DIVISION S-5—SOIL GENESIS, MORPHOLOGY & CLASSIFICATION

Texture, Mineralogy, and Lamellae Development in Sandy Soils in Michigan

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ABSTRACT

The texture, mineralogy, and to a lesser extent topography, of some sandy soils in Michigan were examined to determine the possible genesis of lamellae in these soils. Differences in lamellae presence and depth were studied in four Haplorthods, one Argic Udipsamments, and one Psammentic Eutroboralf on a subtly undulating lake terrace in northern lower Michigan. Dolomite or feldspar weathering was not pronounced in these well-drained soils; one pedon retained substantial carbonates at depth, probably mainly within lamellae. Significant correlations (r) were observed between the depth to the uppermost textural band (an indication of the amount and development of lamellae for the entire profile) and profile-weighted contents of the following size separates: <50 μm (-0.82^{*}, significant at $P < 0.05$), < 125 μm (-0.92^{*}), 250–2 μm (-0.90^{*}), and 2000–500 μm (0.96^{**}, significant at $P < 0.01$). Correlations between clay content and depth to first *lamella were not significant* ($r = -0.72$), *suggesting that sandy pedons* dominated by fine sands and silts are more likely to have lamellae than are those with more clay. Clay inherited from the parent material was probably rapidly translocated downward to form lamellae; deep translocation out of the solum is especially plausible in the coarser textured Haplorthods. Deposition of clay in textural bands is probably due, initially, to cessation of wetting fronts or flocculation by carbonates. Sieving processes may act to thicken these features, especially in finer textured pedons. Lithologic discontinuities may have also affected lamellae formation by stopping wetting fronts at or near sites of textural change. Topographic factors also contributed to lamellae formation; pedons within and near a small depression had thicker and shallower lamellae than did those on uplands, possibly due to lateral translocation of colloids.

SANDY SOILS with fine-textured, subsurface bands (lamellae) are common in the Great Lakes region, where their presence can dramatically affect water retention and movement and plant growth (Gardner and Whiteside, 1952; Wurman et al., 1959; Franzmeier and Whiteside, 1963a,b; Dijkerman et al., 1967; Miles and Franzmeier, 1981; Berg, 1984; Mokma et al., 1990). The processes by which lamellae develop are not clearly understood. Reviews of lamellae formation have been compiled by Dijkerman et al. (1967) and Wurman et al. (1959). In most soils, a pedogenic origin is indicated (Folks and Riecken, 1956; Soil Survey Staff, 1975; Gile, 1979; Torrent et al., 1980; Brussaard and Runia, 1984; Kemp and McIntosh, 1989). Generally, deposition of clay particles and colloids is ascribed to (i) the presence of free Fe oxides or carbonates, (ii) cessation of wetting fronts, or (iii) capillary discontinuities. Illuviation of clay into lamellae has been verified in the laboratory in columns of sand (Folks and Riecken, 1956; Bond, 1986). In some soils, lamellae are associated with original, sedimentary stratification (Robinson and Rich, 1960; Hannah and Zahner, 1970). Sieving processes are also believed to be important in lamellae formation in some soils (Folks and Riecken, 1956; Wurman et al., 1959; Robinson and Rich, 1960; Bond, 1986).

In this study, soils with weak to strong spodic morphology and with varying expressions of lamellae were studied to ascertain how subtle differences in parent material and surface topography relate to their morphology, primarily with respect to lamellae expression.

MATERIALS AND METHODS

Study Area

The study area is located on a sandy plain of 1 to 4% slopes in central Cheboygan County, Michigan (Fig. 1). This area was last deglaciated by the retreat of Wisconsinan ice approximately 11500 yr BP (Futyma, 1981). After deglaciation, the area was inundated by the middle stage of glacial Lake Algonquin (11200–10000 yr BP; Larsen, 1987). Due to isostatic rebound and exposure of new lake outlets, lake levels fluctuated several times. Beaches for two such lakes (Battlefield and Nipissing) exist to the east of the study area (Fig. 1). Thus, surficial materials are interpreted to be wave-worked fine and medium sands and coarse silts on a lake terrace. Sand thickness over glacial till decreases immediately north of the study area, such that sandy-over-loamy and loamy soil families are found. The western boundary of the geomorphic surface is marked by an abrupt 50-m escarpment onto a hilly region that was probably an island of Wisconsinan till within glacial lakes (Riggsville Island; Burgis, 1977) A 20-m escarpment down to the terrace of glacial Lake Nipissing marks the southeastern margin of the plain (Fig. 1). On the Algonquin terrace, six pedons with differing degrees of spodic horizon and lamellae development were selected for sampling. Four of these (C, D, E, and F) are located within or at the periphery of a small (≈300-m-diam.), closed depression; others (A and B) are on a flatter surface of integrated drainage (Fig. 1).

Podzolization is the dominant pedogenic process in this area (Franzmeier and Whiteside, 1963b; Schaetzl and Isard, 1991). Soils on the terrace are in sandy families of Spodosols. Some have lamellae below their Bs horizons. The climate of the study area is cool, humid continental; soils are classified within the frigid soil temperature regime. Mean monthly temperatures and precipitation totals for Cheboy-

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Published in Soil Sci. Soc. Am. J. 56:1538–1545 (1992).

Abbreviations: BP, before present; ODOE, optical density of the oxalate extract; ICP, inductively coupled plasma; XRD, x-ray diffraction; P/Q, plagioclase feldspar/quartz; K/Q, K-feldspar/quartz; D/Q, dolomite/quartz; F/Q, feldspar/quartz; $\mathrm{Fe_{ox}}$ and $\mathrm{Al_{ox}}$, acid-oxalate-extractable Fe and Al.

