

TIME FACTOR AND THE GENESIS OF SOILS ON EARLY WISCONSIN TILL^{1, 2}

by

D. R. HENSEL³ AND JOE L. WHITE

Agronomy Department, Purdue University, Lafayette, Indiana

ABSTRACT

Radiocarbon dates indicate that the maximum time of weathering for soils of the Tazewell substage may be about 6400 years longer than that available for weathering of soils of the Cary substage.

Detailed mineralogical and chemical studies were made of the 2-0.2 μ fractions of 0-6 in. and 30-36 in. samples from 24 sites along a traverse extending from the Cary substage across the Tazewell substage in east-central Indiana. The major clay mineral constituents of the 0-6 in. samples were illite and 14 Å material; illite and montmorillonite were the main components in the 30-36 in. samples. The correlation coefficients between illite content and percentage K₂O for the 0-6 in. and 30-36 in. samples were 0.85 and 0.92, respectively.

The end and terminal moraines of the Tazewell substage were found to have a higher illite content than the ground moraines. This was attributed to superglacial movement and enrichment of foreign materials, i.e. mica schists from the Canadian shield, on end and terminal moraines.

The results of saturation of the clay fraction with potassium and magnesium on the proportion of 10 Å, 12.7 Å and 14 Å spacings indicated that weathering had lowered the surface charge density of the micaceous minerals in the 0-6 in. samples to a greater extent than in the 30-36 in. samples. This effect, in addition to other weathering reactions, resulted in partially expanded micaceous minerals in the 0-6 in. samples which were much more resistant to collapse than were the minerals in the 30-36 in. samples.

The rate of weathering of K₂O from the 2-0.2 μ fraction of the 0-6 in. samples located on ground moraines was estimated to be about 0.1 percent per 1000 years. This value was used in estimating the ages of the morainic systems of the Tazewell in Indiana. The estimated ages were as follows: Mississinewa, (radiocarbon date) 13,140 years; Union City, 14,500 years; Bloomington, 15,500 years; Champaign, 18,700 years; Shelbyville, (radiocarbon date) 19,500 years.

The fertility status of the soils on the Tazewell has been influenced appreciably by the length of the weathering period, the potassium-supplying power of the soils decreasing with increasing age.

¹ Journal Paper no. 1347, Purdue University Agricultural Experiment Station, Lafayette, Indiana.

² Grateful acknowledgement is made to the National Science Foundation for a grant (NSF G-2157) made through the Purdue Research Foundation (PRF 1254) which provided the x-ray diffraction equipment used in this study.

³ Present address, Soils Department, Rutgers University, New Brunswick, N.J.

INTRODUCTION

Radiocarbon dating technique (Libby, 1956) has led to a well-established chronology of the Wisconsin stage of glaciation in North America. Measurements by Suess (1956) and by Rubin and Suess (1955) have established the times of the Cary and Tazewell substages in the Midwest (Fig. 1). The radiocarbon date on a sample of wood (W-165) collected near Greencastle, Indiana, indicates a Tazewell age of 19,500 years. A Cary date of 13,140 years was obtained on a sample of Gytta (W-64) from Wabash County, Indiana. Consideration of all radiocarbon dates from the Midwest indicate

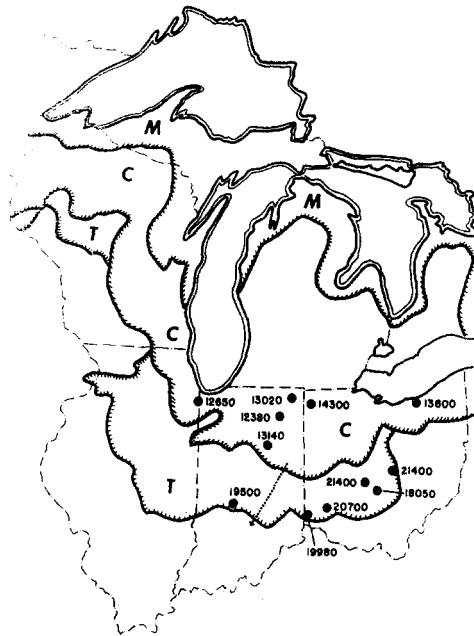


FIGURE 1.—Glacial boundaries and distribution of surface samples dated by radiocarbon in the Midwest. M, Mankato; C, Cary; T, Tazewell (after Horberg, 1955).

Cary dates of between 12,000 and 14,000 years and an interval extending from about 17,000 to 22,000 years for the Tazewell.

Of particular interest in this study is the apparent difference of approximately 6400 years in the weathering intervals for soils on the Tazewell and Cary tills. Would such a difference as this be manifested in the degree of weathering of the soils after 13,000 years, or would all differences be obliterated due to attainment of an equilibrium condition in a relatively short period of time?

