CLAY MINERAL WEATHERING IN SOUTHERN WISCONSIN SOILS DEVELOPED IN LOESS AND IN SHALE-DERIVED TILL*

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ABSTRACT

LOESS is the dominant soil parent material covering the western and central portions of southern Wisconsin. Glacial till derived mainly from Devonian shales and Silurian dolomite is the most extensive parent material in extreme southeastern Wisconsin. The soils developed in loess are coarser in texture, leached of carbonates to greater depths and more acid and contain a higher percentage of zirconium in their coarse silt than those developed in the till. The clay of the soils developed in loess contains a higher proportion of minerals of more advanced weathering indices (montmorillonite, " pedogenic " chlorite and kaolinite) formed by weathering. The clay mineralogy was fairly uniform in the four soils developed from loess, but the two Gray-Brown Podzolic soils were found to contain only about one-half as high a percentage of total clay and one-fourth as high a percentage of medium and fine clay in their A horizons (which were also 7 in. less in thickness) than the A horizons of their prairie soil analogues. The Varna soil developed in the till contains clay with a higher proportion of minerals of less-advanced weathering indices (mafic chlorite and dioctahedral mica), largely inherited from the parent material. There has been some transformation of mica and mafic chlorite to expansible layer silicates and amorphous material in the Varna solum and the ratio of ferrous to total iron decreased both with decreasing particle size (from fine silt through fine clay) and with approach to the soil surface (in the whole clay).

INTRODUCTION

LOESS is the dominant soil parent material covering the western and central portions of southern Wisconsin (Fig. 1). Expansible layer silicates, especially montmorillonite, have been reported as the dominant clay minerals of loess and loessial soils in the Mississippi Valley region (Beavers *et al.*, 1955; Glenn *et al.*, 1960; Frye, Glass and Willman, 1962). This montmorillonite is some-

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what ferruginous (Glenn *et al.*, 1960), apparently with about one out of every four octahedral cations of the montmorillonite being iron; weathering of mafic silt minerals, such as biotite, vermiculite, chlorite and amphiboles, accompanies the formation of the montmorillonite. Frye, Glass and Willman (1962) reported that loess in Illinois from western sources is high in montmorillonite, while loess that is derived from eastern sources is relatively high in mica, and that this corresponds to a difference in the mineralogy of glacial till from the two regions (Willman, Glass and Frye, 1963).

In extreme southeastern Wisconsin, where loess is thin or absent, glacial till derived mainly from Devonian shales and Silurian dolomite is the most extensive soil parent material. Mica with considerable chlorite has been indicated as the main clay mineral of glacial till in southeastern Wisconsin (Dixon and Jackson, 1960), northeastern Illinois (Beavers *et al.*, 1955; Wascher *et al.*, 1960), and northern Indiana and Ohio (Murray and Leininger, 1956; Droste, Bhattacharya and Sunderman, 1962).

The purpose of the present study was to improve the understanding of the clay mineralogy of soils developed in these two contrasting materials in southern Wisconsin.

EXPERIMENTAL

Materials

Three soils developed in moderately deep loess were compared to the Tama soil developed in deep loess (Glenn *et al.*, 1960) and to Varna soil developed in fine-textured till in southeastern Wisconsin. Loess becomes thinner in depth

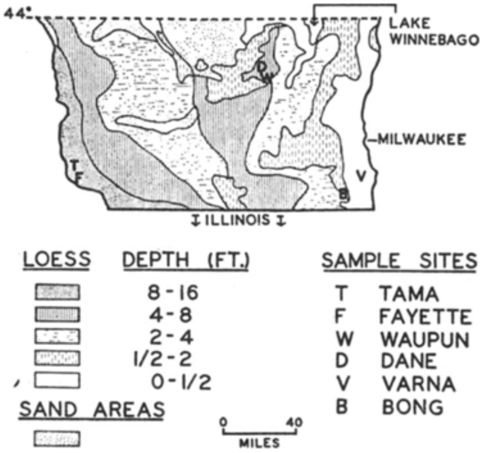

Fig. 1. Map (generalized after a map by F. D. Hole, Department of Soil Science, University of Wisconsin, Madison) showing the location of the soil profiles and the Bong deep till sample that were studied in relation to the distribution of loess in southern Wisconsin

and shows a decrease in particle size with increasing distance from the floodplain of the Ancient Mississippi River (Smith, 1942). The Tama and Fayette soils developed in the deep loess along the Mississippi River in southwestern Wisconsin (Fig. 1). Loess thickness relationships (Fig. 1) indicate that the belt of relatively thick loess in southcentral Wisconsin, in which the Waupun and Dane soil profiles developed, originated principally from flood plains along smaller streams within southcentral Wisconsin. Thus the Dane and Waupun soils developed in shallower but not finer textured loess than that in which the Fayette and Tama soils developed (Table 1). The loess of the Dane and Tama soils was somewhat deeper and coarser (closer to source area) than that of the Waupun and Fayette soils.