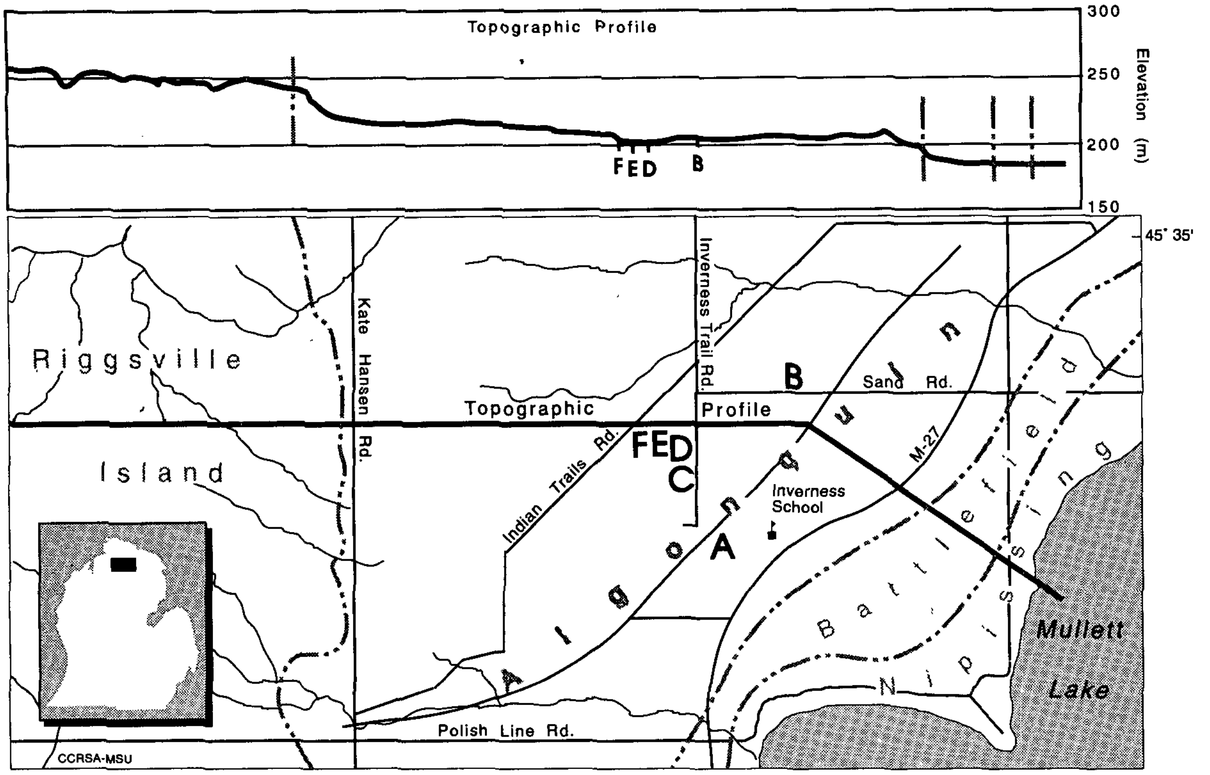

Fig. 1. General study area location, relief, and geomorphology, including extent of terraces from glacial Lakes Algonquin, Battlefield, and Nipissing. Riggsville Island is composed mostly of till. Pedon locations are shown by the letters A through F, near the center of the map.

gan, 9 km north-northeast of the study area, range from −7.2°C for January to 20.0°C for July (for more detail, see Schaetzl, 1991). Mean annual precipitation is 712 mm, of which much falls as snow from November through March.

Field and Laboratory Methods

Following a reconnaissance investigation, six pedons, labelled A through F, were excavated (Fig. 1). Five of the pedons were located in abandoned agricultural fields; the sixth (A) was forested and had not been cultivated. The pedons were described and sampled by genetic horizon (Soil Conservation Service, 1984). Samples from horizons with lamellae were removed in proportion to the amount of lamellae and interlamellae material present in the vertical face. Duplicate samples were analyzed for: (i) particle-size distribution by pipette, following destruction of organic matter with H_2O_2 (Day, 1965), (ii) pH in H_2O, (iii) organic-matter content by a modified Walkley-Black method (Nelson and Sommers, 1982), (iv) Fe and Al extraction by acid oxalate at pH 3.0 in darkness, followed by ICP spectroscopy to determine Fe and Al concentrations in the extracts (Daly, 1982; Soil Conservation Service, 1990). The ODOE was determined on a Perkin-Elmer 320 spectrophotometer (Perkin-Elmer Corp., Norwalk, CT) by measuring transmission at 430 nm. The 16 to 50-μm size fraction (coarse and medium silt) was isolated by elutriation, following dispersion in $(NaPO_3)_{13}{\cdot}Na_2O$, slow shaking overnight, and destruction of organics with H_2O_2 (Follmer and Beavers, 1973).

Fine and very-fine sand and coarse and medium silt mineralogy were determined by XRD on a Philips XRG 3100 diffraction unit (Philips Electronic Instruments, Mahwah, NJ). These fractions were ground to about 20 to 30 μm before mounting on glass slides for XRD analysis. Samples were scanned with Cu-Kα radiation at 35 kV and 15 mA at 3 s per 0.01°, from 21 to 33° 2θ.

Diffractogram data for quartz, feldspars, and dolomite were quantified by comparing peak heights (minus background) for dolomite (d spacing: 2.89 Å), plagioclase feldspars (3.17–3.18 Å), and K-feldspars (orthoclase and microcline; 3.25 Å) with the α-quartz peak (4.26Å; cf. Wurman et al., 1959; Nørnberg et al., 1985), because (i) quartz and feldspars are reported to be the dominant minerals in the silt- and sand-size fractions of Spodosols (Ross et al., 1990) and (ii) dolomite content can be used as an indication of cumulative leaching and weathering intensity. The largest peak was used to indicate the feldspar content where several small peaks were spaced closely together. Mineralogy of the total clay fraction was determined by the XRD method of Willman and Frye (1970) on eight samples. Two were taken from the spodic horizons of pedons without lamellae, and two from each of three pedons that contained abundant lamellae, from which paired samples were taken from lamellae and interlamellae materials.

RESULTS AND DISCUSSION

Soil Morphology and Degree of Development

The six pedons represent the range of spodic horizon expression and lamellae development observed on the terrace (Tables 1 and 2). Coarse fragments were absent from all soils sampled. Sand contents were typically >92%. Most soils were dominated by fine and very-fine sand; coarse and very-coarse sands were rarely observed.

Pedons A and B, with few or no lamellae and stronger spodic morphologies, had more coarse and medium sand and less silt and clay than did pedons with abundant textural bands (see also Wurman et al., 1959). This fact is especially evident when profile-weighted

Table 1. Morphological, physical, and chemical characterization data for the six pedons studied.

