4	Sil	Ms				59.5	7.58	8.33	5.51	1.1	1.99	3.3	0.08	0.56	0.13	12.4	55	136	23	330	11	430
	C1	260–290	10YR 5/4,6/4	Sil	Ms				59	7.37	8.54	5.55	1.16	2.01	3.19	0.08	0.55	0.13	12.6	52	141	25	330	12	390
	C1	290–334	10YR 5/4,6/4	Sil	Ms				57.6	7.15	8.99	5.8	1.1	2.01	3.08	0.07	0.54	0.12	13.4	54	135	25	330	10	400
Pedon 7:	A	0–11	10YR 3/2,4/2	Sil	Mod	Co	Sbk	C	75.6	8.47	1.11	0.46	1.2	2.18	2.64	0.13	0.726	0.16	6.25	77	151	28	546	17	645
Quincy, IL	E	11–21	10YR 4/2,4/3	Sil	Wk	Med	Pl	C	79.5	8.74	0.87	0.46	1.24	2.1	2.67	0.13	0.748	0.12	3.45	80	158	28	564	22	672
39°57.52′	EB	21–30	10YR 5/3	Sil	Mod	Med/fi	Pr	G	78.6	9.39	0.81	0.53	1.23	2.21	2.94	0.08	0.753	0.1	2.95	87	150	23	532	20	620
91°21.11′	Bt1	30–38	10YR 4/4	Sil	Mod	Med	Pr	G	76	10.6	0.8	0.69	1.16	2.27	3.73	0.07	0.754	0.1	2.95	84	136	22	488	17	640
	Bt2	38–59	10YR 4/4	Sicl	Mod	Med	Pr	C	73.9	12	0.83	0.92	1.08	2.12	4.73	0.07	0.746	0.13	3.5	82	145	22	445	21	650
	Bt3	59–105	10YR 4/3	Sicl	Mod	Co	Pr	G	71.5	12.3	0.88	0.99	1.08	2.04	4.89	0.08	0.703	0.14	3.7	76	155	24	413	20	598
Precipitation:	Bt4	105–146	10YR 5/4	Sicl	Mod	Co	Pr	G	71.7	12.1	1.01	0.99	1.22	2.04	5	0.12	0.734	0.16	4.05	72	165	33	396	22	688
1007 mm yr^{-1}	Bt5	146–169	10YR 5/4	Sicl	Wk	Co	Pr	G	73.5	11.5	1.08	0.94	1.31	2.25	4.57	0.08	0.707	0.15	2.75	78	173	32	409	17	643
Quincy, IL	Bw1	169–190	10YR 5/4	Sil	Wk	Co	Pr	G	73.7	11.2	1.14	0.9	1.38	2.34	4.46	0.11	0.731	0.16	2.7	82	172	35	440	17	623
	Bw2	190–215	10YR 5/4	Sil	Wk	Co	Sbk	G	73.9	11.6	1.13	0.98	1.27	2	4.55	0.11	0.759	0.16	3.35	73	179	31	438	36	685
	CB	215–226	10YR 5/4	Sil	Ms			G	74.2	11.1	1.11	0.88	1.3	2.24	4.29	0.09	0.782	0.15	2.7	87	177	34	485	18	629
	C	226–262	10YR 5/4	Sil	Ms				75.6	11	1.15	0.9	1.32	2.23	4.21	0.08	0.785	0.14	2.55	75	183	33	468	20	646
Pedon 6:	Ap	0–14	10YR 4/2	Sil				A	77.1	8.47	0.93	0.43	1.25	2.06	2.39	0.19	0.733	0.12	5.3	73	149	24	530	33	693
Mammoth, IL	AE	14–19	10YR 3/2	Sil	Wk	Med	Sbk	C	77.8	8.53	0.95	0.43	1.27	2.02	2.36	0.22	0.742	0.09	4.35	80	160	25	541	27	695
40°57.84′	E	19–27	10YR 4/3	Sil	Mod	Med	Pl	G	78.9	9.19	0.85	0.49	1.27	2.1	2.69	0.16	0.754	0.07	2.75	79	155	29	540	22	692
90°39.20′	BE	27–34	10YR 4/3	Sil	Mod	Med/fi	Sbk	G	76.7	10.3	0.84	0.65	1.2	2.23	3.38	0.11	0.745	0.08	2.6	93	148	27	496	18	682
	Bt1	34–65	10YR 4/3	Sicl	Mod	Med	Pr	G	72.6	12.1	0.86	0.94	1.11	2.21	4.57	0.08	0.727	0.14	3.5	89	142	26	414	26	647
	Bt2	65–97	10YR 4/4	Sicl	Mod	Co	Pr		70.8	12.4	0.93	1.06	1.07	2.03	4.89	0.1	0.693	0.16	5.05	89	155	30	390	19	648
Precipitation:	Bt2	97–129	10YR 4/3	Sicl	Mod	Co	Pr	G	71.3	12.3	1.01	1.05	1.15	1.98	4.94	0.11	0.694	0.17	4.75	77	161	33	387	20	671
942 mm yr^{-1}	Bt3	129–162	10YR 4/3	Sil	Wk	Co	Pr		73.9	11.9	1.11	1.1	1.22	2.06	4.86	0.11	0.734	0.18	3.1	75	163	33	392	26	732
Monmouth, IL	Bt3	162–196	10YR 4/4	Sil	Wk	Co	Pr	G	73.3	11.6	1.09	1.01	1.23	2.23	4.76	0.11	0.708	0.16	2.9	85	170	37	402	16	669
	CB	196–245	10YR 4/4	Sil	Wk	Co	Sbk	G	75.5	10.9	1.12	0.93	1.23	2.04	4.35	0.1	0.74	0.15	2.9	69	173	35	482	41	599
	C1	245–310	10YR 4/4	Sil	Ms			G	76.1	10.1	1.14	0.76	1.33	2.07	3.69	0.08	0.748	0.13	2.35	72	167	32	548	17	585
	C2	310–340	10YR 4/4	Sil	Ms				73.1	10.2	2.19	1.57	1.19	2.14	3.97	0.08	0.79	0.13	3.9	79	147	26	414	16	530
Pedon 5:	Ap(A+E)	0–20	10YR 3/2	Sil	Str	Co/med	Gr		74.5	9.43	0.84	0.7	1.17	2.17	3.01	0.17	0.75	0.19	6.43	86	132	34	437	13	711
Rapids City, IL	Bt1	20–72	10YR 5/4	Sicl	Str	Med	Pr		71.3	12.1	0.73	1.07	1.02	2.09	4.54	0.06	0.7	0.19	5.7	83	134	29	391	15	628
41°34.02′	Bt2	72–95	10YR 5/6	Sicl	Wk	Co/med	Sbk		70	12.2	0.75	1.12	1.1	2.11	4.65	0.08	0.69	0.2	6.55	78	138	37	366	15	663
90°20.85′	Bt3	95–163	10YR 5/6	Sicl	Wk	Co/med	Sbk		72.5	11.4	0.92	0.99	1.26	2.06	4.42	0.09	0.69	0.21	4.72	74	159	40	439	14	643
	BC	200	10YR 5/4	Sil	Wk	Med/fi	Sbk		72.9	11.4	1.06	1.04	1.37	2.18	4.37	0.1	0.69	0.21	4.45	75	170	41	400	12	659
	BC	250	10YR 5/4	Sil	Wk	Med/fi	Sbk		67.7	9.25	4.09	2.87	1.32	2.04	3.7	0.11	0.65	0.22	7.64	63	158	31	415	11	546
Precipitation:	C	300	10YR 5/4	Sil	Ms				59.2	8	7.87	4.57	1.09	1.77	3.11	0.07	0.56	0.18	13.02	51	147	28	378	10	434
993 mm yr^{-1}	C	350	10YR 6/4	Sil	Ms				58.6	7.6	8.85	4.85	1.15	1.73	2.95	0.07	0.6	0.18	12.93	49	154	28	412	9	432
Moline, IL	C	400	10YR 6/4	Sil	Ms				57.7	7.58	9	4.86	1.05	1.77	2.9	0.07	0.57	0.16	14.05	50	143	26	372	9	395

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Table 1. Continued.

