CLAY MINERAL DISTRIBUTION IN THE HIAWATHA SANDY SOILS OF NORTHERN WISCONSIN[1]

By

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ABSTRACT

Mineralogical analyses were made of the clay, silt, and sand fractions of the Podzols Hiawatha loamy sand and Hiawatha sand. The layer silicates show chemical weathering as a function of depth in both soils. A high charge dioctahedral montmorillonite was dominant in all fractions (-5μ) of the A_2 horizon and its origin was attributed to weathering of an interstratified vermiculite-chlorite similar to that in the B_2 horizon. The 2 to 0.2μ fraction of the Hiawatha loamy sand B_2 horizon contains 14 percent chlorite and 18 percent vermiculite with no montmorillonite, and the Hiawatha loamy sand A_2 horizon contains 33 percent montmorillonite with little interstratified chlorite-vermiculite. Quartz also showed a soil depth function in the fine silt. It is higher in amount in the A_2 than the B_2 horizon, attributable to its relative stability in the Podzol A_2. Below the B_2 it drops markedly in amount, attributable to a difference in silt deposition.

The similarity of ratios of resistant heavy minerals (greater than 2.95 sp. gr.) in different horizons indicates uniform origin of the sand fractions of these soils. Light mineral contents in the sand fractions for all analyzed horizons are also similar. However, particle size data indicate silt and possible clay addition to both the A_2 and B_2 horizons.

Depth functions in these soils are developed to a marked extent, apparently owing to (1) low amount of fine fraction originally present for weathering, (2) greater amount of water cycled through the A_2 than the B_2 horizon, (3) rapid and frequent cycling of available water owing to coarse texture, and possibly (4) effects of podzolization. The Omega, Ahmeek, and Iron River soils of northern Wisconsin also showed a similar though not so marked tendency to accumulate montmorillonite in the A_2 horizon.

INTRODUCTION

Sandy soils of Hiawatha and closely related groups cover about 1,000,000 acres of northern Wisconsin and upper Michigan. Related sandy soils cover 10,000,000 acres in this area. To characterize the mineralogical nature of these soils, analysis was carried out for all size fractions of the two Hiawatha soils. One important objective was to determine to what extent the changes in clay minerals as a function of soil depth are caused by stratification of the parent material and to what extent by chemical weathering. An important principle of chemical weathering is illustrated by a transformation from dioctahedral illite through vermiculite and chlorite to the montmorillonite series as a function of depth in these soils.

REVIEW OF LITERATURE

Changes of clay minerals with depth in a soil may be due either to stratification of parent material or to differential weathering. Studies of the mineralogy

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and distribution of the sand, silt, and clay point out the extent to which each of these two factors causes changes in clay mineralogy with depth. Haseman and Marshall (1945) indicated how heavy-mineral analysis could be used to show geologic differences in the soil. Hseung, Marshall, and Krusekopf (1950) showed depositional differences between till and gumbotil in some Missouri soils by the use of particle-size distribution and light- and heavy-mineral analyses.

The clay of the Hiawatha soils is predominantly of the dioctahedral 2:1 type and at the outset could be inferred to be derived from the weathering of dioctahedral illite. Butler (1953) traced the changes in muscovite from rock to soil in the Cornwall area of England. The structure of the mica changed little but the potassium content dropped and the water content increased. Studies by Bray (1937) on Illinois soils indicated that a dioctahedral (from chemical data) illite gave rise to beidellite by loss of potassium and some isomorphously substituted magnesium. This transition took place more rapidly the more acid the soil conditions. Mitchell (1955) noted that dioctahedral mica resisted decomposition in a Podzol profile where trioctahedral types were being altered markedly. Jackson and others (1952) pointed out that the layer charge might be sufficiently decreased by hydroxylation or dealumination of dioctahedral micas to allow some potassium release from an interlayer space. Once this release had started from a given interlayer (a "preferential weathering plane") it appeared to proceed relatively rapidly until the interlayer space expanded. The zone of expansion becomes detectable by x-ray diffraction only after it has progressed to involve an appreciable number of repetitions of new spacings. Rolfe and Jeffries (1952) considered the amount of interlayer expansion shown by weathered mica after magnesium and calcium saturation as a criterion of the amount of weathering which the mica had undergone. Brown (1953) reported a dioctahedral vermiculite as a minor constituent of the clay in a soil of northwest England, which increased in amount toward the soil surface. Brown (1951) summarized the products of dioctahedral mica decomposition. The mica becomes increasingly depleted in alkalies until finally enough interlayers expand to permit the increase in the basal spacing to be detected by x-rays. The expansion may give either 14A or 18A spacings with formation of the resultant 10–14A or 10–18A mixed layer products.