Since it has been shown that the clay fraction of the Wisconsin till in the Midwest is high in illite (Droste, 1956; Klages and White, 1957), it was postulated that the illite and potassium content of the clay fraction might

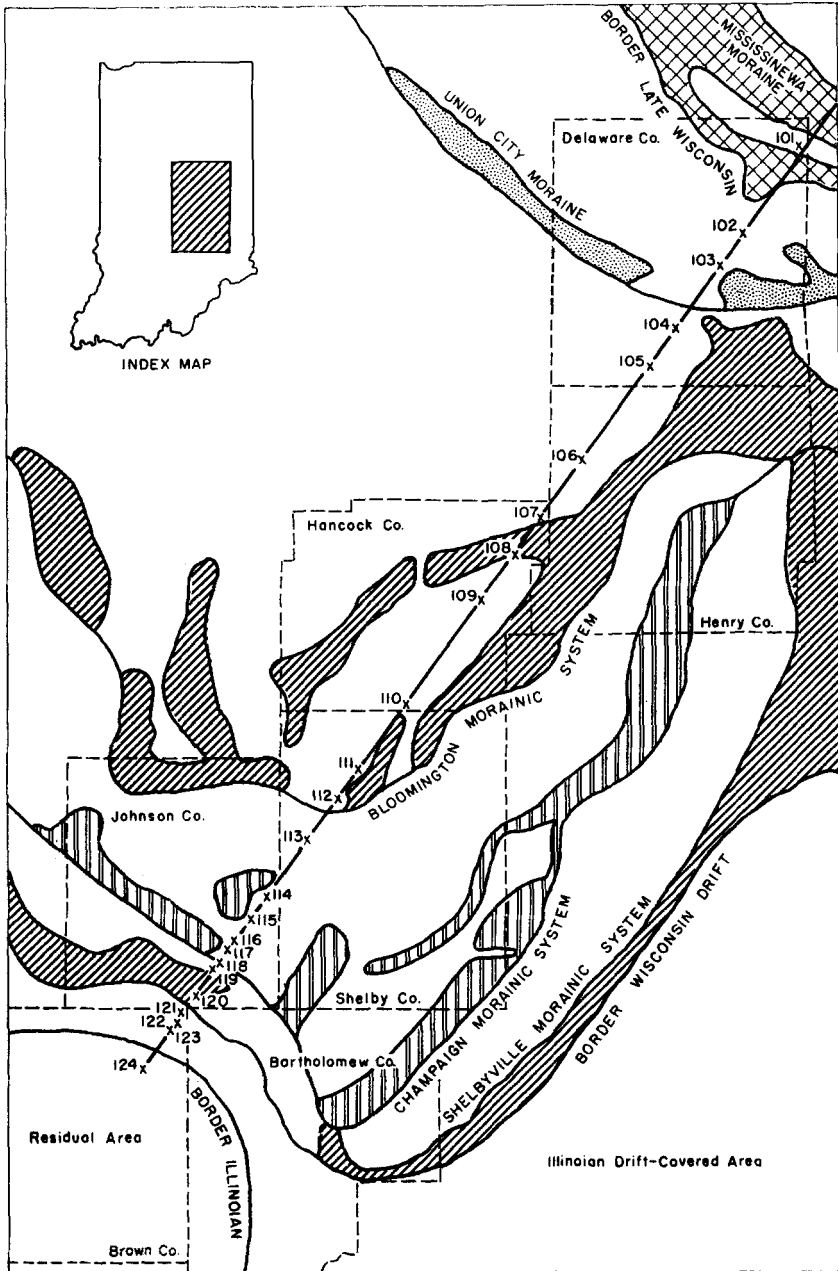


FIGURE 2.—Map showing location of traverse, sample sites and moraines.

be related to age and degree of weathering of surficial deposits in the Tazewell and Cary areas. It was assumed that the clay in the unweathered Wisconsin till was reasonably uniform in composition and that the degree of weathering was rather mild. It was thought that the differences due to duration of weathering of the soils might persist today and permit the determination of an approximate rate of weathering.

EXPERIMENTAL METHODS

Twenty-four individual sample sites were selected primarily in the Tazewell drift area along a traverse parallel to the direction of ice movement. Collection of samples commenced at the northern end of the traverse just inside the Cary boundary (Mississinewa moraine) and extended southward along the traverse to the unglaciated area (Fig. 2).

Soil samples representing imperfectly drained soil (the II drainage profile of Bushnell, 1944) were collected along the traverse from the following areas and catenas: Cary-Morley, Tazewell-Miami and Russell, Illinoian-Cincinnati, and unglaciated-Zanesville. Samples were taken at depths of 0-6 in. and 30-36 in. at each sample site.

Chemical and mineralogical analyses were made on each sample. These included pH determinations, available potash on total soil, total K_2O in the 2-0.2 μ clay fraction, mineralogical composition of the clay fraction, and the effects of magnesium and potassium saturation on the proportion of 10 Å, 12.7 Å, and 14 Å spacing in the 2:1 layer silicates.

pH Determinations

The pH determinations were made on 1:1 soil-water suspensions with a Beckman Model H-2 glass electrode pH-meter.

Available K_2O

Five grams of 10-mesh air-dried soil were extracted with 15 ml of 0.75 N HCl by shaking for 2 min and filtering immediately through no. 402 S & S filter paper. Potassium was then determined in the filtrate with a Perkin-Elmer Model 146 flame photometer using lithium as the internal standard.

Total K_2O in Coarse Clay

The hydrofluoric acid method of Berzelius (Treadwell and Hall, 1947) was used to decompose the coarse clay fraction (2.0-0.2 μ) of the soils. Total potassium was then determined with the Perkin-Elmer Model 146 flame photometer using the direct method.