The loess in which the Waupun and Dane profiles developed is considered to have been deposited after the maximum advance of the Cary (late Woodfordian, Frye and Willman, 1960) and thus is younger than 14- or 15-thousand years. Most of the loess in the "Driftless Area" of southwestern Wisconsin, in which the Fayette and Tama profiles have developed, is of late Wisconsinan age, younger than carbon-14 dates of 29,300 ± 700 years before the present (charcoal at the base of a 19.8 ft section, Hogan and Beatty, 1963) and 24,600 ± 1100 years before present (Black, 1960) for paleosols at the base of loess in southwestern Grant County. These dates are at the end of the Altonian substage and during the Farmdalian interstadial and subsequent Peorion loess deposition (Frye and Willman, 1960). Thus the loess column in southwestern Wisconsin probably extends up through the Woodfordian (Cary) age. The Waupun (Typic Hapludoll or Prairie)* soil was sampled by R. C. Glenn, G. B. Lee, N. L. Johnson and P. H. Hsu, on highway E west of Fox Lake, Wis. Although a plow layer was not evident, it is possible that this was not a virgin soil. The Dane (Typic Normudalf or Gray-Brown Podzolic) soil was sampled by R. C. Glenn and G. B. Lee in the northwest corner of Dodge County, Wis., in a virgin forest consisting mainly of oak species. The Fayette (Typic Normudalf or Gray-Brown Podzolic) soil was sampled by R. C. Glenn, F. D. Hole, M. L. Jackson and J. B. Dixon on the R. Nuti Farm, NW 1/4, SW 1/4, Sec. 31, T4N, R5W, Grant County, Wis., in an oak-hickory forest with a well-developed understory including raspberry, gooseberry, elm, cherry, oak and hickory seedlings and some grass. The Tama (Typic Argiudoll or Prairie) soil was sampled in the NW 1/4, Sec. 18, T4N, R5W, Grant County, Wis.

The area of Varna (Prairie) and Morley (Gray-Brown Podzolic) soils in southeastern Wisconsin are developed on very deep till in a belt south of Milwaukee, which extends inland about 20 miles from Lake Michigan (Fig. 1). The glacial till was derived during several successive glaciations mainly from Devonian shales and Silurian dolomite of the Lake Michigan basin (Alden, 1918; Watson, 1961). The last glaciation in this shale-derived till region occurred during late Woodfordian (Frye and Willman, 1960) or Cary time,

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* Classification according to the Soil Conservation Service new comprehensive classification system (Soil Survey Staff, 1960, as revised) and the older system respectively.

TABLE 1.—PARTICLE-SIZE DISTRIBUTION (AFTER REMOVAL OF CARBONATES, ORGANIC MATTER AND FREE IRON OXIDES, 110°C DRY BASIS) AND pH OF SAMPLES THAT WERE STUDIED

Horizon	Depth, in.	Sand	Silt				Clay				pH
		2–0.05 mm	Coarse 50–20 μ	Medium 20–5 μ	Fine 5–2 μ	Total 50–2 μ	Coarse 2–0.2 μ	Medium 0.2–0.08 μ	Fine <0.08 μ	Total <2 μ	
DANE SOIL, IN 50–70-IN LOESS* UNDER OAK-HICKORY FOREST											
A_1	0–3	15.7	41.9	27.3	6.5	75.7	5.3	2.0	1.1	8.4	6.0
A_2	4–11	16.9	39.5	29.9	6.4	75.8	5.1	1.3	0.9	7.3	5.2
B_{23}	30–34	13.1	37.3	24.6	4.5	66.4	8.1	7.4	4.9	20.4	4.7
C_{21}	56–64	2.1	53.1	19.3	7.0	79.4	6.7	5.9	6.0	18.6	5.2
FAYETTE SOIL IN DEEP LOESS† (OVER 100 IN) UNDER OAK-HICKORY FOREST											
A_1	0–4	3.6	55.1	24.6	6.0	85.7	5.3	— 5.3—		10.6	5.7
A_2	4–8	4.1	57.4	23.7	4.7	85.8	5.7	— 4.4—		10.1	5.3
B_{21}	13–24	3.0	45.8	19.2	5.4	70.4	9.8	—16.7—		26.5	4.9
C_2	75–85	3.3	50.8	23.4	3.7	77.9	5.5	—13.3—		18.8	6.6
IIC_4	101–110	1.9	35.0	24.1	5.0	64.1	11.4	—22.7—		34.1	6.8
$IIIC_5$	118–140	5.7	31.3	17.9	2.5	51.7	12.2	—30.5—		42.3	6.5