MATERIALS AND METHODS

The Hiawatha series includes sandy soils which have developed from acid, siliceous, sandy glacial drift of late Wisconsin age. They are medial Podzols occurring either on the level topography of unpitted outwash or on the hilly land of pitted outwash and morainic landscapes. These soils are found in northern Wisconsin, Minnesota, and Michigan. In some places, reddish-brown clay loam till underlies Hiawatha soils at a depth of eight feet or more. Mineralogical analysis of the sand, coarse and fine silt, and clay was carried out for two Hiawatha soils: the Hiawatha sand and the Hiawatha loamy sand.

Segregation of the soils into various sand, silt, and clay size fractions (Table 1) was done by the methods of Jackson, Whittig, and Pennington (1950). The fractions 5 to 2μ, 2 to 0.2μ, 0.2 to 0.08μ, and -0.08μ were x-rayed by the random powder method and by the technique with parallel orientation. Certain representatives of the random powder samples were potassium saturated, heated at 400°C, and sealed in capillary tubes. This test was used to prevent rehydration of vermiculite and to insure its distinction from chlorite.

TABLE 1. — Particle Size Distribution of the Hiawatha Loamy Sand and Hiawatha Sand, as Percentage of the Inorganic Fraction

Horizon and Depth	Particle size, microns								
	+250	250–100	100–50	50–20	20–5	5–2	2–0.2	0.2–0.08	—0.08
Hiawatha Loamy Sand									
A_2:0-7 in.	74.4	19.2	2.6	1.1	2.9	0.6	0.4	0.13	0.05
B_2:7-16 in.	65.8	27.3	4.5	0.7	1.2	0.4	0.9	0.7	0.7
B_3:16-21 in.	58.1	38.3	2.7	0.6	0.1	0.04	0.06	0.04	0.06
C_{21}:34-51 in.	69.1	29.7	0.9	0.2	0.06	0.005	0.02	0.004	0.005
Hiawatha Sand									
A_2:1-8 in.	44.1	26.4	11.2	7.9	8.5	0.8	0.7	0.2	0.1
B_{21}:8-13 in.	42.6	26.0	9.2	8.0	7.0	1.3	2.9	1.3	1.6
B_{22}:13-27 in.	38.4	35.4	16.1	4.0	2.6	0.2	2.1	0.6	0.7
B_{32}:41-53 in.	41.2	34.3	15.2	4.0	3.0	0.7	0.9	0.5	0.1

The samples of each fraction for parallel orientation were first magnesium saturated and glycerol solvated or potassium saturated and heated prior to analysis with a Geiger counter diffractometer. Elemental analysis (Table 2) for eight elements of each of these fractions was carried out after the procedure of Corey and Jackson (1953). Cation-exchange measurements were made by the method of Swindale and Fieldes (1952), and glycerol-sorption measurements were made after the method outlined by Vanden Heuvel and Jackson (1953). The quantitative composition of the clay fractions was approximated by allocation of elemental constituents and judgment from x-ray intensities with due consideration to the cation-exchange and glycerol-sorption values. Specific gravity separations were made at specific gravity 2.95 with tetrabromoethane, and mineral counts were made by microscopic techniques with refractive index oils.

LAYER SILICATE TRENDS

The occurrence of montmorillonite as the dominant layer silicate in the A_2 horizon is a notable feature of the Hiawatha soils (Figs. 1 and 2). Montmorillonite in the A_2 horizons increases from about 12 percent in the 5 to 2μ fractions of both soils to about 80 percent in the -0.08μ fractions, while in the

TABLE 2. — ELEMENTAL ANALYSIS, HEATING WEIGHT LOSS, CATION-EXCHANGE CAPACITY AND SORBED GLYCEROL FOR FRACTIONS OF TWO HIAWATHA SOILS

