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Mineralogy of fine-loamy and sandy hydrosequences in Michigan

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Michigan State University, 1991

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**MINERALOGY OF FINE-LOAMY AND SANDY HYDROSEQUENCES IN
MICHIGAN**

By

Shawel Haile-mariam

A DISSERTATION

**Submitted to
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ABSTRACT

MINERALOGY OF FINE-LOAMY AND SANDY HYDROSEQUENCES IN MICHIGAN

By

Shawel Haile-mariam

Two texturally different hydrosequences (fine-loamy and sandy) in replicate were selected in forested land to investigate the mineralogy of the clay, silt, and sand fractions in relation to drainage classes.

The sand fraction of all soils in the hydrosequences contained quartz, K-feldspars, plagioclase, sericite, chert, pyroxene and amphibole. Weatherable minerals constitute <5% of the total minerals present. Dolomite is present in the parent material of the fine-loamy hydrosequences except in the Parkhill pedon. Quartz is the predominant mineral followed by feldspars in the silt fractions. Natural drainage does not appear to affect distribution of sand and silt size minerals.

Mica, vermiculite, chlorite, kaolinite, quartz, and feldspars constitute the clay minerals present in the parent material of all the hydrosequences. Smectite is present in the fine clay of the Brookston pedon and Spodosol hydrosequences.

In the fine-loamy hydrosequences, weathering of dioctahedral mica/sericite to smectite through interstratified vermiculite-smectite is the dominant trend in the Brookston pedon, where as direct transformation to vermiculite is the prevalent weathering mechanism in the other drainage classes. Except for the smectite in the Brookston pedon, the fine-loamy soils in this study do not have significant differences in the sand, silt, and clay mineralogies with respect to natural drainage.

In the sandy hydrosequences, the intensity of smectite peak and the presence and absence of vermiculite in the E horizons, indicate increasing weathering intensities from

poorly to well drained soils. The mineral distribution in these hydrosequences suggest a weathering sequence of dioctahedral mica/sericite → vermiculite → smectite with or without mixed-layer formation.

Structural formulas calculated indicates 0.47 and 0.51 mol_c per half unit cell for the Spodosol (E) and Mollisol (Btg) horizons, respectively. The mean layer charge determined by the alkyl ammonium method is 0.41 and 0.43 mol_c per half unit cell for the E and Btg fine-clays, respectively. The paraffin type configuration indicates the presence of unweathered mica cores in these samples. The re-expansion property suggest the presence of heterogeneous layer charge and a layer charge between 0.46 and 0.57 per half unit cell. The Greene-Kelly test, re-expansion property, and 060 x-ray powder diffraction indicates the smectite is dioctahedral of beidellitic type.

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TABLE OF CONTENTS

List of Tables	vi
List of Figures	vii
INTRODUCTION	1
LITERATURE REVIEW	3
Mineral weathering sequence	3
Smectite formation in acidic environments	6
Mechanism of mica weathering	7
Clay mineral weathering in relation to drainage	8
List of references	11
CHAPTER 1. Sand, silt, and clay mineralogy of two fine-loamy hydrosequences in Michigan.	16
Abstract	16
Introduction	17
Materials and Methods	18
Results and Discussion	21
Summary and Conclusions	51
List of references	61
CHAPTER 2. Mineralogy of two Sandy hydrosequences in Michigan.	65
Abstract	65
Introduction	66
Materials and Methods	67
Results and Discussion	69
Conclusions	86
List of references	95
CHAPTER 3. Characterization of smectite in a Spodosol and a Mollisol.	98
Abstract	99
Introduction	100
Materials and Methods	101

Results and Discussion	102
List of references	112
General Conclusions	116
Apendix 1. Pedon descriptions	118