WAUPUN SOIL, IN 50–70-IN LOESS* UNDER PRAIRIE GRASSES											
A_{12}	11–16	3.9	39.7	28.6	4.4	72.7	10.2	5.3	7.9	23.4	5.1
B_{21}	21–31	2.5	47.6	20.8	3.8	72.2	8.8	8.9	7.7	25.4	4.8
IIC_2‡	54–61	9.1	19.8	33.8	10.5	64.1	14.6	6.0	6.2	26.8	6.2
$IIIC_3$	61–70	58.3	19.5	6.8	5.5	31.8	4.9	3.9	1.1	9.9	7.7§
TAMA SOIL IN DEEP LOESS† (OVER 100 IN) UNDER PRAIRIE GRASSES											
A_{12}	6–12	4.7	44.5	20.5	6.2	71.2	8.3	8.4	7.4	24.1	6.4
B_1	24–31	5.4	46.6	14.7	4.1	65.4	10.1	10.0	9.2	29.3	4.9
C_3	66–72	7.3	53.1	14.3	3.8	71.2	8.6	6.8	6.1	21.5	5.8
C_4	96–102	6.8	57.8	14.1	3.9	75.8	6.8	5.2	5.4	17.4	6.0
C_5	122–130	5.2	53.6	17.8	3.9	75.3	7.8	5.8	6.0	19.6	7.8
C_6	150–157	3.6	55.5	18.5	4.6	78.6	7.5	5.0	5.3	17.8	7.8§
VARNA SOIL IN FINE TEXTURED TILL IN SOUTHEASTERN (RACINE CO.) WIS.											
A_p	0–8	18.2	16.1	29.8	4.9	50.8	16.2	7.5	7.3	31.0	6.7
B_2	8–16	9.8	11.7	25.7	6.6	44.0	28.0	11.5	6.7	46.2	7.5
C_1	23–37	12.0	12.0	23.4	12.1	47.5	18.0	14.8	7.7	40.5	Calc.§
C_3	48–56	18.2	15.8	24.3	6.9	47.0	20.5	10.2	4.1	34.8	Calc.§
BONG AIR FORCE BASE, DEEP TILL SAMPLE IN SOUTHEASTERN (KENOSHA CO.) WIS.											
—	—	7.6	8.9	20.3	13.6	42.8	24.5	12.9	12.1	49.5	Calc.§

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* Overlying calcareous, channery loam glacial till in southcentral (Dodge Co.) Wis.

† In southwestern (Grant Co.) Wis. Tama data from Glenn (1959).

‡ Although this horizon was considered to be loess in the field description, particle size and mineralogical evidence indicates that it was not " good " loess. It has thus been given Roman numeral II to indicate an unconformity with the overlying loess.

§ Calcareous.

about 14,000 years before present. A later glaciation (the Valderan) advanced as far south as Milwaukee (Thwaites, 1943). The Varna (Typic Argiudoll or Prairie) soil developed in the shale-derived till was sampled by members of the University of Wisconsin Department of Soil Science and members of the U.S. Soil Conservation Service in a cultivated field in SE 1/4, NE 1/4, Sec. 6, T3N, R22E. The deep core sample of calcareous, gray, fine-textured, shale-derived till from about a 60-foot depth from SE 1/4, SE 1/4, Sec. 16, T2N, R20E, was supplied by J. Steingraber, S.C.S. soil scientist, Waukesha, Wis.

Methods

The carbonates, organic matter and free iron oxides were removed, and the samples were fractionated into sand, silt and clay fractions and analyzed according to standard methods (Jackson, 1956). Mica was determined on a 10 per cent K_2O basis after allowance for feldspar K from the quartz–feldspar determination (Kiely and Jackson, 1964). Except for the Fayette profile, the fine silt and clay fractions were analyzed by X-ray diffraction with Mg-saturated, glycerol-solvated, parallel orientation specimens; K-saturated specimens were heated to 300° or 350°C and 500° or 550°C (Fanning, 1964). Total iron was determined colorimetrically with Tiron after HF decomposition and ferrous iron was titrated with $K_2Cr_2O_7$ after decomposition with H_2SO_4 and HF (Jackson, 1958). The pH values (Table 1) were determined by a glass electrode with a 1 : 1 (weight basis) soil to water ratio.