| Fraction	Percent	Sorbed Glycerol, mg/50 mg	Cation-Exchange Capacity meq/100 g	Elemental Composition, Percentage								Heating Weight Loss, Percent
				SiO₂	Al₂O₃	Fe₂O₃	TiO₂	MgO	CaO	Na₂O	K₂O	
Hiawatha Loamy Sand												
A_2 horizon 0-7 in. (0.39 percent Fe_2O_3 extracted)												
5-2μ	0.6	2.9	18.0	80.7	10.3	1.48	1.56	0.19	0.08	1.06	3.44	4.85
2-0.2	0.4	7.2	53.9	68.5	16.6	3.08	2.26	0.67	0.0	0.94	2.84	8.0
0.2-0.08	0.13	15.6	100	55.3	23.1	7.70	1.60	1.10	0.1	0.47	1.42	10.65
-0.08	0.05	19.3	116	51.3	20.9	9.14	1.25	2.00	0.03	0.11	1.52	14.9
B_2 horizon 7-16 in. (1.01 percent Fe_2O_3 extracted)												
5-2	0.4	2.9	20.5	68.6	11.5	1.70	0.82	0.59	0.1	1.09	3.27	14.9
2-0.2	0.9	5.8	43.8	59.5	19.0	2.95	1.23	0.85	0.04	1.5	2.72	13.8
0.2-0.08	0.7	11.8	77.4	47.2	27.8	5.72	1.11	1.33	0.02	N.D.	1.30	13.6
-0.08	0.7	18.8	108	45.4	27.6	7.51	0.83	1.11	0.01	N.D.	0.92	15.8
B_3 horizon 16-21 in. (0.65 percent Fe_2O_3 extracted)												
5-2	0.04	4.2	27.3	54.2	17.7	4.34	1.24	1.5	0.05	1.0	2.72	17.0
2-0.2	0.06	5.5	34.5	53.4	26.4	5.78	1.37	1.34	0.0	0.71	2.69	14.6
0.2-0.08	0.04	11.3	92.6	42.8	29.7	8.19	1.10	0.89	0.03	N.D.	0.96	16.9
-0.08	0.06	17.1	162	35.6	33.7	6.36	0.70	0.47	0.0	0.5	0.38	25.3
C_{21} horizon 34-51 in. (0.43 percent Fe_2O_3 extracted)												
5-2	0.005	N.D.	16.9	N.D.	N.D.	8.97	2.25	2.76	0.2	1.0	3.35	11.0
2-0.2	0.02	5.2	26.5	53.1	18.6	11.5	2.00	1.82	0.1	1.0	2.51	10.8
0.2-0.08	0.004	12.9	85	42.4	31.6	(17.0)	1.29	1.15	0.0	0.2	1.3	18.1
-0.08	0.005	18.4	123	N.D.	N.D.	9.8	0.7	0.69	0.0	0.2	0.47	28.5
Hiawatha Sand												
A_2 horizon 0-8 in. (0.42 percent Fe_2O_3 extracted)												
5-2	0.8	1.5	13.0	81.3	11.3	0.96	1.56	0.34	0.0	0.9	3.48	3.3
2-0.2	0.7	(4.6)	37.1	70.1	17.7	2.66	2.12	0.71	0.15	0.67	3.58	6.1
0.2-0.08	0.2	(25)	62.0	53.9	23.0	8.70	1.52	1.48	0.2	0.38	1.98	12.0
-0.08	0.1	(36)	112	N.D.	N.D.	9.8	1.25	1.46	0.1	0.7	1.64	16.0
B_{21} horizon 8-13 in. (1.28 percent Fe_2O_3 extracted)												
5-2	1.3	1.8	12.5	74.4	14.0	2.64	1.19	0.72	0.1	1.68	3.71	4.6
2-0.2	2.9	4.2	42.8	64.1	21.1	3.97	1.38	1.02	0.0	1.1	3.08	7.6
0.2-0.08	1.3	21.6	62.8	50.8	28.0	7.36	1.04	1.22	0.0	0.6	1.62	13.2
-0.08	1.6	23.7	112	49.0	28.3	8.43	0.56	0.3	—	(1.04)	1.25	14.7
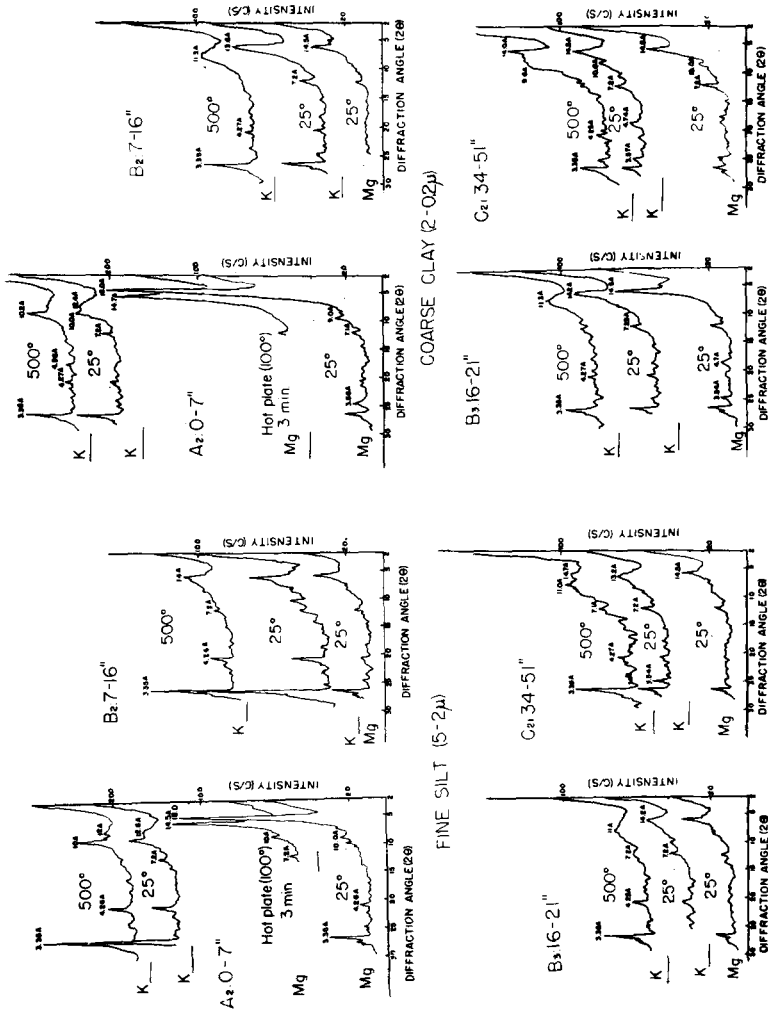
Figure 1. — X-ray diffraction diagrams of Hiawatha loamy sand, 5 to 2μ and 2 to 0.2μ fractions oriented in parallel, showing effects of magnesium saturation with glycerol solvation and potassium saturation with heat treatments.
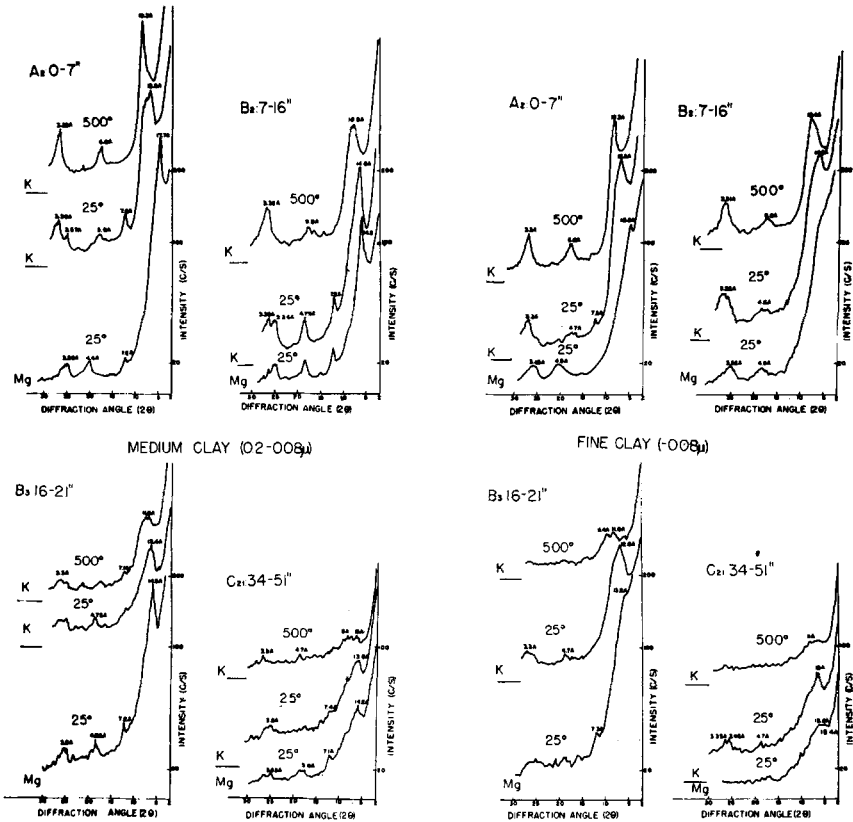
FIGURE 2. — X-ray diffraction diagrams of Hiawatha loamy sand, 0.2 to 0.08μ and -0.08μ fractions oriented in parallel, showing effects of magnesium saturation with glycerol solvation and potassium saturation with heat treatments.