Preparation and x-ray Diffraction Analysis of Clay Specimens

Clay specimens were prepared by use of the porous tile technique of Kinter and Diamond (1955). Thus it was possible to follow the effect of glycol solvation, magnesium saturation and potassium saturation on the same

sample with a minimum of change in the orientation in the specimen. To minimize hydration effects on the magnesium-saturated samples, a cylindrical chamber having a Saran window was placed over the specimen and dry nitrogen gas passed through the chamber while the diffractometer tracing was being made.

In order to make the diffraction intensities of the various treatments directly comparable, a quartz standard was used to adjust the kV setting for the copper tube so that intensities with and without the Saran window cover were equal.

Mineralogical Composition of the Coarse Clay Fraction

The clay mineral composition of the coarse clay fractions was estimated by a combination of the methods of Johns, Grim and Bradley (1954) and Talvenheimo and White (1952). The former was used for the 2:1 layer silicates and the latter for estimation of kaolinite.

TABLE 1.—CHEMICAL DATA FOR 0-6 IN. AND 30-36 IN. SAMPLES

Sample No.	Distance along Traverse (miles)	0-6 in. Samples			30-36 in. Samples		
		pH	Available K ₂ O (lb/ac)	Total K ₂ O in Clay (%)	pH	Available K ₂ O (lb/ac)	Total K ₂ O in Clay (%)
101	0.0	6.1	200	2.93	7.7	182	2.90
102	8.0	6.9	164	2.68	8.0	119	4.43
103	11.5	7.1	182	2.89	6.9	169	3.35
104	17.0	5.4	160	2.71	6.4	152	2.47
105	19.8	6.8	169	2.77	7.7	160	3.45
106	28.7	6.3	152	2.70	8.2	160	4.06
107	35.0	6.8	160	2.71	8.0	160	2.98
108	38.5	7.1	191	2.69	8.0	111	3.80
109	41.5	7.2	160	2.55	8.1	90	3.77
110	52.5	6.8	90	2.63	7.0	144	2.64
111	57.5	6.0	224	3.19	5.4	268	3.71
112	61.5	6.7	360	3.38	5.8	298	3.98
113	64.0	7.4	111	2.59	6.8	191	2.65
114	70.0	7.3	98	2.23	7.7	144	3.54
115	73.2	6.7	127	2.17	7.2	148	2.57
116	75.0	7.2	77	2.21	7.4	115	2.57
117	75.5	6.3	106	2.09	6.8	111	2.40
118	77.0	7.1	127	2.13	7.0	173	2.29
119	78.3	7.1	81	2.38	6.0	102	2.36
120	80.5	5.7	106	3.04	6.2	144	2.93
121	81.5	4.9	160	2.89	5.1	164	2.63
122	81.8	5.3	94	2.77	5.6	204	2.73
123	82.2	5.6	94	2.69	6.7	195	2.62
124	82.5	6.9	160	3.63	5.1	90	3.67

RESULTS AND DISCUSSION

pH Values

Examination of the pH values of the samples as a function of distance along the traverse (Table 1) shows two pH minima in the Tazewell area. The first occurs in the vicinity of the Union City moraine (sample no. 104) and is manifested by low values for both the 0–6 in. and 30–36 in. samples. The second minimum in the Tazewell area occurs near the southern border of the Bloomington morainic system (sample nos. 111 and 112). The pH of the surface samples in the Illinoian area ranges from 4.9 to 5.7 with an average of 5.4. The average pH value for the 30–36 in. samples in the Illinoian area is 5.9. Neglecting the 3 samples in which minimum pH values occur, the average pH of the 0–6 in. samples in the Tazewell area is 6.9 while that of the 30–36 in. samples is 7.4. There appears to be no consistent trend in pH values within the Tazewell area with respect to age.

Available K₂O

There is good agreement between locations of terminal moraines and maxima in acid-soluble potassium for the 0–6 in. samples (Fig. 3). In the 30–36 in. samples these relationships are less pronounced. The relation of these observations to the glacial geology of the area and to soil weathering processes will be discussed after presentation of the mineralogical data.

Total K₂O in Clay Fraction

The total K₂O content of the 0–6 in. coarse clay fraction tends to decrease from 2.9 to about 2.2 percent in going from the Cary to the southern border of the Tazewell (Fig. 4). There are several maxima, the most pronounced ones being on the southern border of the Bloomington and Champaign morainic systems.

The total K₂O content of the 30–36 in. clay fraction shows much more fluctuation than that of the surface samples (Fig. 5). There are pronounced minima in samples on or just behind each terminal moraine. The illite content follows a very similar pattern. The suggested reasons for these variations will be given in the discussion on the mineralogical composition of the clay fraction.

Mineralogical Composition of the Clay Fraction

The order of abundance of clay minerals in the 0–6 in. samples was illite > 14 Å mineral > montmorillonite > kaolinite; for the 30–36 in. samples the order was illite > montmorillonite > 14 Å mineral > kaolinite (Table 2). There were several distinct maxima and minima for illite in both the 0–6 in. and 30–36 in. samples. The proportion of 2:1 lattice minerals (illite, montmorillonite and 14 Å mineral) in the 0–6 in. and 30–36 in. samples is shown in Fig. 6.