Particle-Size Distribution

Considerably lower percentages of clay were found in the A_1 and A_2 horizons of the two Gray-Brown Podzolic soils than in the A_{12} horizons of the two prairie soils, and a greater difference occurred in the finer clay than in coarse clay (Table 2). The ratio of the finer to coarser clay was somewhat lower in the A_2 horizon than in the A_1 horizon in the Gray-Brown Podzolic soils. Schrader (1950) also found, for a large number of profiles developed in loess in Missouri and Iowa with equal clay content of the B horizons, about twice as much clay and a more montmorillonitic type of clay in the A horizons of Prairie soils than in Gray-Brown Podzolic soils.

The little difference in the content of finer clay in the B horizons of the Prairie and Gray-Brown Podzolic soils (Table 1) suggests that the low content of finer clay in the A horizons of the Gray-Brown Podzolic soils is not a result of preferential movement of the clay from the A to the B horizon of these soils. The B_{21} horizons of the Gray-Brown Podzolic soils (Dane at 18–23 in., Fanning, 1964, and Fayette at 13–24 in.) are 7 in. shallower in depth than the B_1 horizons of the Prairie soils (Waupun at 21–31 in. and Tama at 24–31 in.). More active and deeper pedoturbation (Hole, 1961) in the surface of the Prairie soils may return more clay back to the surface of these soils. The surface of the Prairie soils may provide a more favorable environment for the formation of montmorillonitic clay. Reasons for a faster rate of clay formation under grass than under forest vegetation have been suggested (Barshad, 1959). The

TABLE 2.—CLAY CONTENT* AND RATIOS OF COARSE TO FINE CLAY IN THE A HORIZONS OF TWO GRAY-BROWN PODZOLIC AND TWO PRAIRIE SOILS DEVELOPED IN LOESS

Soil and horizon	$\% < 0.2\mu$ clay	$\%\ 2-0.2\mu$ clay	$\frac{\% < 0.2\mu}{\%\ 2-0.2\mu}$
	GRAY-BROWN PODZOLIC		
Dane A_1	3.1	5.3	0.58
A_2	2.2	5.1	0.43
Fayette A_1	5.3	5.3	1.00
A_2	4.4	5.7	0.77
	PRAIRIE		
Waupun A_{12}	13.2	10.2	1.29
Tama A_{12}	15.8	8.3	1.90

* As per cent of minerals from which carbonates, organic matter and free iron oxides had been removed, 110°C dry basis.

finer clay may be preferentially destroyed in the A horizons of the Gray-Brown Podzolic soils; this may be related to the observation of greater amounts of pedogenic chlorite in the coarse clay and fine silt of the Dane A horizon as opposed to the Waupun soil (discussed below).

In the Varna profile sample and the Bong Air Force Base deep till sample (Table 1), the medium silt was the most abundant silt fraction and the coarse clay was the most abundant clay fraction. The A_p and C_3 horizons contained slightly more sand and coarse silt than did the B_2 and C_1, more than can be accounted for by clay migration into the B_2 and C_1 horizons. The deep till sample contained somewhat more clay and reflects the fine texture of the shale-derived till of southeastern Wisconsin.

Clay Mineralogy

Soils developed in loess

The clay mineralogy for Tama soil (B_1 horizon, Fig. 2 and Table 3) is similar to that of the various clay fractions from other soils (Fanning, 1964) developed in loess in southern Wisconsin. Montmorillonite is the most abundant clay mineral and in the fine clay it is the dominant mineral. With increasing particle size from the fine through the coarse clay, the percentage of montmorillonite decreases and that of mica and vermiculite increases. Kaolinite is present in both the coarse and medium clay fractions; small amounts of quartz and feldspars are present in the coarse clay. An increase in pedogenic chlorite (14 Å spacing after 550°C heating) occurs in the fine silt and coarse clay with approach to the surface of the Tama soil (Glenn *et al.*, 1960). The increase is more marked (Fig. 3) in the Dane soil (developed under forest) than in the Waupun and Tama soil (developed under grass). The Dane soil profile was acid throughout (Table 1) and the chlorite of the fine silt and clay fractions of this soil is probably aluminous and dioctahedral. A mechanism for the formation of " pedogenic " chlorite during acid weathering involves

TABLE 3.—CLAY MINERALOGY OF VARNA AND TAMA, B HORIZONS

	% Minerals (carbonates and free iron oxides removed)							
	Varna B_2 on till, southeastern Wis.				Tama* B_1 on loess, southwestern Wis.			
Mineral	c†	m	f	Total	c	m	f	Total
Mica	50	46	38	48	29	17	8	18
Kaolinite	0	0	0	0	11	11	0	8
Chlorite	10	5	0	7	5	Tr	0	2
Vermiculite	12	19	—	12	19	6	0	9
Montmorillonite	—	19	51	12	18	51	70	44
Amorphous	5	10	11	7	5	14	22	13
Quartz	17	0	0	10	8	0	0	3
Feldspars	5	0	0	3	5	0	0	2
Anatase	—	—	—	1	—	—	—	1
Of total clay, %	61	25	14	100	35	34	31	100

* Data of Glenn *et al.* (1960).