Location	Horizon	Depth	Color moist	Texture	Grade	Structure Size	Structure Type	Bound	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	Fe_2O_3	MnO	TiO_2	P_2O_5	LOI	Rb	Sr	Y	Zr	Nb	Ba
		cm							%											Mg Kg^{-1}					
Pedon 4:	Ap	0–19	10YR 3/2	Sil	Str	Co/med	Gr		75.4	8.32	0.78	0.48	1.25	2.01	2.49	0.15	0.73	0.15	7.78	78	147	35	504	11	654
Morrison, IL	EB	19–26	10YR 4/3	Sil	Str	Co/med	Gr		77.6	9.39	0.72	0.59	1.29	2.13	2.78	0.11	0.77	0.12	3.85	74	138	32	488	15	660
41°49.02′	Bt1	26–38	10YR 5/4	Sicl	Str	Fi	Abk		75.1	10.5	0.74	0.73	1.21	2.09	3.46	0.08	0.76	0.12	4.68	78	136	28	444	12	652
89°57.94′	Bt2	38–71	10YR 5/6	Sicl	Str	Med	Abk		71.5	12	0.82	0.98	1.14	2.02	4.59	0.06	0.72	0.16	5.4	73	137	30	406	14	622
	Bt3	71–97	10YR 5/6	Sicl	Str	Co	Abk		73	11.3	1.01	0.88	1.33	1.96	4.34	0.08	0.65	0.19	4.87	63	160	32	437	12	592
	Bt4	97–129	10YR 4/6	Sil	Wk	Co	Col		75.6	10.4	1.16	0.78	1.5	1.96	3.71	0.08	0.61	0.18	3.46	62	178	34	443	9	605
Precipitation:	BCt	129–176	10YR 4/6	Sil	Wk	Co	Col		76.5	10	1.25	0.73	1.57	1.99	3.45	0.08	0.61	0.18	3.04	62	189	30	482	12	598
936 mm yr^{-1}	C1	176–213	10YR 5/4	Sil	Ms				77.5	9.59	1.32	0.72	1.63	2	3.23	0.08	0.58	0.18	2.45	62	196	32	467	10	554
Morrison, IL	C1	213–250	10YR 5/4	Sil	Ms				73.6	9.36	2.76	1.67	1.49	2	3.27	0.08	0.61	0.19	4.76	59	182	32	470	10	582
Pedon 3:	Ap	0–20	10YR 4/2-3/2	Sil			Pl	A	78.6	9.15	0.83	0.55	1.15	2.04	2.76	0.17	0.723	0.1	3.9	85	136	24	547	20	664
Mt. Carroll, IL	BA	20–27	10YR 4/3	Sil	Wk	Med/fi	Sbk	C	74	11.5	0.8	0.87	1	1.88	4.16	0.1	0.716	0.1	3.45	95	155	29	480	26	583
42°11.11′	Bt1	27–46	10YR 4/4	Sil	Mod	Med	Pr	G	73.2	12.3	0.86	1	1	1.98	4.72	0.09	0.7	0.11	3.6	85	140	24	429	20	612
89°59.72′	Bt2	46–77	10YR 4/4	Sil	Mod	Co	Pr	C	73.2	12.5	0.9	1.1	1.11	1.97	4.92	0.09	0.697	0.14	3.4	75	159	31	435	19	623
	Bt3	77–86	10YR 4/4	Sicl	Mod	Co	Pr	G	71	12.2	0.95	1.1	1.09	2	4.91	0.1	0.674	0.13	3.85	78	150	30	417	20	589
	Bt4	86–107	10YR 4/4	Sicl	Mod	Co	Pr	G	72.4	12.3	0.91	1.07	1.11	1.97	4.81	0.1	0.685	0.13	3.5	80	153	33	421	19	635
Precipitation:	Bt5	107–132	10YR 4/4	Sil	Wk	Co	Pr	G	73.1	11.7	1.02	0.98	1.23	2.04	4.55	0.09	0.684	0.14	3.1	75	164	35	434	17	650
926 mm yr^{-1}	Bw	132–174	10YR 4/4-5/4	Sil	V. wk	Co	Col	G	73.4	11.2	1.07	0.95	1.25	2.06	4.64	0.12	0.72	0.14	3	70	164	33	455	18	595
Mt. Carroll, IL	BC	174–197	10YR 4/4-5/4	Sil	Ms			G	73.9	10.8	1.07	0.89	1.23	2.21	4.52	0.09	0.732	0.14	2.8	78	158	33	495	16	562
	C1	197–250	10YR 5/3-5/4	Sil	Ms				76.1	11	1.19	0.94	1.27	2.13	4.02	0.09	0.756	0.13	2.4	67	170	33	506	20	599
	C2	250–300	10YR 5/3-5/4	Sil	Ms				62	9.03	6.65	4.3	1.12	1.92	3.49	0.09	0.675	0.14	10.1	70	150	32	450	16	450
Pedon 2:	A	0–12	10YR 3/2	Sil	Mod	Med	Gr	C	75.4	7.93	0.93	0.41	1.18	1.96	2.2	0.18	0.664	0.14	7.15	81	148	21	504	21	660
Galena, IL	AE	12–22	10YR 4/2-4/3	Sil	Wk	Med	Sbk	G	80	8.31	0.79	0.41	1.24	1.92	2.23	0.19	0.684	0.09	3.85	83	149	22	526	17	680
42°26.22′	E	22–34	10YR 5/3-4/3	Sil	Mod	Med	Pl	G	80.4	9.12	0.78	0.49	1.19	1.96	2.59	0.12	0.687	0.06	2.4	77	152	24	524	18	687
90°30.46′	BE	34–49	10YR 5/4-4/4	Sil	Mod	Med	Sbk	G	77.7	10.3	0.84	0.65	1.15	1.91	3.41	0.1	0.687	0.07	3.2	75	153	23	485	19	668
	Bt1	49–79	10YR 4/4	Sicl	Mod	Med	Sbk	C	73.3	11.7	0.9	0.91	1.1	1.96	4.34	0.1	0.66	0.09	3.55	85	145	22	424	17	607
	Bt2	79–95	10YR 4/4	Sicl	Mod/str	Med	Sbk	C	73.4	12.1	1.01	1.02	1.15	1.86	4.64	0.1	0.661	0.13	4	72	155	13	412	16	603
	Bt3	95–110	10YR 4/6	Sicl	Mod	Co/med	Pr	G	72.3	12	1.09	0.97	1.29	2.03	4.62	0.07	0.642	0.15	3.3	75	163	29	411	15	615
Precipitation:	Bt4	110–150	10YR 4/6	Sicl	Mod	Co	Pr	G	73.3	12.2	1.21	1.01	1.29	1.8	4.57	0.1	0.642	0.15	3.7	77	180	30	423	27	661
904 mm yr^{-1}	Bt5	150–189	10YR 4/6	Sil	Wk	Co	Pr	G	72.9	11.6	1.21	1.04	1.29	2.15	4.22	0.11	0.65	0.15	3.15	81	175	34	412	21	665
Galena, IL	Bw1	189–209	10YR 5/6	Sil	V. wk	Co	Pr	C	73.6	11.6	1.28	1.02	1.31	2.06	4.13	0.12	0.641	0.16	2.9	79	183	29	409	18	673
	Bw2	209–229	10YR 5/6	Sil	V. wk	Co/med	Pr	C	74.6	11.1	1.47	0.94	1.41	1.82	3.82	0.09	0.642	0.17	3.1	67	194	27	453	21	644
	C1	229–260	10YR 5/4-5/6	Sil	Ms			G	65.9	10.1	4.51	2.93	1.3	1.86	3.58	0.07	0.613	0.16	7.25	78	184	25	386	31	565
	C2	260–303	2.5YR 5/4	Sil	Ms			C	62.7	9.48	6.16	3.62	1.25	1.92	3.83	0.1	0.592	0.15	9.1	73	173	25	363	23	505
	C3	303–350	2.5YR 6/2	Sil	Ms				60.8	8.89	7.76	4.04	1.22	2.01	2.76	0.06	0.606	0.13	10.8	73	162	24	361	13	476
Pedon 1:	A	0–9	10YR 3/2	Sil	Mod	Med/fi	Gr	G	71.7	8.08	0.99	0.63	1.22	2.19	2.26	0.16	0.647	0.13	7.75	77	137	28	452	15	640
Clayton County, IA	E1	9–29	10YR 4/2	Sil	Mod	Med/fi	Pl	G	77.6	8.66	0.66	0.63	1.29	2.33	2.43	0.19	0.698	0.1	3.55	84	140	29	483	18	676
42°59.00′	E2	29–48	10YR 4/2	Sil	Mod	Med	Pl	G	76.4	9.46	0.7	0.76	1.22	2.27	2.74	0.16	0.719	0.1	3.45	94	137	29	426	18	678
91°12.66′	Bt1	48–65	10YR 4/3	Sil	Mod	Med	Sbk	G	73.8	11.4	0.69	0.97	1.1	2.13	3.83	0.13	0.698	0.1	4.35	92	134	28	391	15	649
	Bt2	65–102	10YR 4/4	Sicl	Mod	Co/med	Pr	G	70.3	12.4	0.84	1.14	1.11	2.12	4.76	0.15	0.644	0.13	4.8	83	143	28	366	15	636
	Bt3	102–151	10YR 4/4	Sil	Mod	Co	Pr	C	70.3	12.1	0.94	1.09	1.25	2.13	4.49	0.1	0.634	0.14	3.85	89	160	28	383	14	629
Precipitation:	Bt4	151–211	10YR 4/4,4/6	Sil	Wk	Co	Pr	G	71.1	12.1	0.96	1.11	1.22	2.12	4.71	0.16	0.646	0.16	4.3	81	158	37	373	14	622
777 mm yr^{-1}	CB	211–263	10YR 5/4	Sil	V. wk	Co	Pr	G	73.8	11.2	1.14	1.03	1.43	2.09	4.09	0.12	0.671	0.16	3.3	73	179	32	405	14	627
Praire du Chien, WI	C1	263–296	10YR 5/4	Sil	Ms			G	72.8	10.9	1.21	0.99	1.49	2.37	3.96	0.09	0.697	0.15	3.25	77	179	35	433	15	552
	C2	296–364	10YR 5/3	Sil	Ms			C	74.5	10.8	1.53	1.16	1.49	2.25	3.38	0.07	0.714	0.13	3	73	176	34	452	16	513
	C3	364–390	10YR 5/2	Sil	Ms				66	9.54	5.09	3.38	1.39	2.07	2.48	0.03	0.667	0.12	7.95	65	168	32	438	13	458