In the 0–6 in. samples the illite maxima coincide closely with the location

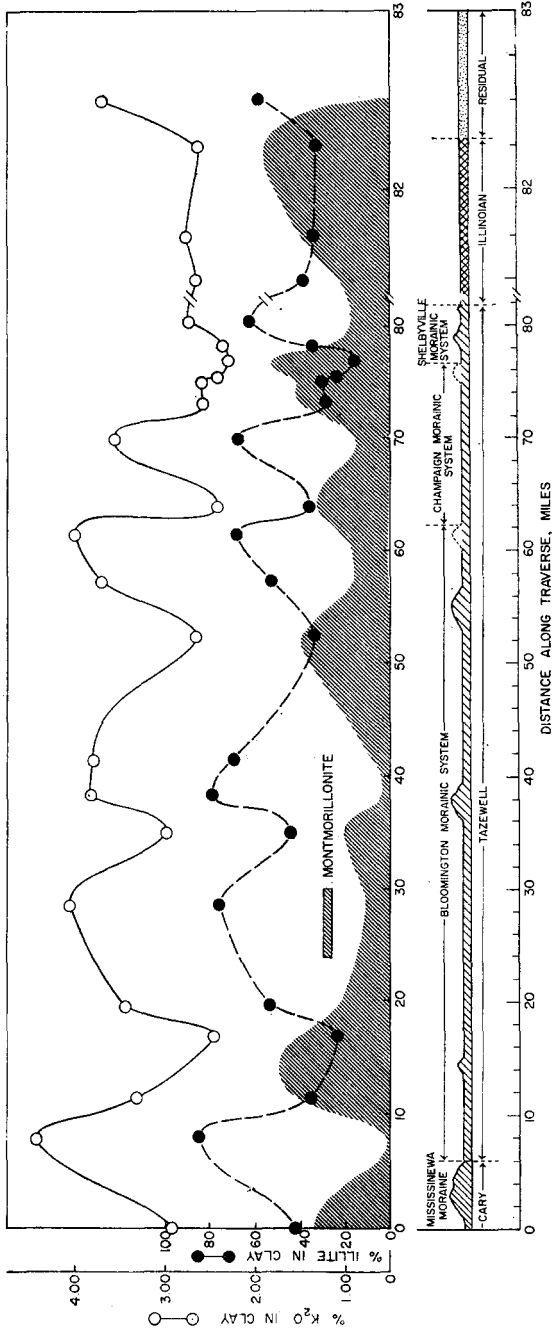


FIGURE 3.—Variation in available K₂O (lb/ac) in whole soil and percentage illite in the 2.0-2.2 μ fraction of 0-6 in. samples along traverse.

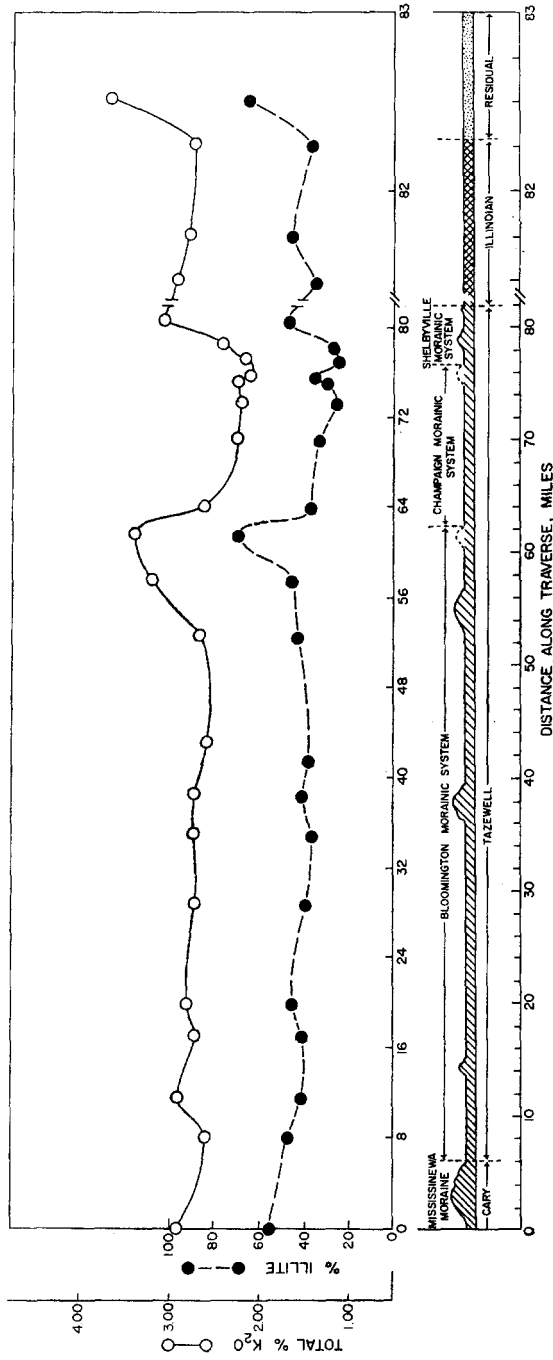


FIGURE 4.—Variation in percent total K₂O and illite content of the 2-0.2μ fraction of 0-6 in. samples along traverse.