			Texture			Sand fractions†										
Horizon	Depth	Color‡	Sand	Silt	Clay	vc	c	m	f	vf	Texture§	Fe$_{ox}$¶	Al$_{ox}$¶	ODOE#	pH (2:1 H_2O)	Organic matter
	cm		% of <2-mm fraction									mg kg^{-1}				g kg^{-1}
Pedon A: Typic Haplorthod (Wallace series)																
A	0–8	10YR 2/2	91.7	4.8	3.5	0.1	4.4	38.5	45.7	3.0	s	0.5	0.6	0.04	5.06	0.12
E	8–25	7.5YR 5/2	94.6	3.5	1.9	0.0	3.6	37.7	50.0	3.3	fs	0.2	0.1	0.01	4.80	0.02
Bsm	25–53	5YR 3/3 & 7.5YR 4/6	95.6	1.4	3.0	0.1	2.1	34.0	56.7	2.7	fs	1.6	3.6	0.11	5.33	0.07
Bs	53–76	10YR 4/6	98.4	0.3	1.3	0.0	2.0	53.5	42.1	0.8	s	0.5	1.6	0.02	6.18	0.02
BC	76–124	10YR 6/6	98.6	0.3	1.1	0.0	0.4	25.0	72.1	1.1	fs	0.4	1.4	0.02	5.84	0.01
C	124–152+	10YR 6/6	98.9	0.0	1.1	0.0	0.9	42.0	55.0	1.0	fs	0.3	0.6	0.01	5.86	0.01
Pedon B: Entic Haplorthod (Rousseau series)																
Ap	0–18	10YR 3/2	92.8	2.6	4.6	0.5	4.2	36.5	48.8	2.8	s	1.0	1.4	0.09	4.51	0.09
Bs1††	18–32	7.5YR 4/6	95.5	1.9	2.6	0.4	0.8	18.6	72.6	3.1	fs	1.3	4.0	0.13	4.84	0.07
Bs2††	32–80	10YR 5/6	97.7	0.6	1.7	0.0	0.3	12.4	82.2	2.8	fs	0.5	1.8	0.04	5.68	0.02
BC	80–112	10YR 5/6	98.9	0.0	1.1	0.0	0.5	8.0	86.7	3.7	fs	0.5	1.0	0.02	5.78	0.01
C	112–146+	10YR 5/4	99.2	0.0	0.8	0.1	1.5	24.2	70.1	3.3	fs	0.3	0.7	0.01	5.22	0.00
Pedon C: Entic Haplorthod (Rousseau series)																
Ap	0–17	10YR 3/2	91.5	5.2	3.3	0.0	0.4	16.1	65.9	9.1	fs	0.7	0.9	0.04	4.80	0.10
E	17–29	10YR 5/2	92.6	5.3	2.1	0.0	0.3	11.2	70.0	11.1	fs	0.1	0.2	0.01	5.66	0.02
Bs1	29–48	7.5YR 3/4	93.3	3.2	3.5	0.0	0.1	8.9	72.4	11.9	fs	2.1	3.6	0.13	5.26	0.07
Bs2	48–88	10YR 5/6	97.4	1.1	1.5	0.0	0.1	16.7	73.6	7.0	fs	0.5	1.0	0.02	5.87	0.02
2E/Bt (bulk)	88–155+		93.3	4.7	2.0	0.0	0.1	2.7	67.1	23.4	fs	0.9	1.2	0.03	5.86	0.02
(E)		10YR 6.4	nd‡‡	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
(B)		5YR 5/8	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Pedon D: Argic Udipsamment (Zimmerman series)																
Ap	0–21	10YR 3/3	90.4	5.3	4.3	0.0	0.0	6.0	68.3	16.1	fs	1.5	1.6	0.09	5.57	0.09
Bs1	21–37	7.5YR 4/6	93.5	3.9	2.6	0.0	0.0	4.7	73.8	15.0	fs	1.0	2.0	0.03	5.87	0.03
Bs2	37–79	10YR 5/4	92.0	6.0	2.0	0.0	0.0	3.2	64.4	24.4	fs	0.9	1.2	0.02	6.02	0.01
E/Bt (E)	79–160+	10YR 6/4	95.5	2.9	1.6	0.0	0.0	2.9	73.6	19.0	fs	nd	nd	nd	6.28	0.01
(B§§)		7.5YR 4/6	95.7	1.6	2.7	0.0	0.0	3.7	75.9	16.1	fs	nd	nd	nd	5.75	0.01
Pedon E: Alfic Haplorthod (no series has been established for this pedon)																
Ap	0–26	10YR 3/2	79.3	15.9	4.8	0.0	0.1	2.2	41.8	35.2	lfs	1.1	0.9	0.05	5.47	0.09
Bs1	26–37	7.5YR 3/4	83.5	11.9	4.6	0.0	0.1	1.8	49.9	31.7	lfs	4.8	4.6	0.20	5.71	0.12
Bs2	37–49	7.5YR 4/6	82.6	14.1	3.3	0.0	0.1	1.0	43.5	38.0	lfs	1.8	3.8	0.09	5.66	0.06
Bs3	49–80	10YR 4/6	78.3	18.9	2.8	0.1	0.0	0.4	35.3	42.5	lfs	1.2	2.3	0.06	5.21	0.03
2E/Bt1 (bulk)	80–118		93.8	4.0	2.2	0.0	0.0	0.7	73.2	19.9	fs	0.7	0.9	0.04	6.64	nd
(E)		10YR 4/4	92.0	5.9	2.1	0.0	0.0	0.7	63.8	27.5	fs	nd	nd	nd	6.40	0.01
(B)		10YR 3/4	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
2E/Bt2 (E)	118–160+	10YR 5/4	94.8	3.1	2.1	0.0	0.0	0.7	71.2	22.9	fs	nd	nd	nd	6.72	0.04
2E/Bt2 (B)		7.5YR 4/6	90.1	0.2	9.7	0.0	0.0	1.1	70.5	18.5	fs	nd	nd	nd	6.68	nd
Pedon F: Psammentic Eutroboralf (no series has been established for this pedon)																
Ap	0–19	10YR 3/2	78.3	16.9	4.8	0.0	0.1	5.9	40.9	31.4	lfs	1.7	1.4	0.07	6.05	0.11
Bs1	19–37	7.5YR 3/4	76.3	21.3	2.4	0.1	0.3	2.5	34.1	39.3	lfs	2.1	3.7	0.13	6.04	0.08
Bs2	37–54	7.5YR 5/4	87.2	10.1	2.7	0.0	0.1	0.8	56.2	30.1	fs	0.7	1.4	0.06	6.06	0.03
2E/Bt1 (bulk)	54–94		92.2	5.0	2.8	0.0	0.0	0.8	68.4	23.0	fs	0.5	0.7	0.02	6.08	0.01
(E)		10YR 5/4	92.4	5.2	2.4	0.0	0.0	0.9	68.2	23.3	fs	nd	nd	nd	6.25	0.01
(B)		5YR 4/6	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
3E/Bt2 (E)	94–135	10YR 5/4	85.5	11.3	3.2	0.0	0.0	0.5	53.4	31.6	lfs	nd	nd	nd	6.14	0.01
(B)		5YR 4/4	47.2	30.9	21.9	0.0	0.0	0.1	20.5	26.6	l	nd	nd	nd	7.54	0.04
4E/Bt3 (E)	135–165+	7.5YR 6/4	90.7	7.0	2.3	0.0	0.0	0.4	58.1	32.2	fs	nd	nd	nd	8.72	0.01
(B)		5YR 4/6	86.8	1.8	11.4	0.0	0.0	0.9	62.2	23.7	lfs	nd	nd	nd	7.21	0.01