horizons below the A_2 horizon, montmorillonite is usually below x-ray detection limits (Table 3). The montmorillonite of the fine silt gives a very intense first-order peak (Figs. 1 and 3) and weak following orders even though its amount (Table 3) is only 12 to 13 percent. An approximate formula for the montmorillonite species was calculated from the elemental analysis, allocation, and cation-exchange data for the 0.2 to 0.08μ fraction, A_2 horizon of the Hiawatha loamy sand. Montmorillonite was allocated as 80 percent of this fraction, and the montmorillonite formula was calculated from the elemental constituents left over after the constituents judged to make up the illite and kaolin had been subtracted from the total elemental composition. That the montmorillonite was dioctahedral was indicated from measurement of the 060 line and the layer charge on the montmorillonite was adjusted to give approximately the observed exchange capacity for the whole size fraction (100 meq/100 g).

The formula thus calculated is:

$$(Si_{7.3} \underset{Na_1}{Al_{0.7}}) (Al_{2.8} Fe^{3+}_{0.9} Mg_{0.3}) \cdot O_{20}(OH)_4 \cdot nH_2O$$
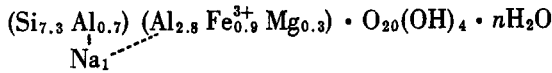
The layer charge of this mineral is high for a montmorillonite (120 meq/100 g) but this montmorillonite has many characteristics of vermiculite, showing collapse to 14A upon slight heating on the steam plate (Fig. 1) and partial collapse to 10A with potassium saturation.