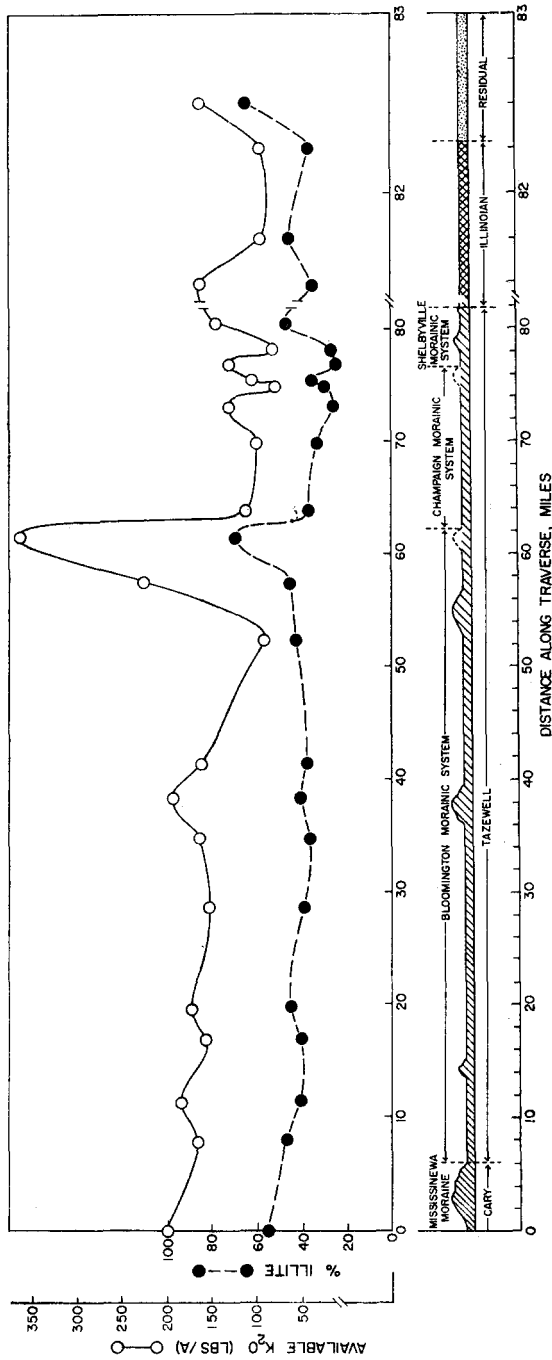


FIGURE 5.—Variation in percentage total K_2O , illite and montmorillonite content of the 2-0.2 μ fraction of 30-36 in. samples along traverse.

TABLE 2.—ESTIMATED CLAY MINERAL COMPOSITION OF THE 2-0.2 μ FRACTIONS (PERCENT)

Sample No.	0-6 in. Samples				30-36 in. Samples			
	Montmorillonite	14 Å Mineral	Illite	Kaolinite	Montmorillonite	14 Å Mineral	Illite	Kaolinite
101	12	24	58	6	32	16	43	9
102	14	34	46	6	—	7	84	9
103	14	37	41	8	40	11	36	13
104	17	36	40	7	39	24	24	13
105	17	30	44	9	21	16	53	10
106	24	31	38	7	11	7	75	7
107	18	39	35	8	21	23	44	12
108	27	25	40	8	5	8	78	9
109	13	48	31	8	8	13	69	10
110	7	43	42	8	39	15	33	13
111	10	26	54	10	16	17	52	15
112	6	18	69	7	19	—	67	14
113	12	42	36	10	32	21	35	12
114	15	41	32	12	14	10	67	9
115	22	43	25	10	40	20	29	11
116	19	33	39	9	38	21	29	12
117	16	38	35	11	42	21	24	13
118	22	42	24	12	52	21	16	11
119	19	41	27	13	28	23	34	15
120	14	28	47	11	17	10	62	11
121	6	46	35	13	22	23	38	17
122	15	35	45	5	38	17	33	12
123	21	31	37	11	55	—	32	13
124	5	23	64	8	—	22	58	20

of terminal moraines (Fig. 3). The agreement in the location of maxima for percentage of illite, total K_2O in the coarse clay and acid-soluble K_2O points very definitely to a higher mica content in the terminal moraines than in the ground moraines. Jørstad (1957) has reported a study of Norwegian moraines which showed that the ratio of local material to foreign material was about 80/20 in the ground moraine and 20/80 in the terminal moraines.¹ The reversal in this relationship was ascribed to superglacial movement and enrichment of foreign materials on terminal moraines. Thus, for the Midwest it might have been possible for foreign material, i.e. mica schists from the Canadian shield, to accumulate preferentially at the front of the glacier, particularly when the rate of melting was almost equal to the rate of advance.

Thus, it would appear that measurement of any one of these three quantities, i.e. percentage illite in clay fraction, total K_2O in clay fraction or acid-soluble K_2O , would aid in establishment of locations of morainic systems and in fixing of glacial boundaries for the Cary and Tazewell substages in the

¹ Dr. Wayne Harrison of the Indiana Geological Survey very kindly brought this work to our attention and suggested that a similar situation might occur on the Tazewell.

Midwest. The most convenient method would be the determination of acid-soluble K_2O .

In the 30-36 in. samples from the Tazewell area the percent illite values show minima on or just beyond each terminal moraine (Fig. 5). This is in good agreement with the total K_2O content.