† vc = very coarse (2–1-mm diam.), c = coarse (1–0.5 mm), m = medium (0.5–0.25 mm), f = fine (0.25–0.125 mm), vf = very fine (0.125–0.05 mm).
‡ Moist colors.
§ lfs = loamy fine sand; fs = fine sand; s = sand; l = loam.
¶ Acid-oxalate-extractable Fe and Al.
# Optical density of the oxalate extract at 430 nm.
†† The Bs1 horizon contained approximately 25–35% Bsm material. The Bs2 horizon contained approximately 15–20% Bsm material.
‡‡ Not determined.
§§ This sample was approximately 60% B material; the remainder was E.

means are compared (Table 3), and is apparent despite parent-material variability. These pedons are on the nearly level, eastern part of the terrace, and have developed in uniform parent material composed of 91 to 99% sand. Silt and clay contents are typically <5% and decrease with depth (Table 1). Pedon D is near the depression and differs from Pedons A and B by having five to 10 times as much very-fine sand and twice as much silt and clay. Pedons C E, and F, also in or near the depression, contain two or more parent materials (Table 1). One parent material is similar to that of Pedons A and B; the other is like that of Pedon D. Thus, two distinct parent materials are present on the terrace surface: Material 1 is dominated by medium and fine sand and contains <5% silt and clay. Its textural class is fine sand or sand. Material 2 is similar to 1 but it has more very-fine sand, silt, and clay, and has almost no coarse and very-coarse sand.

Table 2. Soil classification and characteristics of lamellae.

	Pedon classification†	Lamellae thickness and development
A	Sandy, mixed, ortstein Typic Haplorthod‡	None observed to 152 cm.
B	Sandy, mixed, ortstein Entic Haplorthod‡	Few 1-mm-thick lamellae at 140 cm.
C	Sandy, mixed, Entic Haplorthod‡	1–2 mm thick, discontinuous within 2E/Bt.
D	Mixed, Argic Udipsamment	1–4 mm thick in E/Bt.
E	Mixed, Alfic Haplorthod	2–10 mm thick in 2E/Bt1; up to 25-mm thick in 2E/Bt2.
F	Sandy, mixed Psammentic Eutroboralf	2–3 mm thick in 2E/Bt1; up to 90 mm thickness in 3E/Bt2; up to 50 mm thick in 4E/Bt3.

† Soil temperature class has been omitted from the family classification; all soils are in the frigid soil temperature regime.

‡ Spodosol classifications are based on revised criteria, (R. Engel, 1991, personal communication; International Committee on Spodosols, 1991).

Table 3. Comparative data for pedons with no, few, and abundant lamellae.

		Pedons		
Comparative element(s)	Units	A & B†	C & D‡	E & F§
Strongest "spodic" color	—	5YR 3/3	7.5YR 3/4	7.5YR 3/4
Bs horizon weighted Fe_{ox}¶	mg kg^{-1}	1.1 (A)	1.9 (C)	2.1 (E)
		0.8 (B)	0.9 (D)	1.4 (F)
Bs horizon weighted Al_{ox}¶	mg kg^{-1}	2.7 (A)	1.8 (C)	3.1 (E)
		2.6 (B)	1.4 (D)	2.6 (F)
Bs horizon weighted ODOE¶	—	0.06 (A)	0.06 (C)	0.10 (E)
		0.07 (B)	0.02 (D)	0.10 (F)
Textural classes encountered#	—	s,fs	fs	fs,lfs,l
Depth to first lamella	cm	>152 (A)	88 (C)	80 (E)
		152 (B)	79 (D)	54 (F)
Profile-weighted 2000–500-μm fraction	%	1.6 (A)	0.1 (C)	0.1 (E)
		1.3 (B)	0.0 (D)	0.1 (F)
Profile-weighted 250–50-μm fraction	%	59.3 (A)	84.8 (C)	85.9 (E)
		78.2 (B)	90.2 (D)	80.9 (F)
Profile-weighted 250–2-μm fraction	%	60.4 (A)	88.4 (C)	95.8 (E)
		79.0 (B)	94.3 (D)	92.9 (F)
Profile-weighted 50–2-μm fraction	%	2.7 (A)	5.9 (C)	13.0 (E)
		2.6 (B)	6.3 (D)	17.6 (F)
Profile-weighted <125-*μm* fraction	%	4.4 (A)	21.1 (C)	42.6 (E)
		5.8 (B)	25.9 (D)	46.6 (F)
Profile-weighted <2-μm fraction	%	1.7 (A)	2.2 (C)	3.2 (E)
		1.9 (B)	2.2 (D)	5.6 (F)
Profile-weighted feldspar/quartz ratio††	unitless	52 (A)	208 (C)	183 (E)
		131 (B)	153 (D)	266 (F)

† Representative of pedons that lack lamellae within the upper meter, or the solum, whichever is thickest.

‡ Representative of pedons that have common, thin lamellae.

§ Representative of pedons that have many, thick lamellae.

¶ Acid-oxalate-extractable Fe and Al (Fe_{ox} and Al_{ox}) and the optical density of the oxalate extracts (ODOE) calculated as: $[\Sigma(ZH_t)]/D$ where Z is the soil constituent under consideration (e.g., Fe_{ox}), H_t is the thickness of the subhorizon (cm), and D is the cumulative thickness of all Bs subhorizons (cm). The summation (Σ) is calculated for all Bs horizons.

lfs = loamy fine sand; fs = fine sand; s = sand; l = loam.