† Abbreviations: A, abrupt; Abk, angular blocky; C, clear; Co, coarse; Col, columnar; Fi, fine; G, gradual; Gr, granular; Med, medium; Mod, moderate; Pl, platy; Pr, prismatic; S, smooth; Sbk, subangular blocky; Sicl, silty clay loam; Sil, silt loam; Str, strong; W, wavy; Wk, weak.

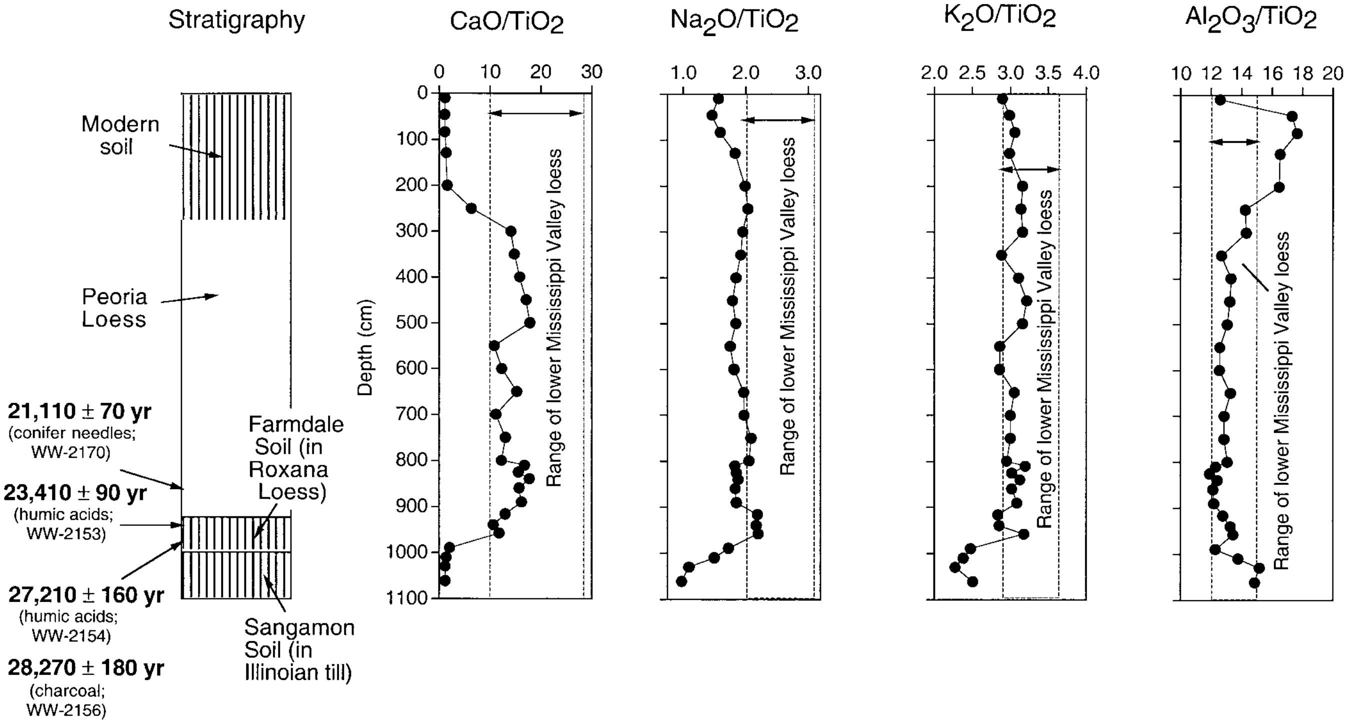


Fig. 2. Stratigraphy of Rapids City B, Illinois loess section (locality 5 on Fig. 1), new accelerator mass spectrometric (AMS) radiocarbon ages, major element ratios (data from Muhs and Bettis, 2000, except for TiO_2, reported for the first time here), and ranges of major element ratios in deep, unleached Peoria Loess from the southern Mississippi River valley (data from Pye and Johnson, 1988).