The percentage of montmorillonite appears to be inversely related to the percent of illite, and for each 30-36 in. sample having a low illite content there is a corresponding montmorillonite maximum (Fig. 5). It is postulated that these illite minima and montmorillonite maxima on or just behind the terminal moraines are due to weathering of the subsoil clay under conditions

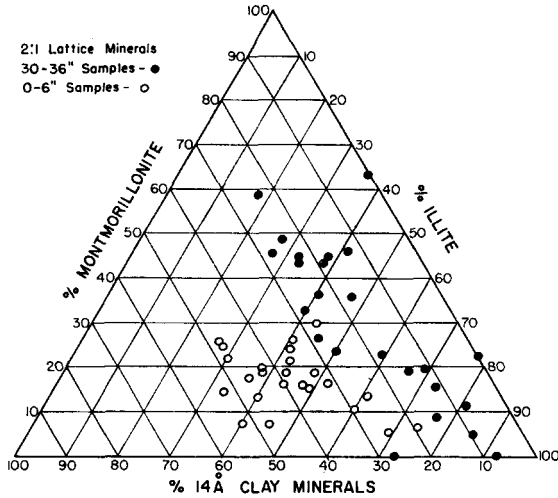


FIGURE 6.—Percentage composition of the 2 : 1 layer silicates in the 2-0.2 μ fraction of the 0-6 in. and 30-36 in. samples.

of poor drainage. Thus one might speculate that the melt water impounded by the terminal moraines contributed to excess moisture and consequent poor drainage in the immediate vicinity of the terminal moraine with the resultant weathering of the illite to montmorillonite (Mitchell, 1955).

As previously mentioned, there was good agreement between percent illite in the coarse clay and total K_2O in the coarse clay, the correlation coefficients for the 0-6 in. and 30-36 in. samples being 0.85 and 0.92, respectively.

Brown (1955) has shown that the theoretical effect of replacing interlayer potassium with oxonium ion (H_3O^+) in micas is to increase the absolute intensity of the 001 reflection. The 002 reflection is increased to a lesser extent. Thus, removal or replacement, or both, of interlayer potassium by an ion having a smaller scattering factor will increase the intensity ratio 001/002.

The slopes of the regression lines for the percent K_2O vs. percentage illite relationship for the 0-6 in. and 30-36 in. samples are very similar, 0.0290 and 0.0299, respectively. In Fig. 7 these slopes have been averaged and the

regression lines plotted. The percent K_2O intercept of the line for the 30–36 in. samples is about 0.25 higher than that of the 0–6 in. samples. Thus for a given K_2O content, the more highly weathered 0–6 in. samples appear to contain approximately 8 percent more illite than the 30–36 in. samples. These data are in qualitative agreement with the effects predicted by Brown (1955).

A comparison of the mica 001/002 intensity ratios for 14 pairs of surface (0–6 in.) and subsurface (30–36 in.) samples from ground moraines in the Tazewell area of Indiana showed the mean 001/002 ratio for the 0–6 in. samples to be 3.75 ± 0.173 , while that for the 30–36 in. samples was 2.02

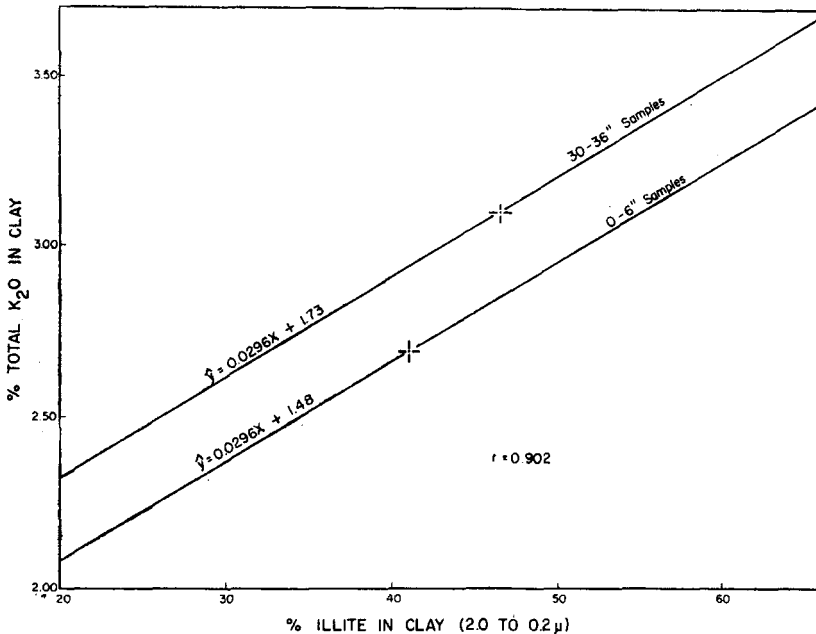


FIGURE 7.—Relationships between total K_2O and percentage illite in the 2–0.2 μ fraction of the 0–6 in. and 30–36 in. samples using the average slope of the regression lines.

± 0.180 . The difference between means was 1.73 ± 0.259 . A t -test on the difference between means indicated a significance at the 1 percent level. Thus, the 001/002 intensity ratio is about 1.85 times greater for the surface samples than for the subsurface. This is also in agreement with the postulated effects of weathering on the mica 001/002 intensity ratio.