The dominant layer silicate in all fractions of the B and C horizons of both soils is an interstratified vermiculite-chlorite. This is typified by the occurrence in the Hiawatha loamy sand B_2 horizon, 2 to 0.2μ fraction, in which the

TABLE 3. — MINERAL COMPOSITION AS PERCENTAGE OF THE FINE SILT AND CLAY OF TWO HIAWATHA SOILS

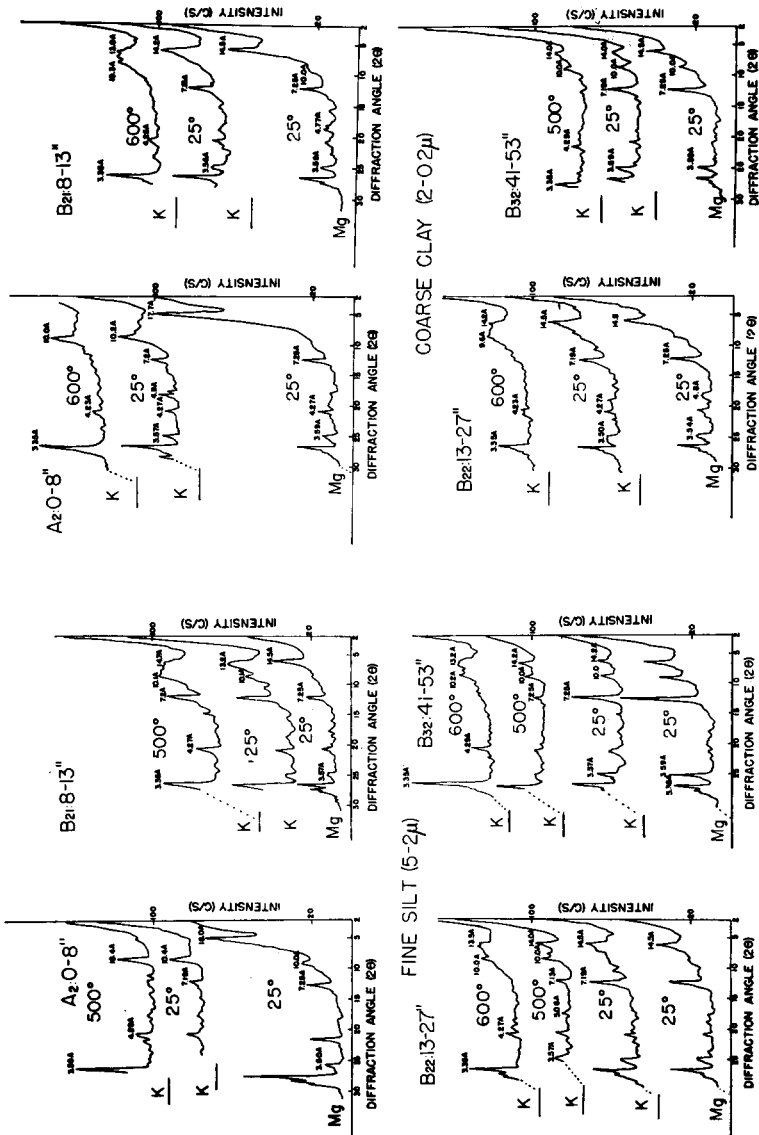| Soil and Horizon	Quartz	Ortho-clase	Plagio-clase	Illite	Vermiculite	Chlorite	Montmor-illonite	Kaol-inite	Excess Alumina
Hiawatha Loamy Sand									
				5-2μ					
A_2	53	18	8	2	—	—	12	5	—
B_2	43	18	9	6	10	9	—	2	—
B_3	18	13	8	6	32	16	—	5	—
C_{21}	25	15	5	10	30	10	—	5	—
				2-0.2μ					
A_2	32	12	7	7	—	—	33	10	—
B_2	26	12	8	8	18	14	—	13	—
B_3	10	9	4	12	37	28	—	13	—
C_{21}	8	8	5	10	47	21	—	—	—
				0.2-0.08μ					
A_2	3	—	—	13	—	—	80	5	—
B_2	—	—	—	12	66	16	—	6	—
B_3	2	—	—	9	51	31	—	10	—
C_{21}	—	—	—	13	52	35	—	—	—
				-0.08μ					
A_2	—	—	—	14	—	—	85	—	—
B_2	—	—	—	8	50	14	20	—	4
B_3	—	—	—	4	16	45	16	—	13
C_{21}	—	—	—	4	Abundant	Abundant	Abundant	—	Present
Hiawatha Sand									
				5-2μ					
A_2	54	11	6	6	—	—	13	10	—
B_{21}	42	16	10	10	12	8	—	5	—
				2-0.2μ					
A_2	30	14	5	11	—	—	29	12	—
B_{21}	28	12	5	10	28	7	—	12	—
				0.2-0.08μ					
A_2	3	—	—	18	—	—	69	13	—
B_{21}	2	—	—	14	60	19	—	12	—
				-0.08μ					
A_2	—	—	—	14	—	—	80	5	—
B_{21}	—	—	—	12	78	10	—	—	—

Figure 3. — X-ray diffraction diagrams of Hiawatha sand, 5 to 2μ and 2 to 0.2μ fractions oriented in parallel, showing effects of magnesium saturation with glycerol solvation and potassium saturation with heat treatments.