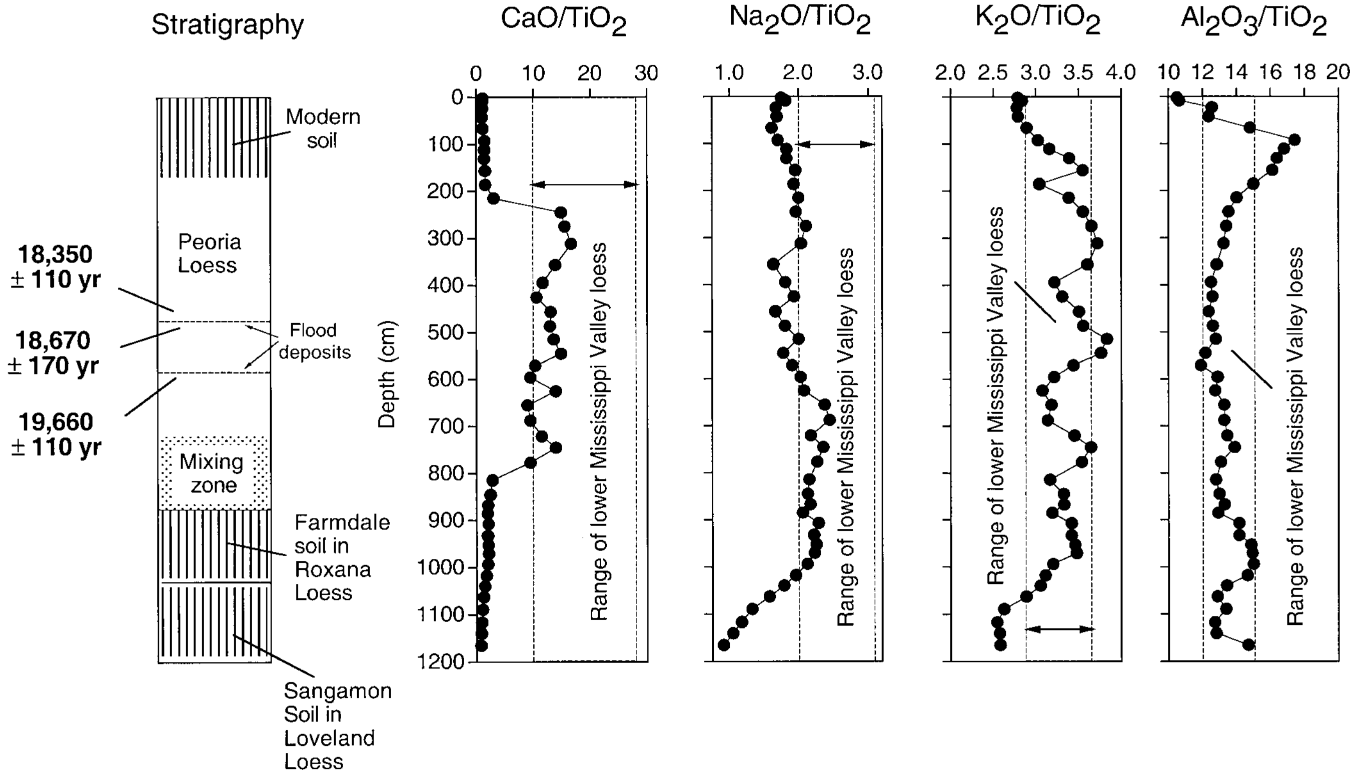
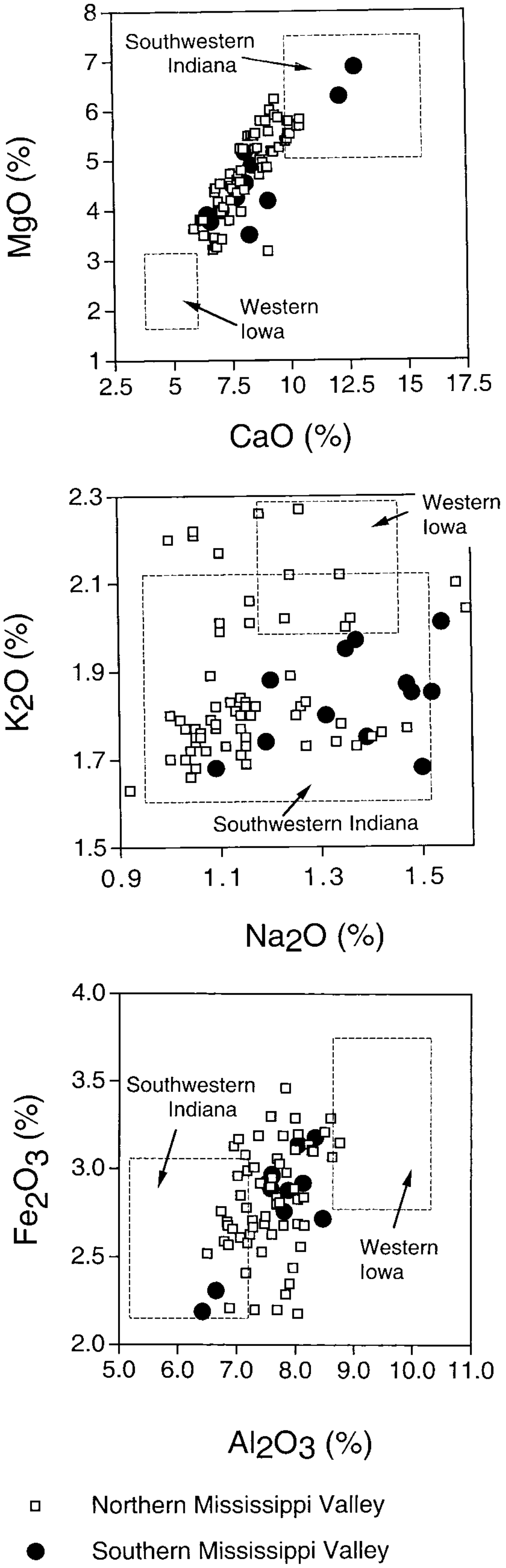


Fig. 3. Stratigraphy of Greenbay Hollow, Illinois loess section (locality 8 on Fig. 1), major element ratios (data from this study) and ranges of major element ratios in deep, unleached Peoria Loess from the southern Mississippi River valley (data from Pye and Johnson, 1988). Radiocarbon ages shown are from correlative flood deposits from a locality in adjacent Missouri and are from Grimley et al. (1998).

Mississippi (Natchez and Vicksburg) sections. We conclude, therefore, that loess composition (soil parent material) was initially similar throughout the valley and, based on the radiocarbon chronologies above, pedogenesis began at about the same time, perhaps around 13 000 to 10 000 ^{14}C yr BP.



Soil Morphology and Chemistry

Ruhe (1984b,c) reported that soils along the Mississippi River valley are thicker, redder, and lower in clay in the southern portion of the valley compared with the northern portion of the valley. Our observations are in agreement with some of the trends reported by Ruhe. Ruhe (1984b) reported that soil B horizon colors become redder, from 10YR to 7.5YR to 5YR as one moves from the north to south in the valley. Most northern valley pedons we studied have 10YR hues and most southern valley soils have 7.5YR hues (Table 1). This is in agreement with Ruhe's observations and loess soil studies by Lindbo et al. (1997) and Rhoton et al. (1998). The Bt horizons of most soils in the southern part of the valley are silt loams whereas many of the Bt horizons in soils of the northern part of the valley are silty clay loams. Geochemical evidence for higher clay content in northern valley soils, which we discuss below, is in agreement with Ruhe's observations. Ruhe (1984b,c) reported that sola in the southern valley are thicker than those in the northern valley. We tested this conclusion by detailed measurements of solum thickness. In our studies, we considered the solum depth to terminate where there was no evidence of subangular blocky, columnar, or prismatic structure (Table 1). This depth usually occurs well below where the deepest clay films occur. On the basis of this definition of solum thickness, we observed no systematic geographic relation for overall solum thickness. Soil Bt horizons, defined by those depths where there are well-defined clay films, are actually thicker in the northern valley (Fig. 5).

In soil climosequence studies, it is generally assumed that in regions with higher rainfall, there should be greater depletion of primary minerals (Birkeland, 1999, p. 430). We therefore compared soluble elements that proxy for primary minerals (Ca and Mg for calcite, dolomite, and other Ca- and Mg-bearing minerals such as hornblende, Na for plagioclase and hornblende, and K for mica) with Ti and Zr. Profile average CaO/TiO_2 shows an inverse relation to mean annual precipitation (Fig. 6). The coefficient of determination shows that the precipitation gradient explains about 75% of the variation in this weathering ratio. The same relation is obtained if Zr is used as the stable element instead of Ti. Profile average MgO values show similar trends and

Fig. 4. Plots of concentrations of CaO, MgO, K_2O, Na_2O, Al_2O_3, and Fe_2O_3 in deep, unweathered loess from the northern Mississippi Valley, the southern Mississipi Valley, western Iowa, and southwestern Indiana. Northern Mississippi Valley loess samples are Peoria loess from the Morrison, Rapids City B, and Greenbay Hollow sections in Illinois (this study); southern Mississippi Valley loess samples are unleached Peoria loess from the Vicksburg and Natchez sections, Mississippi reported by Pye and Johnson (1988). Shown for comparison are ranges of concentrations for the same elements from the Loveland, Iowa loess section (Muhs and Bettis, 2000), and the Mount Vernon, Indiana loess section (section described by Hayward and Lowell, 1993; geochemical data are from the present authors).