Effect of Potassium Saturation and Magnesium Saturation on Proportion of 10 Å, 12.7 Å and 14 Å Spacings in the 2 : 1 Layer Silicate

Magnesium and potassium treatments were selected to aid in differentiation of weathering stages of the micas. Norrish (1954) has suggested a close

relationship between hydration energy of cations and surface charge density on swelling of 2:1 layer silicates. The hydration energy of magnesium is over five times that of potassium. Thus, for micaceous minerals having a surface charge density of from 0.6×10^5 to 1×10^5 e.s.u./cm², magnesium saturation produces a spacing of approximately 14 Å, whereas potassium treatment gives a spacing of from 10 to 11 Å.

Three spacings, 14 Å, 12.7 Å and 10 Å, were produced in various proportions as a result of the magnesium and potassium treatments on the 2:1 minerals. The 14 Å spacing was considered to represent expanding or highly weathered mica; the 12.7 Å spacing was considered to represent the partially expanding

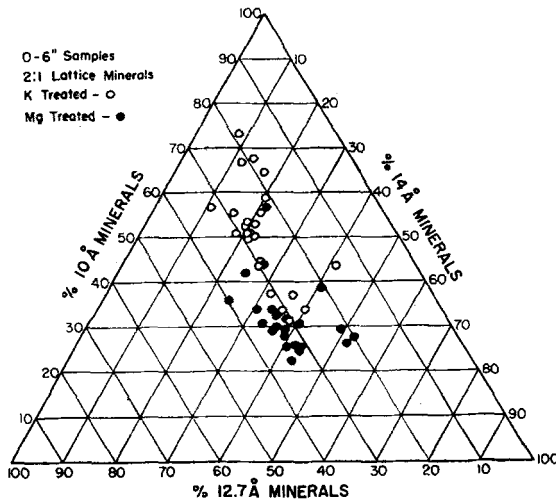


FIGURE 8.—The effect of K and Mg saturation on the percentage of 2:1 layer silicates having spacings of 10 Å, 12.7 Å, and 14 Å in the 2-0.2 μ fraction of the 0-6 in. samples.

mica intermediates; the 10 Å spacing represents nonexpanding, relatively unweathered mica. The results are summarized in Figs. 8 and 9.

The number of samples having a high proportion of 10 Å spacing was increased only slightly for the 0-6 in. samples by potassium saturation. Thus it is concluded that weathering has resulted in substantial lowering of the surface charge density of partially expanded minerals in this layer. The presence of hydrated aluminum ions may also prevent complete collapse. The number of 30-36 in. samples showing 41-80 percent of the 10 Å spacing in the untreated specimens was almost doubled by potassium saturation. This indicates that the partially expanded minerals in this layer have a considerably higher surface charge density than those in the 0-6 in. samples.

The proportion of 12.7 Å component in the 0-6 in. samples was affected to about the same extent by both magnesium and potassium saturation (Fig. 8). In the 30-36 in. samples, however, saturation with potassium resulted in half the samples having 0-20 percent of the 12.7 Å component, and half having

21–40 percent (Fig. 9). Magnesium saturation caused an approximate doubling of the number of samples showing 21–40 percent of the 12.7 Å component, when compared to the potassium saturation treatment. These observations indicate that the stability of the 12.7 Å material is appreciably greater in the 0–6 in. samples than in the 30–36 in. samples. It is postulated that weathering has resulted in partially expanded micaceous minerals in which resistance to collapse is a function of intensity of weathering.

Potassium saturation reduced the number of samples having a high proportion of the 14 Å component in both the 0–6 and 30–36 in. samples. This reduction was much more marked in the 30–36 in. samples and this again indicates a high surface charge density for these minerals (White, 1958).

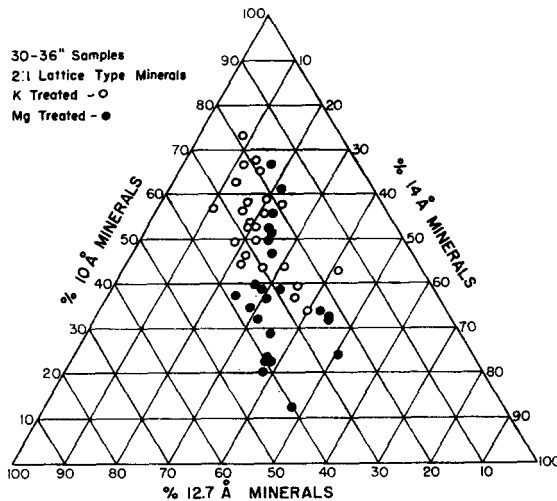


FIGURE 9.—The effect of K and Mg saturation on the percentage of 2 : 1 layer silicates having spacings of 10 Å, 12.7 Å and 14 Å in the 2–0.2 μ fraction of the 30–36 in. samples.