†† Calculated as: $(\Sigma\{[(P/Q)H_tP] + [(K/Q)H_tP]\})/P_t$ where P/Q is the plagioclase/quartz peak height ratio, H_t is the thickness of the horizon (cm), P is the percentage (w/w) of fine sand, very-fine sand, or total silt in the horizon, K/Q is the K-feldspar/quartz peak height ratio, and P_t is the profile thickness (cm).

Its textural class is fine sand or loamy fine sand. Each parent material occurs in layers ≥40 cm in thickness. Pedons A and B are comprised entirely of Material 1; Pedon D is wholly Material 2; Pedon C is 1/2; Pedon E is 2/1; and Pedon F has combinations of the two in a sequence of four parent materials. Although the lamellae in Pedons C, E, and F are found in the second (lower) parent material, they may occur in either Material 1 or 2.

Pedons with abundant lamellae are finer textured and contain eight to 10 times as much profile-weighted very-fine sand plus silt and clay than did pedons without lamellae (Table 3). More total clay and perhaps silt might be expected in pedons with lamellae; however, they also have greater percentages of the finer sand fractions, and often more silt. Similar relationships were found in sandy soils in Michigan (Wurman et al., 1959), Indiana (Miles and Franzmeier, 1981), and Illinois (Berg, 1984).

In the E horizons of Pedons A and C, loss of clay from eluvial zones was evident (Table 1). In the remaining pedons the Ap horizon generally had similar or greater clay contents than the illuvial zone (Bs horizons). Sedimentary processes in the near-shore environment probably produced relatively large silt plus clay contents in the upper few tens of centimeters of each profile during deposition. Eluviation processes have not erased this trend. Even in these soils, close incremental sampling of unplowed profiles might detect an eluvial trend, but clay losses from E horizons would probably be <2% (Berg, 1984). Decreases in silt contents with depth in sandy Spodosols and spodic-like soils are evident here and are usually attributed to the effects of eolian silt additions or increased physical weathering of sand-sized particles to silt (Franzmeier and Whiteside, 1963b; Nørnberg, 1977, 1980; Protz et al, 1984). Although the possibility of eolian inputs of silt cannot be disregarded for these soils, P/Q and K/Q ratios in the upper sola (Fig. 2, other data not shown) do not indicate noticeably increased weathering of feldspars in the fine and very-fine sand fractions.

The pH values in the six pedons were relatively similar and ranged from slightly to moderately acid (Table 1). Natural pH differences between surface and near-surface horizons may have been masked, however, by previous additions of agricultural lime. Horizons with thick lamellae (Pedon F: 3E/Bt2 and 4E/Bt3 horizons) had pH values >7.0, associated with intense dolomite XRD peaks.

Mineralogy

In spodic horizons of Pedons A and B, kaolinite–chlorite was the most common clay mineral group. Very small amounts of other 14-Å minerals were present; illite was not detected. In E/Bt horizons of pedons with abundant lamellae, the clay mineralogy was dominated by kaolinite–chlorite and illite with minor quantities of 14-Å minerals. Inter-lamellae (E) samples had clay mineral suites similar to that of the lamellae, but with smaller amounts of illite. Destruction of illite in Pedons A and B due to acidity and the intensity of podzolization processes (*sensu* Fridland, 1958, or Guillet et al., 1975) is suggested by this pattern but has not been verified. Also possible is a lack of illite in the parent materials of these soils, or deep translocation of illite due to the coarser textures of Pedons A and B.

Peak height ratios for P/Q, K/Q, and D/Q for the fine sand, very-fine sand, and silt fractions (data not shown) were generally largest for the silt-size fraction. Peak heights of the K-feldspars were two to three times greater than were those for plagioclase feldspars (see

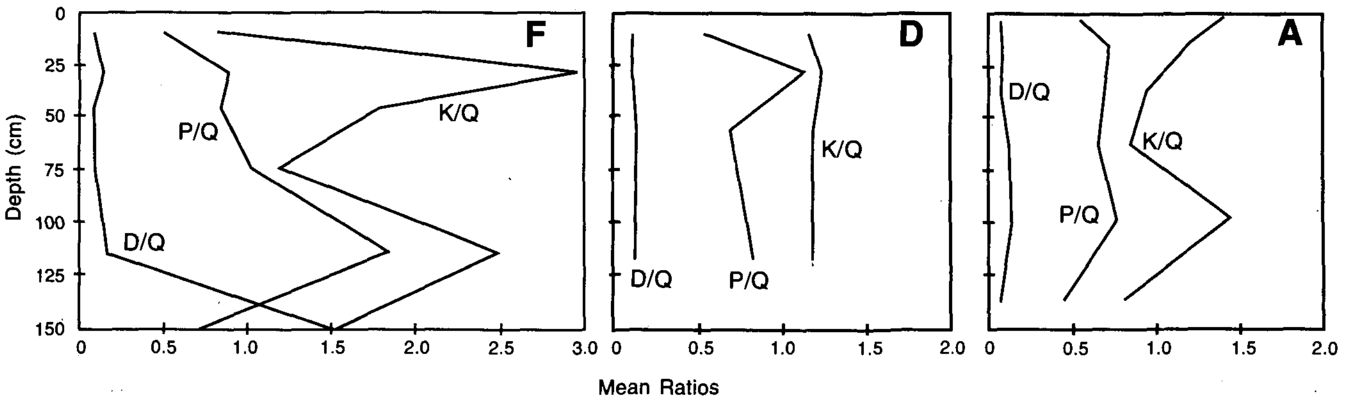

Fig. 2. Depth trends for K-feldspars (K), plagioclase feldspars (P), and dolomite (D), as expressed by peak height ratios with quartz (Q) for representative Pedons A, D, and F. Values shown are means of the ratios for the silt, very-fine-sand, and fine-sand fractions for each horizon (with each fraction given equal weight).

also Wurman et al., 1959; Guillet et al., 1975). In general, depth trends showed small or no increases in F/Q ratios with depth (Fig. 2), suggesting that the relatively young age and low water-holding capacities of these soils has not allowed for substantial feldspar hydrolysis in the solum. Small XRD peaks for dolomite suggested that this mineral may be present in minute quantities in many horizons; it also did not display a noticeable depth trend in any pedon (Fig. 2). The large D/Q ratio in the 4E/Bt3 horizon of Pedon F, the largest of which was in the silt fraction of the loamy-fine-sand textural bands, coupled with the high pH of the lower horizons of Pedon F (Table 1) suggest that the finer textured pedons, though leached, contain some free carbonates that may in part account for the flocculation of clays (Berg, 1984). In general, however, the small amounts of dolomite in each pedon do not appear to have limited clay migration, possibly due to excessive infiltration capacities and porosities of the parent materials (Berg, 1984).