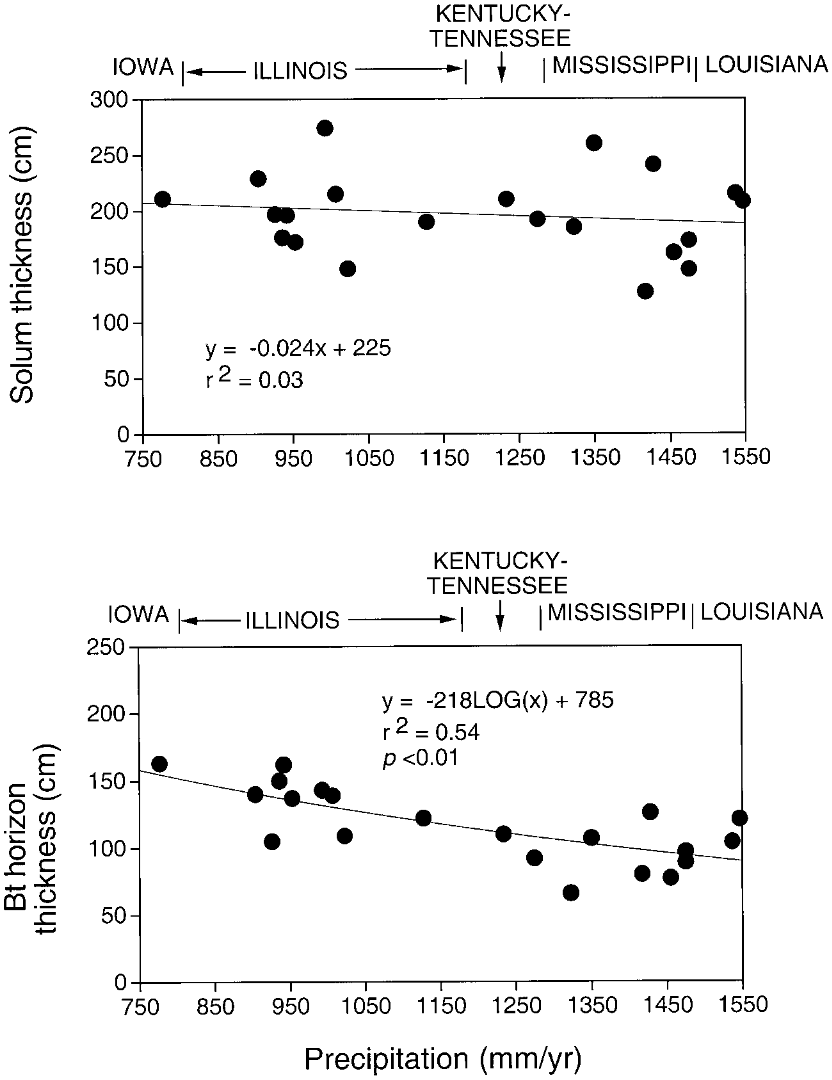


Fig. 5. Solum and Bt horizon thicknesses shown as a function of mean annual precipitation (1961–1990 means) in the transect.

a similar degree of explanation, whether we use Ti or Zr as the stable element (Fig. 6).

Plagioclase is the main Na carrier, and profile average Na_2O/TiO_2 values show a logarithmic decline with increasing precipitation (Fig. 7). Profile average Na_2O values, normalized to ZrO_2, also show a decline with increasing precipitation, although the relation is linear. Na_2O/ZrO_2 values have a high coefficient of determination that explains nearly 90% of the variability. The two primary minerals that are the main carriers of K are potassium feldspar and mica (biotite, muscovite, and illite). Profile average K_2O/TiO_2 and K_2O/ZrO_2 both show linear declines with increasing precipitation, although the coefficients of determination are not as high as for the other elements (Fig. 7). The lower coefficient of determination for K vs. precipitation could be because of the fact that K is found in both weatherable (mica) and resistant (potassium feldspar) minerals.

Concentrations of soluble trace elements, relative to stable Zr, are consistent with the major element weathering ratios (Fig. 8). Strontium substitutes for Ca in Ca-bearing minerals and shows a decline in abundance relative to Zr with mean annual precipitation. Both Ba and Rb substitute for K in potassium feldspar and mica and both elements show significant decreases in abundance with mean annual precipitation, although neither has the degree of explanation shown for K.

Ruhe (1984b) showed that profile average clay contents of loess-derived soils in the Mississippi River valley decrease with increasing precipitation. He attributed this counterintuitive finding to the effects of local sediment supply rather than any pedogenic process. Because total (as opposed to dithionite or oxalate-extractable) Al_2O_3 and Fe_2O_3 are highly correlated with clay content (Markewich et al., 1998; Mason and Jacobs, 1998; Muhs and Bettis, 2000), these values, normalized to TiO_2, tend to be highest in soil Bt horizons (Fig. 2 and 3; Table 1). Profile average Al_2O_3/TiO_2 and Fe_2O_3/TiO_2 values are thus indirect measures of profile average clay content. In our transect, profile average Al_2O_3/TiO_2 and $Fe_2O_3/$

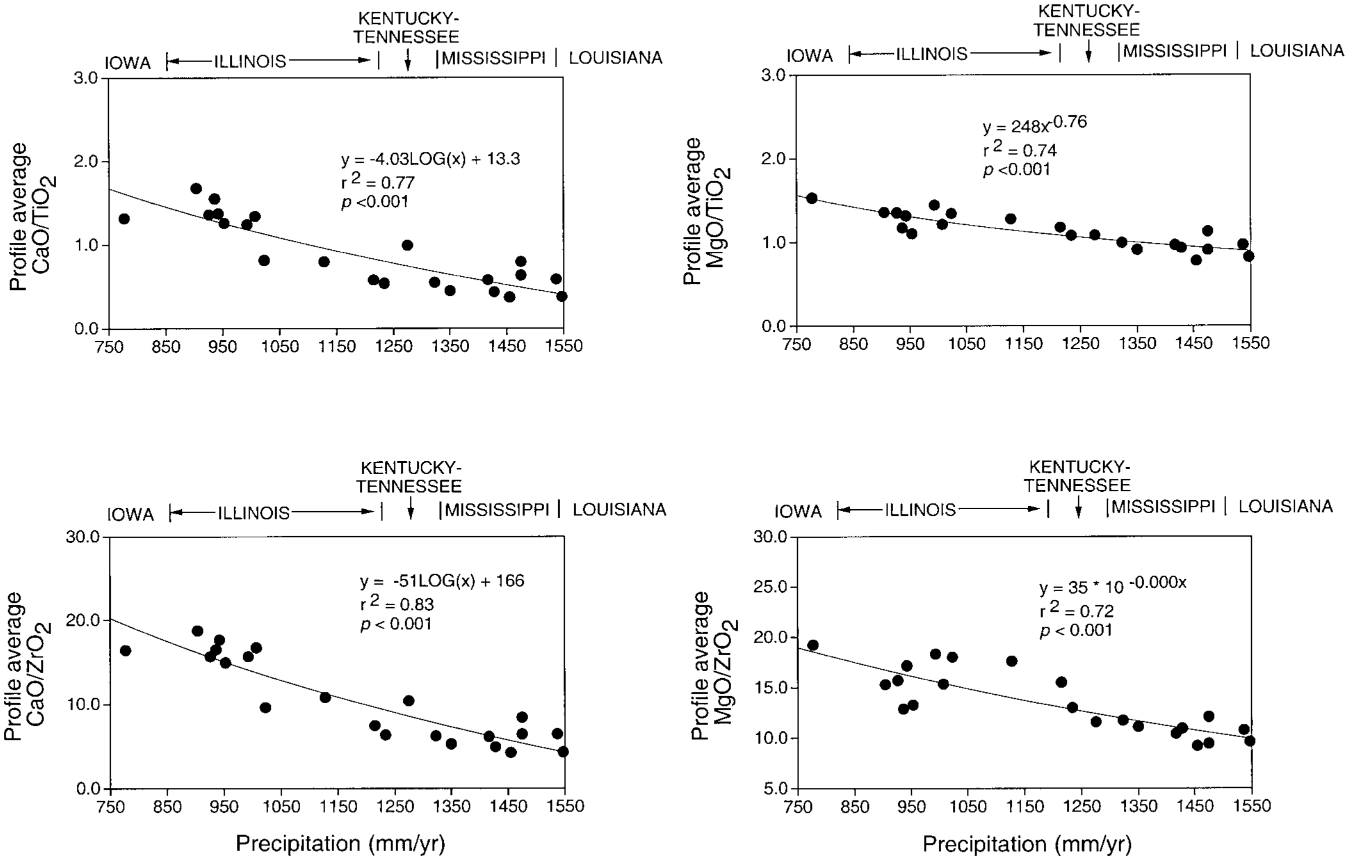


Fig. 6. Profile average values of CaO/TiO$_2$, MgO/TiO$_2$, CaO/ZrO$_2$, and MgO/ZrO$_2$ as a function of mean annual precipitation in the transect.