Estimation of Rate of Weathering and Age of Morainic Systems

All evidence obtained in this study indicates a higher mica content in the terminal and end moraines. It was suggested that this might be explained by a higher ratio of foreign to local materials in end moraines than in ground moraines (Jørstad, 1957). Omitting, therefore, the samples on or adjacent to end moraines and examining the chemical and mineralogical data for the 0–6 in. samples from ground moraines (Table 3) one can see that there is a general decrease in the content of K_2O and illite in the coarse clay and a decrease in acid-soluble potassium with distance along the traverse. Assuming that the composition of the clay materials in the Wisconsin till was initially rather uniform, it is possible to calculate approximate rates of weathering. Data from Table 3 show that the ground moraine associated with the earliest morainic system of the Tazewell, the Shelbyville, has an average of 2.25 per-

TABLE 3.—AVERAGE CHEMICAL AND MINERALOGICAL DATA FOR THE 2-0.2 μ FRACTION, AND WHOLE SOIL OF 0-6 IN. GROUND MORAINIC SAMPLES AND ESTIMATED AGES OF THE VARIOUS MORAINIC SYSTEMS OF THE TAZEWELL SUBSTAGE OF THE WISCONSIN GLACIATION

Morainic System	Sample No.	Total K ₂ O in Clay (average) (%)	Illite (average) (%)	Available K ₂ O (average) (lb/ac)	Estimated Age (years)
Mississinewa	101	2.93	58	200	13,000 ¹
Union City	102	2.78	43	173	14,500
	103				
Bloomington	104	2.68	38	160	15,500
	105				
	106				
	107				
Champaign	109	2.33	31	112	18,700
	113				
	114				
Shelbyville	115	2.25	25	104	19,500 ¹
	118				
	119				

¹ Radiocarbon dates.

cent K₂O in the coarse clay fraction of the soil. The sample from the Cary substage contains 2.93 percent K₂O. Thus there is a difference of 0.68 percent K₂O for a time difference of about 6360 years. Assuming that the K₂O content decreased at a constant rate during this interval and that the soils are of similar origin, one can estimate a decrease of about 0.107 percent K₂O per 1000 years and relative dates can be assigned to the morainic systems. Studies of soils on the Illinoian till indicate a decrease in weathering rate with increasing length of the weathering period. Extrapolation of the estimated rate of weathering over longer time intervals would thus be questionable.

If the total K₂O content of the clay fraction from the sample taken just inside the Mississinewa moraine is used as the reference point for the youngest material, the product of the difference in total K₂O content between the reference and the average value on one of the morainic systems multiplied by the factor (1000/0.107) gives the difference between the ages of the Mississinewa and the morainic system being compared. Applying the factor given above, the estimated ages of the morainic systems were computed and are shown in Table 3 along with averages of the chemical and mineralogical data for the 0-6 in. ground moraine samples.

The fertility status of the soils on the Tazewell has been influenced appreciably by the length of the weathering period. The amount of available K_2O in the whole soil as well as the total K_2O and illite content of the 2–0.2 μ fraction decrease with increasing age.

REFERENCES

- Brown, George (1955) The effect of isomorphous substitutions on the intensities of the (00 l) reflections of mica- and chlorite-type structures : *Min. Mag.*, v. 30, pp. 657–665.
- Bushnell, T. M. (1944) The story of Indiana soils : *Purdue Univ. Agr. Expt. Sta.*, Special Circular 1, 52 pp.
- Droste, J. B. (1956) Alteration of clay minerals by weathering in Wisconsin tills : *Bull. Geol. Soc. Amer.*, v. 67, pp. 911–918.
- Horberg, Leland (1955) Radiocarbon dates and Pleistocene chronological problems in the Mississippi Valley region : *J. Geol.*, v. 63, pp. 278–286.
- Johns, W. D., Grim, R. E. and Bradley, W. F. (1954) Quantitative estimations of clay minerals by diffraction methods : *J. Sed. Petrol.*, v. 24, pp. 242–251.
- Jørstad, F. A. (1957) Stone countings in Quaternary deposits in Solør, southern Norway : *Norsk Geol. Tidsskr.*, v. 37, pp. 257–266.
- Kinter, E. B. and Diamond, S. (1955) A new method for preparation and treatment of oriented-aggregate specimens of soil clays for x-ray diffraction analysis : *Soil Sci.*, v. 81, pp. 111–120.
- Klages, M. G. and White, J. L. (1957) A chlorite-like mineral in Indiana soils : *Soil Sci. Soc. Amer., Proc.*, v. 21, pp. 16–20.
- Libby, W. F. (1956) Radiocarbon dating : *Amer. Scientist*, v. 44, pp. 98–112.
- Mitchell, W. A. (1955) A review of the mineralogy of Scottish soil clays : *J. Soil. Sci.*, v. 6, pp. 94–98.
- Norrish, K. (1954) The swelling of montmorillonite : *Disc. Faraday Soc.*, v. 18, pp. 120–134.
- Rubin, M. and Suess, H. E. (1955) U.S. Geological Survey radiocarbon dates. II : *Science*, v. 121, pp. 481–488.
- Suess, H. E. (1956) Absolute chronology of the last glaciation : *Science*, v. 123, pp. 355–357.
- Talvenheimo, G. and White, J. L. (1952) Quantitative analysis of clay minerals with the x-ray spectrometer : *Analyt. Chem.*, v. 24, pp. 1784–1789.
- Treadwell, F. P. and Hall, W. T. (1947) *Analytical Chemistry*, v. 2, *Quantitative Analysis* (9th Ed.), pp. 418–419 : John Wiley, New York.
- White, J. L. (1958) Layer charge and interlamellar expansion in a muscovite : in *Clays and Clay Minerals*, Nat. Acad. Sci.—Nat. Res. Council, pub. 566, pp. 289–294.