It cannot be assumed that depth trends in peak height ratios are solely an indication of weathering intensity. Rather, assuming that weathering in these soils has been minimal and (presumably) more or less similar among the pedons, it is likely that these trends primarily reflect the relative amounts of minerals in the parent material. As such, F/Q ratio data may provide insight into the potential for clay synthesis and release of metals into the soil solution (e.g., Guillet et al., 1975; Miles and Franzmeier, 1981).

Weighted peak height ratios were calculated for each horizon by multiplying the ratios by both the horizon thickness (cm) and the percentage (w/w) of silt, very-fine sand, and fine sand. A summation of the resultant values (data not shown) provided a comparative indication of the weighted amount of weatherable minerals in the 250- to 16-μm fraction of each horizon. This type of weighting yields values that may more accurately reflect the weathered or weatherable nature of the horizons than would a technique using only peak height ratios. Pedons with abundant lamellae, especially C, D, and F, have the greatest weighted F/Q ratios (Table 3). Similarly, Miles and Franzmeier (1981) found that soils with lamellae had more weatherable minerals than sandy soils without lamellae, and they further suggested that much of the clay in the lamellae had formed from weathering of feldspars. Wurman et al. (1959) noted that >90% of the nonclay fraction of sandy soils is usually quartz and feldspar, which contribute little to in situ clay formation. Pedon A had no lamellae, exhibited the strongest spodic expression, and had the smallest F/Q and D/Q ratios (Table 3).

Soil Classification

The pedons were classified using spodic-materials criteria (International Committee on Spodosols, 1991). Non-Spodosols were classified according to the Soil Survey Staff (1990). Under the new definition, soils would be classified as having spodic materials if they meet the following criteria. Briefly summarized, spodic materials must:

1. have a pH in water of 5.9 or less, AND
2. have an organic C content of 0.6% or greater, AND
3. (a) underlie an albic horizon and meet one of the following color criteria: 5YR or redder, 7.5YR 5/4 or darker or redder, 10YR 2/ or darker, or 10YR 3/1, OR
   (b) meet one of the criteria in (a) AND have ortstein in ≥ 50% of the pedon, OR have cracked coatings on sand grains, OR have ≥ 0.50% Al_{ox} plus $Fe_{ox}/2$ and ≥ two times the Al_{ox} plus $Fe_{ox}/2$ of an overlying eluvial horizon, OR an ODOE of ≥ 0.25 and ≥ two times the ODOE of an overlying eluvial horizon.

For these six pedons, classification within the Spodosol order necessitates that they have spodic materials that (i) are ≥10 cm in thickness OR underlie an Ap horizon OR are present as ortstein, AND (ii) have their lower boundary at a depth of ≥25 cm.

All six pedons were classified within either the Psamment suborder or sandy textural families of Spodosols or Alfisols (Table 2) and exhibited some expression of spodic morphology, as indicated by Bs horizons. Only the Bs horizon of Pedon E met the chemical requirements for spodic materials (Table 1). Pedons A and B contained spodic materials and a spodic horizon based on the presence of ortstein (Bsm) in ≥50% of the pedon. Pedons B, D, and F did not have spodic materials based on color criteria alone because the E horizon had been destroyed by plowing. Pedon C met the color criteria and was classified as a Spodosol because part of the E horizon remained below the plow layer.

Pedons A and B had well-expressed spodic morphology. Pedons E and F had weaker spodic morphology but more Fe_{ox} and Al_{ox} than did Pedons A and B. The finer textured pedons (E and F) had the greatest ODOE values, a relationship that has been observed for soils with spodic morphology. The lower sola of Pedons E and F contain argillic horizons, based on combined thicknesses of the lamellae. Assuming a base saturation of >60% in all subhorizons of their argillic horizons, Pedon E was classified as an Alfic Haplorthod, and Pedon F was classified as a Psammentic Eutroboralf (Soil Survey Staff, 1990). Pedon D has an intermediate degree of lamellae development and was classified as an Alfic Udipsamment.

Genesis of Lamellae

Small amounts of clay are easily and quickly translocated in sandy materials (Berg, 1984; Bond, 1986). Hallsworth (1963) showed that clay translocation was greater in columns containing coarser sand, and that a greater percentage of clay was translocated in sandy vs. loamy soils. Columns of sand with 5% clay have been reported to restrict clay translocation (Hallsworth, 1963), in a manner consistent with the sieving hypothesis of lamellae formation (Robinson and Rich, 1960; Bond, 1986). These findings suggest that much of the clay has been translocated out of the upper 150 cm of Pedons A and B, which are wholly composed of the coarser Material 1. Conversely, in pedons composed entirely of finer sands (D), more clay may have been sieved out by the closely packed sand grains to produce lamellae at shallower depths.

Clay may flocculate and lamellae may form when the maximum colloidal-suspension concentration is achieved (Bond, 1986). Attaining this threshold would be more likely to occur in the finer textured pedons (e.g., E and F) and in the finer textured parent material (2). Finer textures in otherwise sandy soils may reduce percolation rates and porosities and cause more wetting fronts to stop at discontinuities in the lower solum (Gile, 1979; Berg, 1984). Pedons C, E, and F contain lithologic discontinuities that, however, are not abrupt and no lamellae were observed to occur exactly at the lithologic boundaries. Nonetheless, the variability in parent materials and associated permeabilities may have induced wetting fronts to stop at or near these areas. Once stopped, these wetting fronts may deposit carbonates and clay (Wurman et al., 1959). Clay deposition may then be accentuated for succeeding wetting fronts due to sieving action and changes in capillarity (Folks and Riecken, 1956; Gile, 1979). Clay illuviation in sandy sola, leading to the formation of clay-enriched (Beta) horizons, has been documented by Bartelli and Odell (1960). Evidence for a sole geologic or sedimentary origin of the lamellae (e.g., Hannah and Zahner, 1970) is lacking, however, because the clay bands cross-cut the thick (>40 cm) sedimentary strata that exist in some pedons.