14A line (Fig. 1) in the magnesium saturated, glycerol-solvated sample collapses to 11.3A upon potassium saturation and heating. This spacing represents an allocation of 18 percent vermiculite and 14 percent chlorite by weight. The random powder photographs of the vermiculite-chlorite mixtures in the -0.2μ fractions where the quartz content is low and does not interfere with observation of a possible trioctahedral 060 line indicate that the vermiculite-chlorite mixture is dominantly dioctahedral, since only the 060 line at 1.50A appears. To check the possibility that the "chlorite" was in reality a rehydrated vermiculite certain key samples were heated to 400°C for several hours and their capillary tubes sealed upon removal from the furnace. These results agreed substantially with the diffractometer patterns of the potassium-saturated and heated samples. It can not be shown definitely in such a mixed sample whether the chlorite also may be dioctahedral but these data point in that direction. Rich and Obenshain (1955) give evidence for an Al interlayer in a dioctahedral vermiculite which prevented complete collapse of the mineral. Brindley and Gillery (1956) state that it is difficult to decide from x-ray intensities whether a chlorite has one or both layers of the dioctahedral type. The b parameter, measured best by the 060 reflection, is the best indication of the di- or trioctahedral nature of the layers. The 600°C heating of the vermiculite-chlorite mixtures in the Hiawatha sand B_{21}, B_{22}, and B_{32} horizons, -0.2μ fractions, caused a collapse which gave sharpened peaks in the region 10 to 11A (Figs. 2, 4) while 500°C heating did not cause such collapse. Magnesian chlorites as reported by Brindley and Ali (1950) have the 14A intensity increased by 600°C heating. The atypical behavior of the chlorite in these samples may be due to fine particle size and poor crystallinity of the chlorite or it may be due to the possible dioctahedral nature of the chlorite.

The vermiculite-chlorite mixture tends to become more chloritic below the upper B horizon. Thus in the Hiawatha loamy sand B_2 horizon, the 0.2 to 0.08μ fraction contains 66 percent vermiculite and 16 percent chlorite (Table 3) while the B_3 horizon contains 51 percent vermiculite and 31 percent chlorite and the C_{21} horizon contains 52 percent vermiculite and 35 percent chlorite.

The probable source of much of this material is muscovite, which could have formed such a chlorite-vermiculite mixture by loss of layer charge and potassium to form the vermiculite member, and retention of weathered-out alumina, magnesia, and iron between certain of the layers to give the aluminous chlorite member. Other aluminosilicates such as feldspar may also be source materials for the chlorite-vermiculite mixtures. The presence of some of the vermiculite-chlorite in the B_3 and C horizons indicates that much of it is present in the soil parent material, which may have changed more or less since its original deposition.

The broad weak maxima noted in the -0.08μ fractions (Figs. 2, 4) are usually produced by the combination of fine particle size and poor crystallinity with complex interstratification. Some dilution with amorphous material may contribute to these x-ray diffraction characteristics.
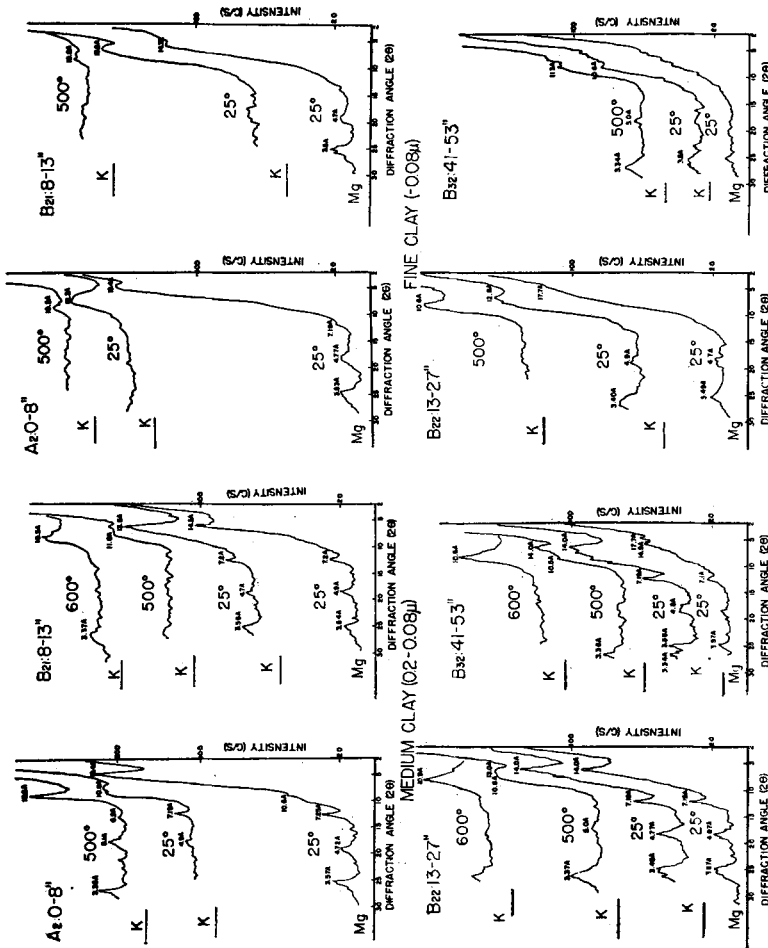
FIGURE 4. — X-ray diffraction diagrams of Hiawatha sand, 0.2 to 0.08μ and –0.08μ fractions oriented in parallel, showing effects of magnesium saturation with glycerol solvation and potassium saturation with heat treatments.