†c = coarse clay, 2–0.2μ; m = medium clay, 0.2–0.08μ; f = fine clay, <0.08μ.

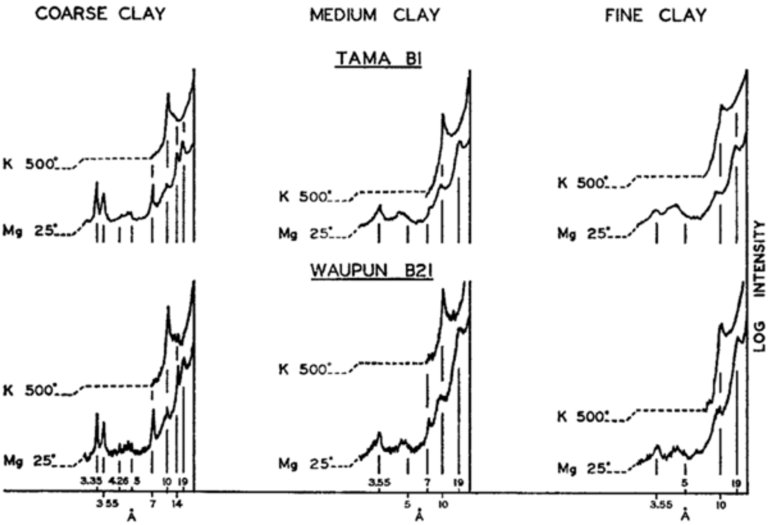

FIG. 2. X-ray diffraction patterns showing the mineralogical similarity of the Tama (loess, southwestern Wisconsin) and Waupun (loess, southcentral Wisconsin) B horizon clay fractions. Mg 25° = Mg saturation, glycerol solvation at room temperature; K 500° = K saturation, then heating at 500°C for 2 hr.

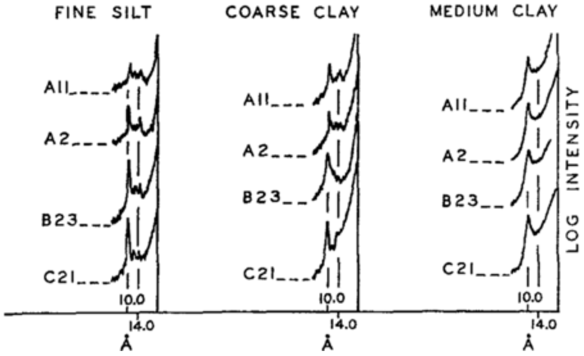

Fig. 3. X-ray diffraction patterns of K saturated Dane fractions after heating at 550°C, showing an increase in chlorite with approach to the soil surface.

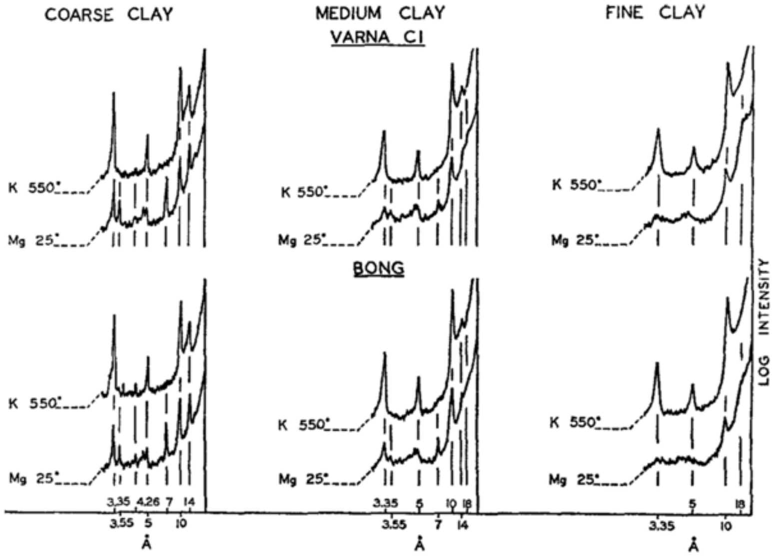

Fig. 4. X-ray diffraction patterns showing the similarity in mineralogy within various clay fractions of the Bong Air Force Base deep till sample and the Varna C_1 horizon. Mg 25° = Mg saturation, glycerol solvation at room temperature; K 550° = K saturation, then heating at 550°C for 2 hr.