Table 4. Statistical correlations between depth to first lamella† and physical and mineralogical characteristics of the six pedons.

Profile-weighted variable	Correlation coefficient (*r*)
2000–500-μm fraction	
for the entire profile	0.96**
for only those horizons above the first lamella	0.96**
250–50-μm fraction	
for the entire profile	−0.77
for only those horizons above the first lamella	−0.77
250–2-μm fraction	
for the entire profile	−0.90
for only those horizons above the first lamella	−0.89*
<125-μm fraction	
for the entire profile	−0.92*
for only those horizons above the first lamella	−0.82*
<50-μm fraction	
for the entire profile	−0.82*
for only those horizons above the first lamella	−0.78
<2-μm fraction	
for the entire profile	−0.72
for only those horizons above the first lamella	−0.86
Feldspar/quartz ratio for the fine-sand, very-fine-sand, and silt fractions	
for the entire profile	−0.89*
for only those horizons above the first lamella	−0.69

*,** Significant at the 0.05 and 0.01 probability levels, respectively.

† As no lamellae were observed in the upper 152 cm (depth of the soil pit) in Pedon A, a depth of 165 cm was assumed for statistical purposes.

Depth to the first lamella was used as a surrogate for overall profile development of these features; pedons with a shallower first lamella also tended to have more and thicker lamellae. Statistical correlations between depth to the first lamella and various textural characteristics indicated that coarser profiles permit deeper clay illuviation; this supports the hypothesis that some filtering of clays may have occurred in the finer textured profiles (Table 4).

Lamellae development is better expressed in Pedons C through F than in A and B. Pedons C through F, located near the depression on the terrace, are generally finer textured and contain more fine and very-fine sand than Pedons A and B, which are on a 1% slope to the east (Fig. 1). The comparatively fine textures of the pedons in this depression may be due to in-washing of clay- and fine-silt-sized particles during waning lake stages. The depression may have provided enough slope to permit clay- and silt-rich waters to accumulate as a small pool, or to wash in via overland flow, possibly at a time when glacial Lake Nipissing existed just 1 km to the east (Fig. 1). Lateral translocation of colloids, leading to lamellae development in the accumulative areas, has been reported for dunes (Gile, 1979). The lithologic discontinuities in Pedons C, E, and F (Table 1) attest to the variable environments of fluvial and fluviolacustrine deposition in and around the depression. Pedons A and B, located in a flat upland position, would not have had such a local source of clay and therefore have formed in "cleaner" sands. Their lamellae are weakly developed or nonexistent. Berg (1984) concluded that most of the clay in lamellae in his study area originated in the parent material, rather than forming by pedogenic weathering; depth trends for F/Q and D/Q ratios and clay-mineralogy data from the six pedons studied here support his contention.

CONCLUSIONS

Apparent relationships were found between morphological, textural, and mineralogical properties in six pedons that ranged from Typic and Entic Haplorthods, to Argic Udipsamments with Bs horizons and thin, deep lamellae, to Psammentic Eutroboralfs with Bs horizons and thicker, shallow lamellae. Pedons with the strongest spodic morphologics had fewer, thinner, and deeper lamellae than did other pedons. The soils with the strongest spodic morphologies and colors (e.g., 5YR 3/3) also exhibited the smallest F/Q and D/Q ratios in each of three subsets of the 250- to 16-μm fraction, and had the coarsest textures. Conversely, pedons with the most abundant and thickest lamellae had larger F/Q and D/Q ratios, finer textures, and generally weaker spodic colors (7.5YR 3/4 and 4/6) in the Bs horizons.

A geologic mode of genesis for the lamellae is not supported by the data, because the lamellae clearly crosscut geologic strata. Although the abundance of lamellae appears to be related to the amount of weatherable minerals in the soils and to the relative amount of <125-μm material, the genesis of the lamellae probably involves the following pedogenic processes:

1. Wetting fronts may stop at or near boundaries of finer over coarser sediments because of differences in capillary forces. Once stopped, they may deposit colloids and cause the formation of an incipient lamella.
2. Flocculation of clays at depth may be partly caused by increased pH and Ca^{2+} and Mg^{2+} activities, and by the presence of free carbonates. Leaching of carbonates would be more limited in the finer textured pedons due to shallower infiltration of wetting fronts. In coarser sands, surface area per unit volume is less than in finer sands, allowing wetting fronts to penetrate deeper and more rapidly, leaching the sola more effectively and carrying fine particles to greater depths.
3. Sieving of clays and silts in the lower sola of finer textured pedons was suggested by strong positive correlations between the amount of fine sand, silt, and clay, and lamellae depth.

Process 1 is the most supported by the presence of abundant lamellae in soils with pronounced lithologic discontinuities. Processes 2 and 3 are supported by strong negative correlations between lamellae depth and amount of coarse and medium sand in the profile.

ACKNOWLEDGMENTS

I thank Sharon Anderson, Stephen Boyd, James Crum, and Delbert Mokma of the Crop and Soil Sciences Dep., Michigan State University, for laboratory support facilities. Cartographic support was supplied by the Center for Cartographic Research and Spatial Analysis, Dep. of Geography, MSU. Comments on previous drafts by L.R. Barrett, J.M. Brixie, S. Businski, W.F. Jaynes, and D.L. Mokma are greatly appreciated.

REFERENCES

Bartelli, L.J., and R.T. Odell. 1960. Laboratory studies and genesis of a clay-enriched horizon in the lowest part of the solum of some Brunizem and grey-brown podzolic soils in Illinois. Soil Sci. Soc. Am. Proc. 24:390–395.

Berg, R.C. 1984. The origin and early genesis of clay bands in youthful sandy soils along Lake Michigan, U.S.A. Geoderma 32:45–62.

Bond, W.J. 1986. Illuvial band formation in a laboratory column of sand. Soil Sci. Soc. Am. J. 50:265–267.

Brussaard, L., and L.T. Runia. 1984. Recent and ancient traces of scarab beetle activity in sandy soils of the Netherlands. Geoderma 34:229–250.

Burgis, W.A. 1977. Late-Wisconsinan history of northeastern lower Michigan. Ph.D. diss. Univ. of Michigan, Ann Arbor (Diss. Abstr. 78–04659).