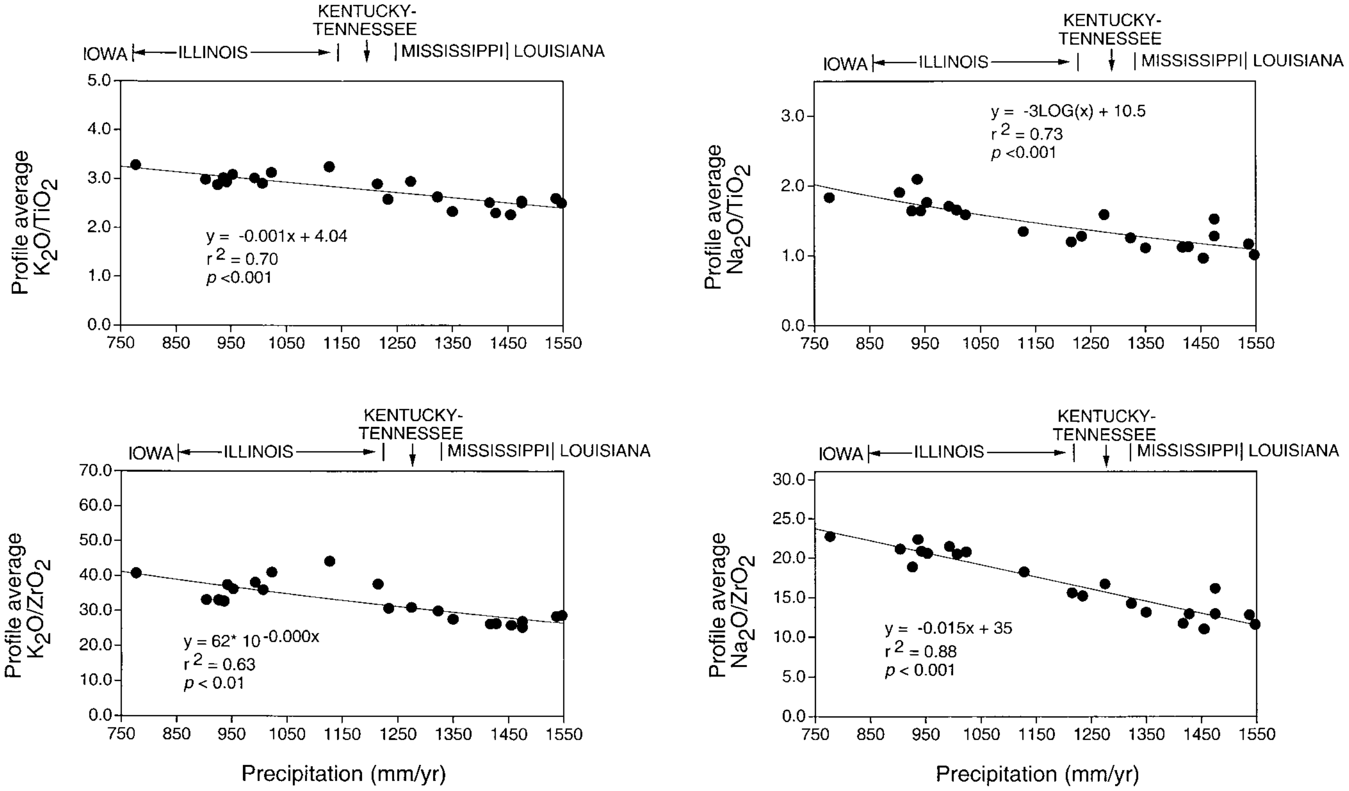


Fig. 7. Profile average values of K$_2$O/TiO$_2$, Na$_2$O/TiO$_2$, K$_2$O/ZrO$_2$, and Na$_2$O/ZrO$_2$ as a function of mean annual precipitation in the transect.

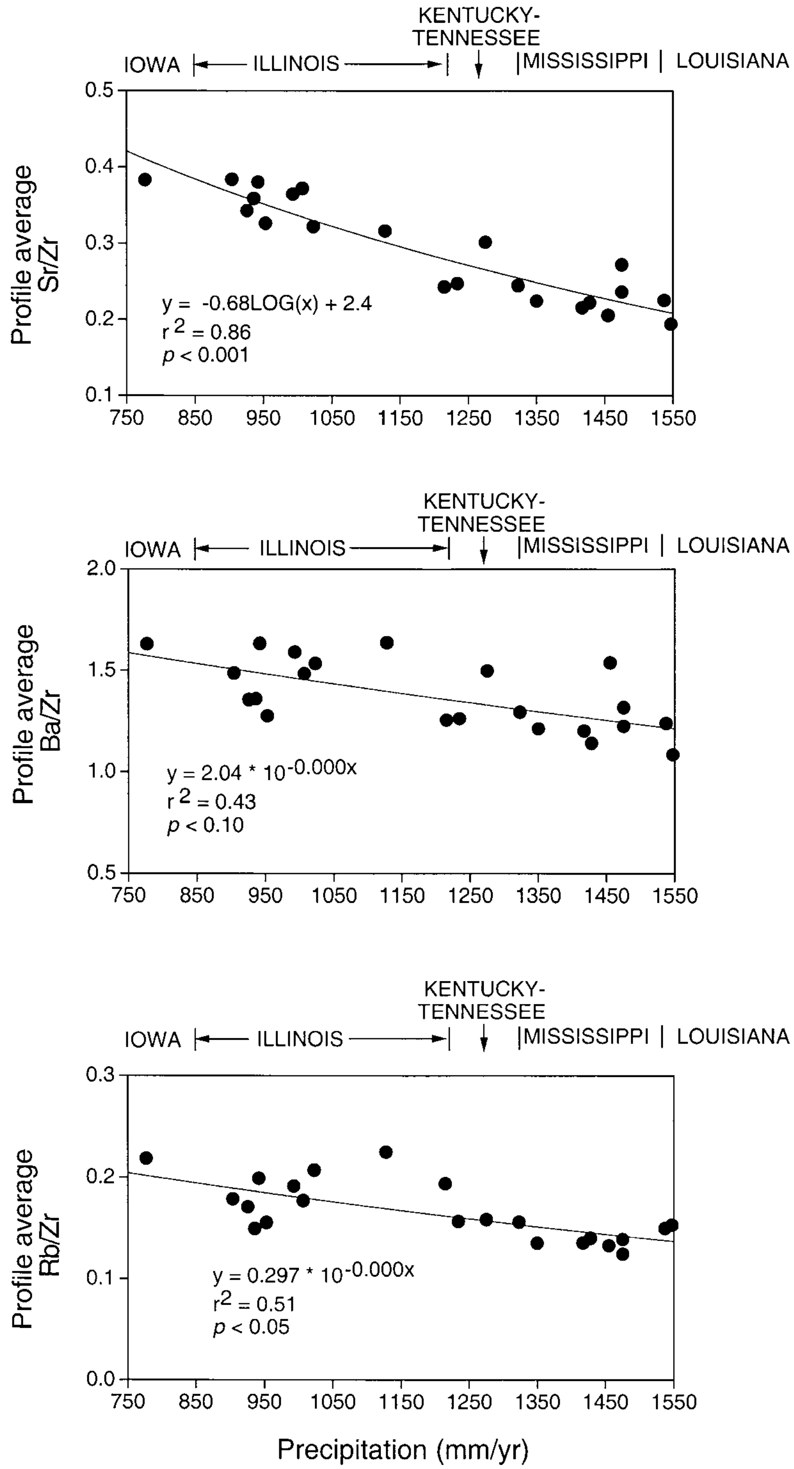


Fig. 8. Profile average values of Sr/Zr, Ba/Zr, and Rb/Zr as a function of mean annual precipitation in the transect.