CAUSES FOR THE LAYER SILICATE DEPTH FUNCTIONS

In order to determine whether the layer silicate depth functions were caused by chemical weathering or parent material stratification, studies were made on the uniformity of the soil parent material by heavy- and light-mineral determinations and particle size distribution. It is of interest that the heavy- and light-mineral studies of the Hiawatha soils showed that over 95 percent of the sandy soil material was derived from the Bayfield group of the Keweenawan sediments and less than 5 percent came from other Keweenawan sediments and flows.

Ratios of resistant species such as zircon/garnet and zircon/tourmaline with 95 percent confidence limits (Fig. 5) show that the sandy fractions of the soil have no major depositional breaks. The altered, ragged appearance of pyroxene in the A_2 horizon contrasted to its more rounded, transparent appearance in the lower horizons is indicative of pyroxene weathering in the surface soil. The garnet/pyroxene and garnet/hornblende ratios tend to be high in the A_2 horizon, attributable to the loss of pyroxene and hornblende by chemical weathering. The percentages of light minerals in the sand fractions (Fig. 6) are fairly uniform at different depths. The mineral distribution of the 50 to 20μ fraction is uniform for the A_2 and B_2 horizons but quartz decreases in the lower two horizons. The particle size distribution (Table 1) shows that there is a definite accumulation of silt and clay in the A_2 and upper B horizons of the two soils indicating the addition of silt and possibly clay to this zone. No apparent depositional boundary exists between the A_2 and upper B horizons in the soils and therefore it appears that the montmorillonite, dominant in the A_2 horizons, has developed from the type of vermiculite-chlorite found in the upper B horizon by chemical weathering. The formation of this montmorillonite from the illite and vermiculite-chlorite assemblage found in the B_2 horizon could take place by removal of the interlayers from the chlorite structure, oxidation of ferrous iron present in the vermiculite, and hydroxylation of some oxygens present in both structures. The effects of agents that mobilize iron and aluminum in the Podzol A_2 may also be important. The reason for the marked depth function in these soils probably lies with the small amount of fine material present to be weathered coupled with the rapidity with which water is cycled through these soils owing to their extremely coarse texture. More water cycles through the A_2 horizon than the B_2 horizon because the average depth of moisture penetration probably extends to about the B_2 horizon. When the A and B horizons freeze, the more rapid thawing of the A in spring causes lateral seepage in the A_2 but none in the B_2 and results in more leaching in the A_2. The Ahmeek (Whittig and Jackson, 1955) and Iron River soils of northern Wisconsin also have shown a tendency to accumulate montmorillonite in the surface so that this tendency may be somewhat general for these sandy northern Wisconsin soils. As was noted, the vermiculite-chlorite mixture tends to become more chloritic in the lower B and C horizons. This change may also reflect weathering of some chlorite to vermiculite as a function of proximity to the soil surface, although the possibility of depositional
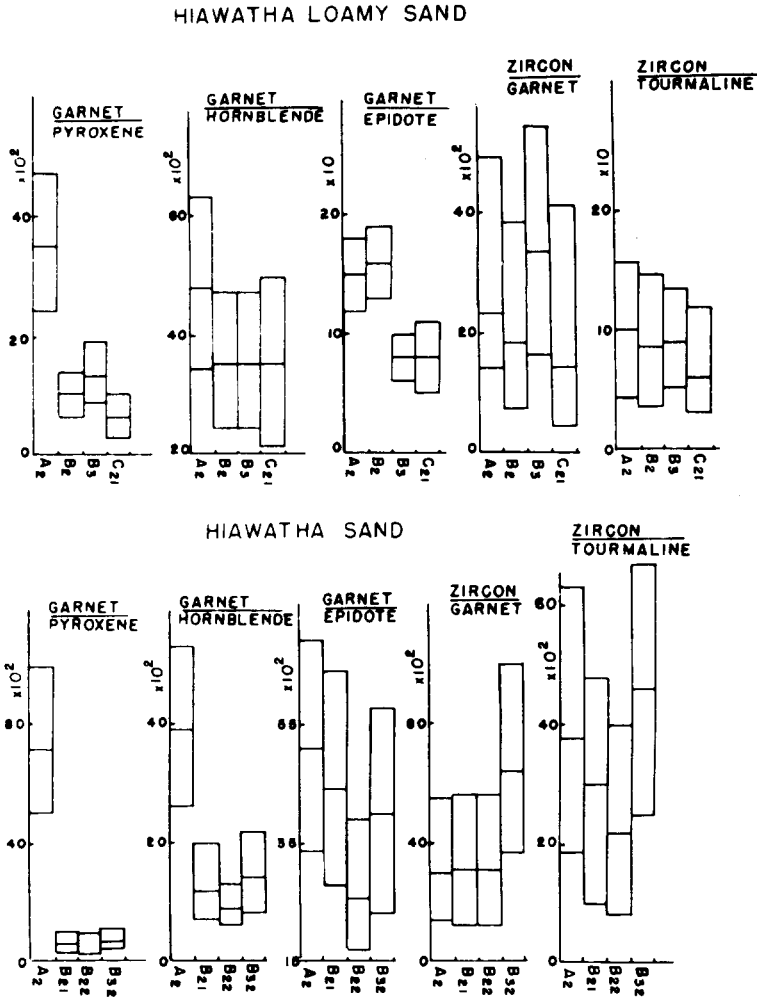
FIGURE 5. — Heavy mineral ratios with 95 percent confidence limits for the A_2, B_2, B_3, and C_{21} horizons for the Hiawatha loamy sand and the A_2, B_{21}, B_{22}, and B_{32} horizons for the Hiawatha sand.