Daly, B.K. 1982. Identification of Podzols and podzolized soils in New Zealand by relative absorbance of oxalate extracts of A and B horizons. Geoderma 28:29–38.

Day, P.R. 1965. Particle fractionation and particle-size analysis. p. 545–567. *In* C.A. Black et al. (ed.) Methods of soil analysis. Part 1. Agron. Monogr. 9. ASA, Madison, WI.

Dijkerman, J.C., M.G. Cline, and G.W. Olson. 1967. Properties and genesis of textural subsoil lamellae. Soil Sci. 104:7–16.

Folks, H.C., and F.F. Riecken. 1956. Physical and chemical properties of some Iowa soil profiles with clay–iron bands. Soil Sci. Soc. Am. Proc. 20:575–580.

Follmer, L.R., and A.H. Beavers. 1973. An elutriator method for particle-size analysis with quantitative silt fractionation. J. Sediment. Petrol. 43:544–549.

Franzmeier, D.P., and E.P. Whiteside. 1963a. A chronosequence of Podzols in northern Michigan. I. Ecology and description of pedons. p. 2–20. *In* Mich. State Univ. Agr. Exp. Stn. Quart. Bull. 46.

Franzmeier, D.P., and E.P. Whiteside. 1963b. A chronosequence of Podzols in northern Michigan. II. Physical and chemical properties. p. 21–36. *In* Mich. State Univ. Agr. Exp. Stn. Quart. Bull. 46.

Fridland, V.M. 1958. Podzolization and illimerization (clay migration). Sov. Soil Sci. (Engl. Transl.) 24–32.

Futyma, R.P. 1981. The northern limits of glacial Lake Algonquin in upper Michigan. Quat. Res. 15:291–310.

Gardner, D.R., and E.P. Whiteside. 1952. Zonal soils in the transition region between the Podzol and Gray-Brown Podzolic regions in Michigan. Soil Sci. Soc. Am. Proc. 16:137–141.

Gile, L.H.. 1979. Holocene soils in eolian sediments of Bailey County, Texas. Soil Sci. Soc. Am. J. 43:994–1003.

Guillet, B., J. Rouiller, and B. Souchier. 1975. Podzolization and clay migration in Spodosols of eastern France. Geoderma 14:223–245.

Hallsworth, E.G. 1963. An examination of some factors affecting the movement of clay in an artificial soil. J. Soil Sci. 14:360–371.

Hannah, P.R., and R. Zahner. 1970. Nonpedogenetic texture bands in outwash sands of Michigan: Their origin, and influence on tree growth. Soil Sci. Soc. Am. Proc. 34:134–136.

International Committee on Spodosols. 1991. ICOMOD Circ. Lett. 10. Misc. Publ. Univ. of Maine, Orono.

Kemp, R.A., and P.D. McIntosh. 1989. Genesis of a texturally banded soil in Southland, New Zealand. Geoderma 45:65–81.

Larsen, C.E. 1987. Geological history of glacial Lake Algonquin and the upper Great Lakes. U.S. Geol. Surv. Bull. 1801.

Miles, R.J., and D.P. Franzmeier. 1981. A lithochronosequence of soils formed in dune sand. Soil Sci. Soc. Am. J. 45:362–367.

Mokma, D.L., R.J. Schaetzl, E.P. Johnson, and J.A. Doolittle. 1990. Assessing Bt horizon character in sandy soils using ground penetrating radar: Implications for soil survey. Soil Surv. Horiz. 31:1–8.

Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter. p. 570–571. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Nørnberg, P. 1977. Soil profile development in sands of varying age in Vendyssel, Denmark. Catena 4:165–179.

Nørnberg, P. 1980. Mineralogy of a podzol formed in sandy materials in northern Denmark. Geoderma 24:25–43.

Nørnberg, P., K. Dalsgaard, and E. Skammelsen. 1985. Morphology and composition of three Mollisol profiles over chalk, Denmark. Geoderma 36:317–342.

Protz, R., G.J. Ross, I.P. Martini, and J. Terasmae. 1984. Rate of podzolic soil formation near Hudson Bay, Ontario. Can. J. Soil Sci. 64:31–49.

Robinson, G.H., and C.I. Rich. 1960. Characteristics of the multiple yellowish-red bands common to certain soils of the southeastern United States. Soil Sci. Soc. Am. Proc. 24:226–230.

Ross, G.J., C. Wang, and H. Kodama. 1990. Mineralogy of Spodosols. p. 289–302. *In* J.M. Kimble and R.D. Yeck (ed.) Proc. Int. Soil Correlation Meet. 5th, ISCOM, Fredericton, New Brunswick. 1–14 Oct. 1987. USDA-SCS, Lincoln, NE.

Schaetzl, R.J. 1991. A lithosequence of soils in extremely gravelly, dolomitic parent materials, Bois Blanc Island, Lake Huron. Geoderma 48:305–320.

Schaetzl, R.J., and S.A. Isard. 1991. The distribution of Spodosol soils in southern Michigan: A climatic interpretation. Ann. Assoc. Am. Geogr. 81:425–442.

Soil Conservation Service. 1984. Procedures for collecting soil samples and methods of analysis for soil survey. USDA-SCS Soil Surv. Invest. Rep. 1. U.S. Gov. Print. Office, Washington, DC.

Soil Conservation Service. 1990. Batch acid oxalate extract, inductively coupled plasma spectroscopy of iron, aluminum, manganese, and silicon and optical density of extract. USDA-SCS Misc. Rep. Version 1. USDA-SCS, Lincoln, NE.

Soil Survey Staff. 1975. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. USDA-SCS Agric. Handb. 436. U.S. Gov. Print. Office, Washington, DC.

Soil Survey Staff. 1990. Keys to soil taxonomy. 4th ed. Soil Manage. Support Serv. Tech. Monogr. no. 6. Va. Polytech. Inst. and State Univ., Blacksburg, VA.

Torrent, J., W.D. Nettleton, and G. Borst. 1980. Clay illuviation and lamellae formation in a Psammentic Haploxeralf in southern California. Soil Sci. Soc. Am. J. 44:363–369.

Willman, H.B., and J.C. Frye. 1970. Pleistocene stratigraphy of Illinois. Ill. State Geol. Surv. Bull. 94.

Wurman, E., E.P Whiteside, and M.M. Mortland. 1959. Properties and genesis of finer textured subsoil bands in some sandy Michigan soils. Soil Sci. Soc. Am. Proc. 23:135–143.