TABLE 4.—CLAY MINERALOGY OF VARNA, LESS THAN 2μ FRACTION.

Mineral	% Clay fraction in horizons (after removal of carbonates and free iron oxides)			
	A_p	B_2	C_1	C_3
Mica	42	48	47	53
Chlorite	5	7	9	11
Amorphous material	9	7	7	6
Exp. layer silicates*	30	24	23	16
Quartz	10	10	8	9
Microcline	2	2	3	2
Albite	1	1	1	2
Anatase	1	1	1	1

* Expansible layer silicates (vermiculite and montmorillonite): in the coarse clay mainly vermiculite, in the fine clay mostly montmorillonite, and in the medium clay about equal amounts of the two minerals, according to X-ray diffraction intensities.

the release of aluminum from layer silicate edges and its subsequent polymerization in the interlayers of expansible 2 : 1 layer silicates by steric pinching and hydrolysis effects (Jackson, 1960). The preferential operation of this mechanism at the soil surface, as opposed to the deeper horizons, which in this soil were also acid, may result from the greater biotic activity (larger amounts of carbonic acid) at the soil surface. The greater organic-matter coating of the clay particles in the soils developed under grass is associated with a higher content of expansible clays and a lower content of pedogenic chlorite.

Soil developed in shale-derived till

In the Varna soil, dioctahedral mica was abundant in all clay fractions (Tables 3 and 4). Trioctahedral chlorite was present in the fine silt, coarse clay and medium clay (Figs. 4 and 5 and Table 3), as the main source of the 7 Å peak with unheated specimens (Fig. 4). The absence or near absence of kaolinite in these fractions was shown by NaOH selective dissolution, intersalation and dissolution of the chlorite in boiling 0.1 N HCl, which concurs with previous studies (Dixon and Jackson, 1960; Andrew, Jackson and Wada, 1960). The percentage of expansible 2 : 1 layer silicates increased with proximity to the soil surface (Table 4) and with decreasing particle size (Table 3). Some quartz and feldspars occur in the coarse clay (Table 3). Amorphous material represents the total SiO_2, Al_2O_3 and Fe_2O_3 dissolved from the various fractions when they were boiled in 0.5 N NaOH for 2½ min (Hashimoto and Jackson, 1960) followed by $Na_2S_2O_4$ extraction. Anatase represents, to the nearest

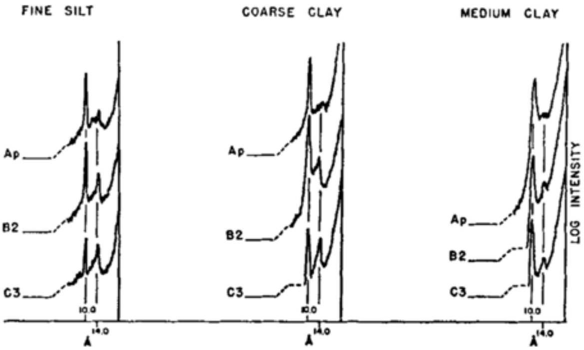

FIG. 5. X-ray diffraction patterns of K saturated Varna fractions after heating at 550°C, showing a decrease in chlorite (14 Å peak) with approach to the soil surface.

per cent, the TiO_2 as determined by elemental analysis. That the clay minerals in the Varna solum have been largely inherited from the parent material is indicated by the similarity of the mineralogy between the soil, the C_1 horizon, and the deep till sample (Fig. 4).

Some transformation of mica and chlorite to expansible layer silicates and amorphous material in the soil profile is indicated (Table 4). The transformation, mica ⟶ expansible 2 : 1 layer silicate + K, has been achieved artificially through the precipitation of K with tetraphenylboron and other methods, by many workers; however, this reaction is reversible. It is suggested that the chemical activity of K in waters that have percolated through the Varna soil profile (which is " mica rich ") has been built up largely in the horizons near the soil surface, and little reaction has occurred in the deeper horizons.

Weathering of chlorite with approach to the soil surface is indicated by the loss of the 14 Å peak of K-saturated fractions that had been heated at 550°C for two hours (Fig. 5). The weathering transformation of chlorite to expansible layer silicates has been suggested previously (Droste, Bhattacharya and Sunderman, 1962). The transformation of mafic chlorite to an expansible layer silicate by removal of the brucite layer through acid treatment could not be achieved because the octahedral layer of the 2 : 1 portion of this chlorite was attacked as rapidly as the brucite layer (in accord with Brindley and Youell, 1951). The tetrahedral sheets, which decompose at a much slower rate than the octahedral sheet on weathering of the chlorite, may yield the increase in amorphous material high in silica in Varna soil (Table 4) as the soil surface is approached. Since the ratio of ferrous to total iron decreased both with decreasing particle size and with approach to the soil surface (Table 5), as did the chlorite, the ferrous iron in these fractions may occur in the mafic chlorite. The oxidation of ferrous iron, perhaps causing lattice instability, has been suggested as a factor in chlorite weathering (Murray and Leininger, 1956). Chlorite weathering has probably been retarded by (a) the