differences (Table 1) in fine silt and clay between the upper and lower parts of the solum cannot be ruled out entirely.

QUARTZ TRENDS

Quartz shows some marked depth functions in both of the Hiawatha soils. From the A_2 to the B_2 horizon of the Hiawatha loamy sand, 5 to 2μ fraction, quartz drops from 53 to 43 percent (Table 3). The same trend is noticed in
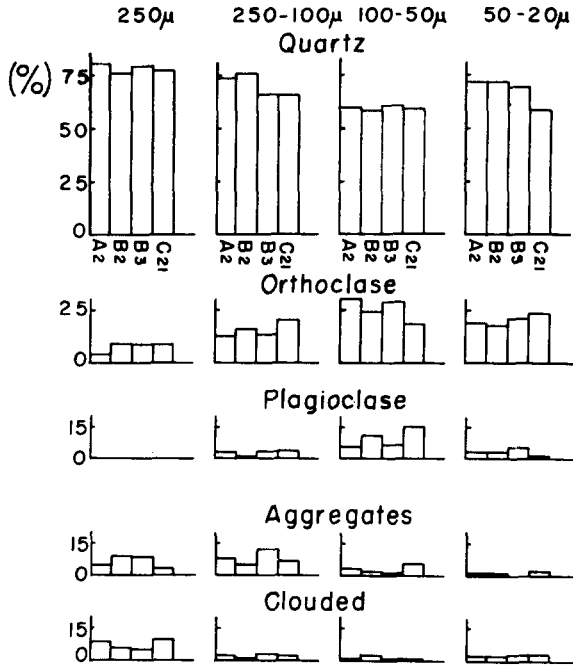
FIGURE 6. — Light mineral content of the sand and coarse silt fractions of the A_2, B_2, B_3, and C_{21} horizons of the Hiawatha loamy sand.

the 2 to 0.2μ fractions but differences are quantitatively smaller. There is little possibility that more quartz was deposited in the A_2 horizon, because particle size data for the two soils (Table 1) indicate that little if any 5 to 2μ silt has been added to the A_2 horizon over that added to the B_2 horizon. It seems probable, therefore, that quartz fine silt accumulation is due to chemical weathering and leaching relations. Also, microscopic analysis of minerals in the 50 to 20μ silt (Fig. 6) shows that this fraction is mineralogically uniform over the A_2–B_2 interval. Bases, especially aluminum and iron, are more easily leached out of a Podzol soil than silica due to a set of processes described by the term *cheluviation* (Swindale and Jackson, 1956). *Cheluviation* refers to dissolution and chelation of the bases (mainly alumina and iron) and their subsequent eluviation. The relative stability of quartz in the fine silt fraction is another factor that causes quartz to accumulate in the A_2. Thus quartz accumulation is not so noticeable in the 2 to 0.2μ fraction, because as quartz approaches finer sizes it becomes relatively less stable compared with alumina and iron even though cheluviation is somewhat operative in this soil. A marked decrease occurs in quartz content in the 5 to 2μ and 2 to 0.2μ fractions between the B_2 and B_3 horizons in the Hiawatha loamy sand. This is evidently due to the silt admixture in the upper two horizons.

CONCLUSIONS

A vermiculite-chlorite mixture has weathered to a high-charge dioctahedral montmorillonite in the A_2 horizon of the two Hiawatha soils. Depth functions of the fine material in these soils are marked because of the very coarse texture which emphasizes differential leaching and rapid changes in the low amount of fine material present. The chlorite of these soils is not typical of standard chlorites and may be dioctahedral. Quartz tends to accumulate in the surface owing to the process of *cheluviation*.

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