TiO_2 values are negatively correlated with precipitation, in agreement with Ruhe's finding of higher clay contents in the northern part of the valley (Fig. 9).

DISCUSSION

Profile average values of CaO/TiO_2, MgO/TiO_2, K_2O/TiO_2, Na_2O/TiO_2, Sr/Zr, Ba/Zr, and Rb/Zr in loess-derived soils of the Mississippi River Valley all show decreases as a function of precipitation. The trends for the major elements are unchanged if Zr is used as a stable index element rather than Ti. Because these soils all lack carbonates, the systematic decreases in CaO/TiO_2 and Sr/Zr are probably because of greater depletion of noncarbonate, Ca-bearing minerals, such as hornblende or Ca-plagioclase in the southern part of the valley. Hornblende and biotite weathering might explain the similar trend for MgO/TiO_2 values.

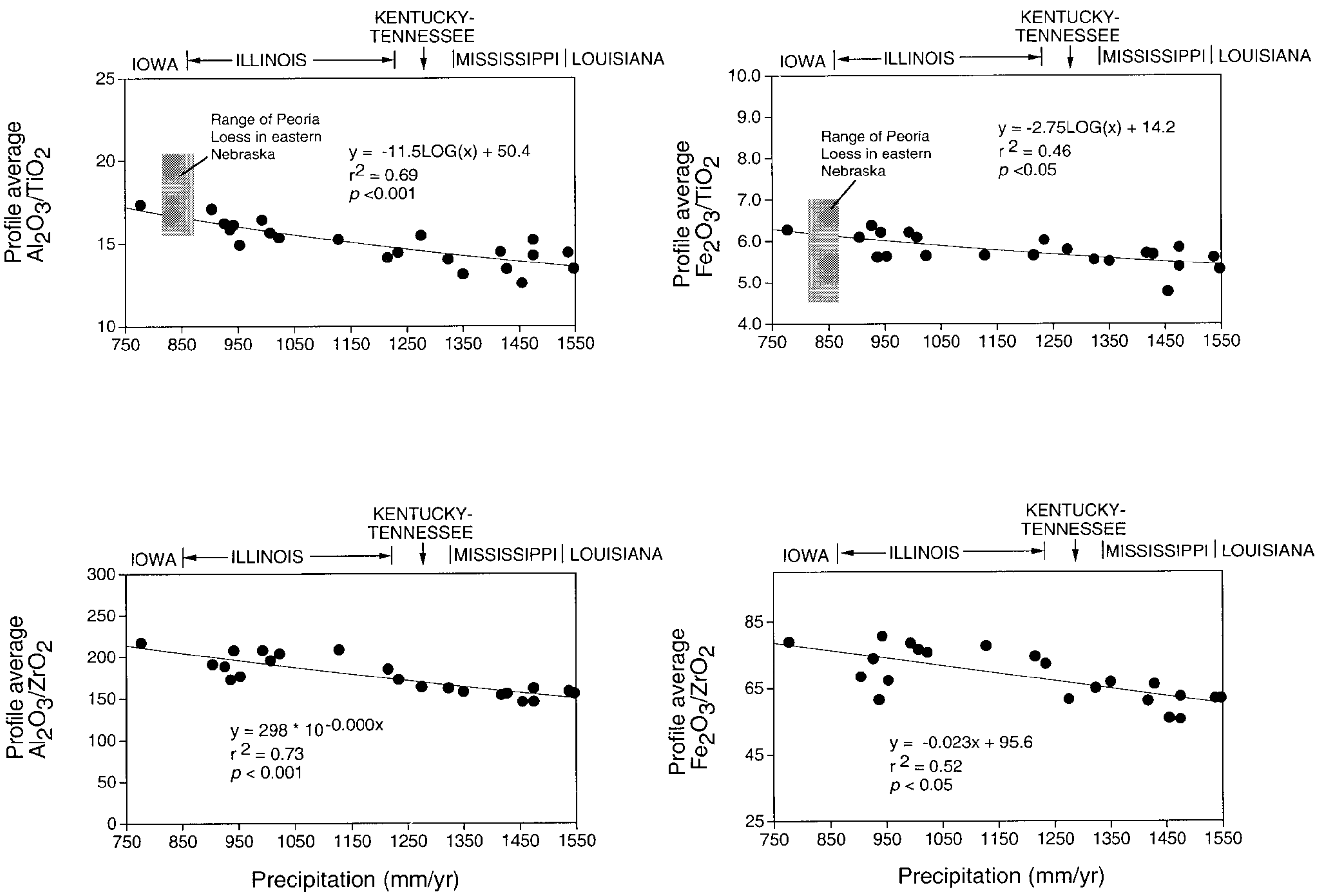


Fig. 9. Profile average values of Al_2O_3/TiO_2, Fe_2O_3/TiO_2, Al_2O_3/ZrO_2, and Fe_2O_3/ZrO_2 as a function of mean annual precipitation in the transect. Range of Al_2O_3/TiO_2 and Fe_2O_3/TiO_2 values in eastern Nebraska loess are from three localities (Plattsmouth, Lincoln, and Elba) reported by Muhs and Bettis (2000).

Both feldspars and micas are common primary minerals in Mississippi Valley loess (Snowden and Priddy, 1968; Pye and Johnson, 1988; Markewich et al., 1998). Previous studies suggest that plagioclase feldspar has undergone depletion in modern soils in at least the southern part of the valley (Krinitzsky and Turnbull, 1967; Pye and Johnson, 1988; and Markewich et al., 1998). The trend of decreasing Na_2O/TiO_2 with increasing precipitation supports these observations, although some of the Na depletion may also come from alteration of hornblende. Both potassium feldspar and mica are carriers of K, Ba, and Rb. Theoretical concepts of mineral stability (such as the Goldich stability series, discussed in Birkeland, 1999, p. 430) combined with empirical studies of rock and loess weathering (Colman, 1982, p. 51 and Markewich et al., 1998) suggest that potassium feldspar is a fairly stable mineral in midlatitude soils. Therefore, we interpret the declines in K_2O/TiO_2, Ba/Zr, and Rb/Zr as a function of increasing precipitation to be primarily the result of mica weathering. Mica is found in both the silt and clay fractions of Mississippi River Valley loess (Snowden and Priddy, 1968).

Many soil climosequence studies, including those conducted in loess, have shown an increase in clay content with increasing precipitation (Birkeland, 1999, p. 430). The usual interpretation of this trend is that greater precipitation produces greater chemical weathering of primary, silt-sized minerals and alteration to clay minerals. Because Ca, Mg, Na, and K all show depletions relative to either stable Ti or Zr in the more humid southern part of the Mississippi Valley, we would have expected that this part of the valley should also show higher clay contents, the usual products of chemical weathering. However, both Ruhe's (1984b) and our results show the opposite trend. Although local sedimentation variability (e.g., loess with higher clay contents at certain points along the transect) could explain this trend, a more random pattern of geographic variability might be expected. Furthermore, deep loess profiles in Illinois show Al_2O_3 concentrations and Al_2O_3/TiO_2 values similar to those in Mississippi (Fig. 2, 3, and 4). This is supported by Ruhe's (1984b) data, which show that clay contents in the C horizons of loess-derived soils have no systematic relation to latitude. We conclude from these observations that soils in the northern part of the Mississippi River Valley may have received secondary additions of clay-rich sediment, a conclusion also reached by Mason and Jacobs (1998), based on mass balance calculations of chemical data from modern, loess-derived soils.