TABLE 5.—TOTAL FE AS PER CENT ELEMENTAL FE AND RATIO OF FE^{2+} TO TOTAL FE FOR THE VARNA CLAY AND FINE SILT FRACTIONS*

Horizon	Fine silt		Coarse clay		Medium clay		Fine clay		Total clay	
	% Fe	$\frac{\text{Fe}^{2+}}{\text{Total Fe}}$	% Fe	$\frac{\text{Fe}^{2+}}{\text{Total Fe}}$	% Fe	$\frac{\text{Fe}^{2+}}{\text{Total Fe}}$	% Fe	$\frac{\text{Fe}^{2+}}{\text{Total Fe}}$	% Fe	$\frac{\text{Fe}^{2+}}{\text{Total Fe}}$
A$_p$	1.69	n.d.†	3.48	0.35	5.03	0.15	5.83	0.10	4.48	0.21
B$_2$	2.38	0.59	3.89	0.42	4.64	0.16‡	5.11	0.13	4.29	0.30
C$_1$	2.30	0.63	3.85	0.52	4.52	0.29	5.71	0.10‡	4.46	0.33
C$_3$	2.32	n.d.	4.15	0.47	4.79	0.26	5.38	0.12‡	4.43	0.36
Av.	2.35	0.61	3.84	0.44	4.75	0.21	5.50	0.11	4.42	0.30

* After removal of carbonates, organic matter and free iron oxides, 110°C dry basis.

† n.d. = no determination.

‡ Value probably somewhat too low because of frothing over during fusion when ferrous iron was determined.

dolomitic limestone in the Varna B_3 and C horizons, which maintained the pH near or above neutral (Table 1) and a high activity of Mg^{2+} in the soil solution, and (b) the fine soil texture, which provides a less oxidizing environment.

DIFFERENCE IN WEATHERING

The soils developed in loess in southwestern and southcentral Wisconsin were found to be coarser in texture, leached of carbonates to much greater depths and more acid than the soils developed in the shale-derived till of southeastern Wisconsin (Table 1). Loess in the Upper Mississippi Valley region is leached of carbonates to depths of about 75 to 150 in. and the solums of soils developed in this loess are normally acid throughout (North Central Regional Publication No. 46, 1955). The pH values of the B horizons are typically about 5 (Table 1). In the Tama soil profile, calcareous loess was encountered at a depth of 144 in. In the Fayette soil profile a slightly calcareous zone was found at a depth of 88 in.; the noncalcareous IIC_4 and $IIIC_5$ horizons are probably remnants of a paleosol occurring below the calcareous zone. Loess in much of southern Wisconsin is shallower than 100 in. (Fig. 1) and is leached of carbonates throughout.

In contrast, the Varna and Morley soils of southeastern Wisconsin and northeastern Illinois are normally leached of carbonates to a depth of 25 to 30 in. (Watson, 1961; Lincoln Laboratory Staff, 1959; Wascher *et al.*, 1960). The Varna profile of the present study was leached of carbonates to a depth of 16 in. and the carbonate content of the B_3 horizon (16–23 in.) was diminished to 23 per cent $CaCO_3$ equivalent, compared to 30 per cent in the C horizons (Lincoln Laboratory Report, 1959). The somewhat shallower than average depth of leaching in this profile appears to be related to a slightly higher than average content of carbonate minerals in the till at this site. The pH values of the solum of this Varna profile (Table 1) were also somewhat higher than the average of around pH 6 for the Varna soil series.

The clay minerals of the B_1 horizon of the Tama soil, which developed in loess in southwestern Wisconsin, are generally more advanced in their weathering indices (Jackson, 1964) than the B_2 horizon of the Varna soil which developed in the shale-derived till of southeastern Wisconsin (Table 3 and Fig. 6). The clay of Tama soil contains high percentages of expansible 2:1 silicates (mainly montmorillonite, of weathering index 9), chlorite (which increases with proximity to the surface and thus is apparently "pedogenic", index 9), kaolinite (index 10) and amorphous material. In contrast, the clay of the Varna contains high percentages of mica (index 7), mafic chlorite (index 4) and quartz (index 6). Additionally, the expansible layer silicates of the Varna contain a higher proportion of vermiculite (index 8).

The more highly weathered nature of the clay of the soils developed in the loess (as represented by the Tama) corresponds to the coarser texture of the loess (silt loam), greater depth of leaching of carbonates and greater acidity

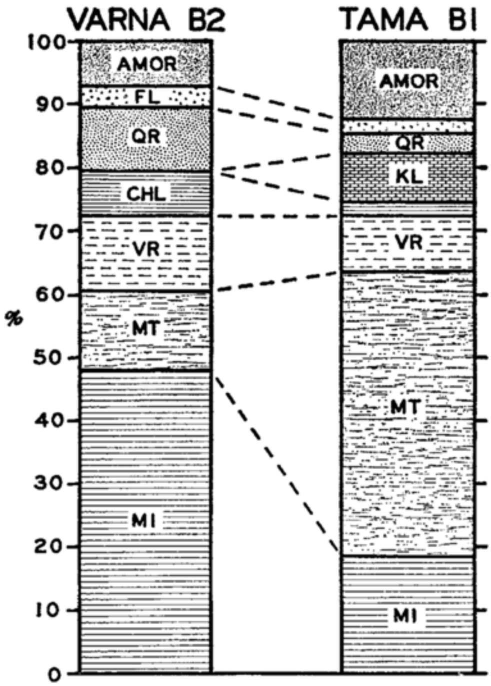

FIG. 6. Bar graph illustrating the differences in mineralogy of the less than 2μ B horizon clay of the Varna (in till, southeastern Wisconsin) versus the Tama (in loess, southwestern Wisconsin). MI = mica, MT = montmorillonite, VR = vermiculite, CHL = chlorite, KL = kaolinite + halloysite, QR = quartz, FL = feldspars, AMOR = amorphous material.

than of soils developed on till in southeastern Wisconsin. It also corresponds with the somewhat higher zirconium content of the coarse silt fractions of the soils developed in loess than of those developed in till in southeastern Wisconsin, as determined by X-ray fluorescence (Table 6).

Since Zr occurs primarily in the resistant mineral zircon, the lower Zr content of the till from southeastern and south central Wisconsin may reflect less intensive weathering compared to more highly weathered till in west central Wisconsin and loess.

Part of the differences in clay mineralogy of the Tama compared to the Varna (Fig. 6) has been inherited from the soil parent materials. A large percentage of the mica, chlorite and quartz in the Varna soil profile has been inherited from the shale-derived till; however, it is much more difficult to predict what proportion of the clay minerals of the Tama and other soils that developed in the loess has been inherited from the parent material. It is known that Cretaceous deposits exist locally in western Wisconsin, in Minnesota, and in other states in the upper Mississippi River Valley region. The

TABLE 6.—X-RAY FLUORESCENCE ANALYSES FOR ZIRCONIUM

Material and location in Wis.	Samples analysed	% Zr in coarse (20–50 μ) silt ($CaCO_3$, organic matter and Fe_2O_3 removed) Av.	Range
Till—West Central	22	0.062	0.051–0.078
Loess—South Central	7	0.060	0.048–0.067
Loess—Southwest	16	0.058	0.050–0.068
Till—Southeast and South Central	11	0.044	0.035–0.053

clay of Cretaceous deposits often contains a high proportion of kaolinite and montmorillonite (Frye, Willman and Glass, 1964). Thus some of the montmorillonite and kaolinite in the soils developed in loess in southwestern Wisconsin may have been derived from Cretaceous materials.

Alternatively, it has been shown (Glenn *et al.*, 1960) that the weathering of mafic minerals of the silt was quantitatively equivalent to the increase in montmorillonite as a function of proximity to the soil surface in the Tama profile. Also, as discussed by Jackson (1964, p. 123), " pedogenic " chlorite and kaolinite can develop from montmorillonite in an acid profile. The similarity in the clay mineralogy of the soils developed in loess in south central Wisconsin to that of those developed in southwestern Wisconsin also appears to support a present cycle pedogenic-weathering origin for the montmorillonite and kaolinite in these soils, since the loess of south central Wisconsin had a different source area and is farther removed from any known Cretaceous deposits.

It is further proposed that much of the difference in clay mineralogy of the Tama as opposed to the Varna may be caused by the lower initial clay content of the loess (wind-sorted rock flour from Cambrian sandstone and Laurentian granitic area), contrasting with the shale-derived till. With a lower initial clay content of the loess, a unit amount of clay formed during pedogenesis (of the more advanced weathering indices, such as montmorillonite) dominates the clay mineralogy of the soils developed in loess more than a unit amount of pedogenic clay mixed in mica and chlorite dominated till of southeastern Wisconsin. An analogous situation appears to have been encountered by Wascher *et al.* (1960), who reported that the percentage of montmorillonite in the clay of some Illinois soils, developed in till, increased as the texture of the till became coarser.

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