As pointed out by Mason and Jacobs (1998), there could be at least two explanations for the clay enrichment in northern Mississippi Valley soils. One possibility is that during the final stages of Peoria Loess sedi-

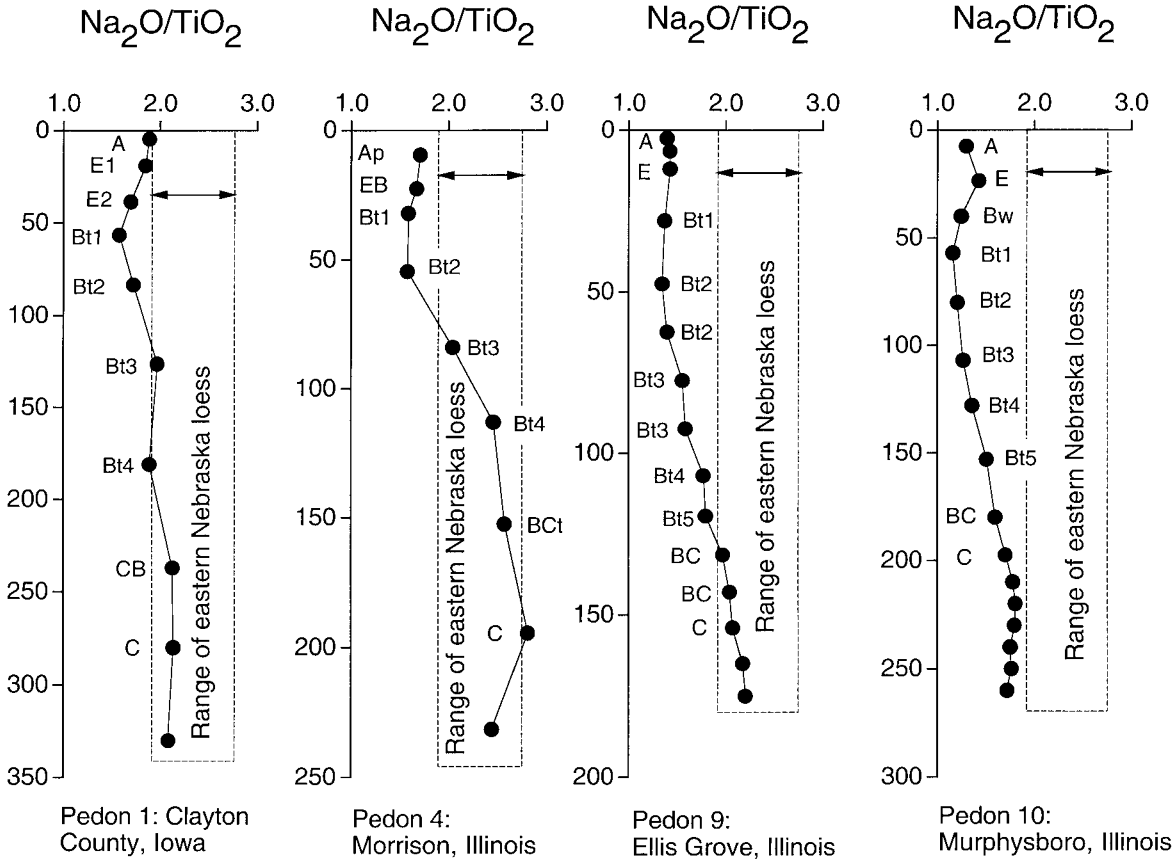


Fig. 10. Plots of Na_2O/TiO_2 values as a function of depth for four pedons in the northern part of the transect. Shown for comparison is the range of Na_2O/TiO_2 values for eastern Nebraska loess (three localities are Plattsmouth, Lincoln, and Elba).

mentation, fine-grained loess derived from a distant source (as well as coarse-grained loess from the local source) was deposited in the upper Mississippi Valley. Recent particle-size and geochemical data suggest that clay and fine silt-enriched dust from a source west of the Missouri River (most likely Nebraska) was deposited in western Iowa during the final stages of Peoria Loess sedimentation (Muhs and Bettis, 2000). It is possible that even finer-grained components of loess from this distant source, or from western Iowa, traveled as far east as western Illinois and added clay minerals enriched in Al and Fe to coarser-grained loess derived from the Mississippi River. Radiocarbon ages show that Peoria Loess deposition in Nebraska did not cease until ~10 500 ^{14}C yr BP (Maat and Johnson, 1996; Muhs et al., 1999), similar to or younger than the final stages of loess deposition in Illinois (Frye et al., 1968; Grimley et al., 1998). This hypothesis could be tested by Pb-isotope compositions of coarse silt, fine silt, and clay fractions of loess in northern Illinois, following the methods outlined by Aleinikoff et al. (1998, 1999).

Another explanation for the high clay mineral content of the northern valley soils is that there have been secondary, fine-grained dust additions to soil surfaces during the Holocene. There is stratigraphic and geochronologic evidence for Holocene loess deposition (referred to as the Bignell Loess; Fig. 1) in the Great Plains region of Nebraska, Kansas, and Colorado (Pye et al., 1995; Maat and Johnson, 1996; Muhs et al., 1999). Even where the Bignell Loess is not identified as a discrete stratigraphic unit in the field, both silt and clay mineralogical differences show that it comprises the upper part of modern soils in some areas of Nebraska (Kuzila, 1995). Because the Great Plains region lies upwind of the northern Mississippi River Valley (Fig. 1), fine-grained components of Bignell Loess could have traveled eastward to Illinois and Iowa. The sediment record from Elk Lake, MN contains Al-rich clays and fine silts that are interpreted to be distant-source eolian sediments that date from a mid-Holocene warm and dry period (Dean, 1997).

It is difficult to determine whether fine-grained eolian additions to soils of the northern Mississippi River Valley occurred during the last glacial period or the Holocene, and it is possible that deposition occurred during both periods. Use of immobile element ratios or Pb-isotopic compositions of potassium feldspars could identify a secondary source that is distinct from the local source, but such data say little about the timing of secondary, fine-grained dust additions. The addition of such material, however, most likely came from a source west of the Mississippi River. The distribution of both Pleistocene and Holocene loess to the west of the Mississippi River Valley and dominantly westerly modern winds and paleowinds (Fig. 1) could explain why soils in Illinois were affected by fine-grained dust additions, but soils south of Illinois were not.

Despite the possible freshening effect that fine-grained late-glacial or Holocene additions of loess may have had, northern valley soils nevertheless show evidence of chemical weathering. Ratios of Na_2O/TiO_2, a proxy for degree of plagioclase depletion, are shown as a function of depth for four pedons in the northern valley in Fig. 10; also plotted is the range of Na_2O/TiO_2 for unweathered loess in eastern Nebraska (same localities as those in Fig. 9). These plots show that in the upper horizons of all pedons, Na_2O/TiO_2 values are lower than the range of values for eastern Nebraska loess. Thus, even in the northern valley, where weathering rates may be slowest, the rate of plagioclase depletion has kept ahead of the rate of younger eolian accretion.

CONCLUSIONS

Profile average weathering ratios of mobile elements (Ca, Mg, Na, K, Sr, Ba, and Rb) to immobile elements (Ti and Zr) show that loess-derived soils of the Mississippi River Valley are more chemically weathered in the humid, southern part of the valley. Depletion of the primary minerals calcite, dolomite, hornblende, plagioclase, and mica are the likely causes of these chemical trends. Greater alteration of primary minerals in the southern part of the valley may be a function of higher rainfall and warmer temperatures, which promote greater chemical weathering.

If primary mineral weathering is greater in the humid southern part of the valley, clay mineral content is expected to be higher there than in the drier, northern part of the valley. Both Al and Fe are highly correlated with clay mineral content. Our studies indicate higher profile average Al and Fe relative to Ti or Zr in the northern part of the valley. These results, while unexpected, are consistent with similar chemical and particle-size data reported by other workers. The trend observed in this study suggests that the northern valley soils may have received fine-grained secondary additions of clay-sized particles from a distant source west of the Mississippi River, based on modern and paleowind directions. Testing of the distant-source hypothesis could be accomplished with Pb-isotopic analyses of different size fractions of the loess and soils (Aleinikoff et al., 1998, 1999).

Our results differ from those of Ruhe (1984b,c), who concluded that climate had little impact on modern loess-derived soils of the Mississippi River Valley and that soils in this region have experienced little chemical weathering. Primary mineral alteration is shown by a number of elemental ratios, and all show a high degree of correlation with mean annual precipitation. However, a trend of higher clay content with northern valley soils suggests that the assumption of a uniform parent material for all soils along the valley may not be valid. Thus, extreme care must be used in interpreting chemical data of paleosols for paleoclimatic interpretations. Nevertheless, the results indicate that major and trace element weathering ratios, when utilized with caution, could be useful paleoclimatic indicators in the interpretation of loess-derived paleosols, such as the Farmdale and Sangamon soils.

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