LIST OF TABLES

TABLE 1.1.	Selected chemical properties of soils in hydrosequence 1	32
TABLE 1.2.	Selected chemical properties of soils in hydrosequence 2	33
TABLE 1.3.	Particle size analysis and bulk density of soils in hydrosequence 1	35
TABLE 1.4.	Particle size analysis and bulk density of soils in hydrosequence 2	36
TABLE 1.5.	Mineralogy of the fine sand fraction	39
TABLE 1.6.	Mineral ratios for the fine sand fraction	40
TABLE 1.7.	Mineralogy of coarse and fine silt fractions	45
TABLE 1.8.	Clay mineralogy of total clay fraction(<2 μ m)	50
TABLE 2.1.	Soils of Hydrosequences	68
TABLE 2.2.	Location and classification of soils in the hydrosequences	68
TABLE 2.3.	Particle size analysis of soils in Chippewa hydrosequence	75
TABLE 2.4.	Particle size analysis of soils in Cheboygan hydrosequence	76
TABLE 2.5.	Selected chemical properties of soils in Chippewa hydrosequence	78
TABLE 2.6.	Selected chemical properties of soils in Cheboygan hydrosequence	79
TABLE 2.7.	Mineralogy of the sand fraction	82
TABLE 2.8.	Mineralogy of coarse and fine silt fractions	83
TABLE 2.9.	Clay mineralogy of total clay fraction(<2 μ m)	84
TABLE 3.1.	Elemental analysis of the Na ⁺ saturated fine clay fraction (<0.2 μ m) from the E horizon of a Spodosol and Btg horizon of a Mollisol	110

LIST OF FIGURES

Figure 1.1.	Location of the study areas in Michigan	20
Figure 1.2.	Average monthly depths to water tables and average monthly precipitation of hydrosequence 1, in Clinton county	23
Figure 1.3.	Average monthly depths to water tables and average monthly precipitation of hydrosequence 2, in Ionia county	24
Figure 1.4.	Percent total time saturated at given depth in poorly drained pedons	25
Figure 1.5.	Average monthly depths to water tables in poorly drained pedons	26
Figure 1.6.	Base saturation and pH in poorly drained pedons	27
Figure 1.7.	Percent total time saturated at given depth in hydrosequence 1	28
Figure 1.8.	Percent total time saturated at given depth in hydrosequence 2	29
Figure 1.9.	Base saturation and pH (0.1N KCl) in pedons of hydrosequence 1	30
Figure 1.10.	Base saturation and pH (0.1N KCl) in pedons hydrosequence 2	31
Figure 1.11.	Quartz to plagioclase ratios.	41
Figure 1.12.	Quartz to K-feldspar ratios	42
Figure 1.13.	Quartz to feldspar ratios	43
Figure 1.14.	X-ray diffractograms of clay fraction (<2um) of pedon M1	52
Figure 1.15.	X-ray diffractograms of clay fraction (<2um) of pedon C1	53
Figure 1.16.	X-ray diffractograms of clay fraction (<2um) of pedon P1	54
Figure 1.17.	X-ray diffractograms of clay fraction (<2um) of pedon M2	55
Figure 1.18.	X-ray diffractograms of clay fraction (<2um) of pedon C2	56
Figure 1.19.	X-ray diffractograms of clay fraction (<2um) of pedon B2	57
Figure 1.20	X-ray diffractograms of pedon B2, fine, medium, and coarse clay fractions after Mg saturated and glycerol solvated.	58
Figure 1.21	X-ray diffractogram of 060 diffraction peak of the total clay fraction of the Bt horizon	59
Figure 2.1.	Average monthly depths to water tables and average monthly precipitation in Chippewa hydrosequence	70
Figure 2.2.	Average monthly depths to water tables and average monthly precipitation in Cheboygan hydrosequence	71

Figure 2.3.	Percent total time saturated at given depth in Chippewa hydrosequence	72
Figure 2.4.	Percent total time saturated at given depth in Cheboygan hydrosequence.	73
Figure 2.5.	X-ray diffractograms of clay fraction ($<2\mu\text{m}$) of the Liminga pedon	87
Figure 2.6.	X-ray diffractograms of clay fraction ($<2\mu\text{m}$) of the Wainola pedon.	88
Figure 2.7.	X-ray diffractograms of clay fraction ($<2\mu\text{m}$) of the Kinross pedon in Chippewa hydrosequence	89
Figure 2.8.	X-ray diffractograms of clay fraction ($<2\mu\text{m}$) of the Rubicon pedon	90
Figure 2.9.	X-ray diffractograms of clay fraction ($<2\mu\text{m}$) of AuGres pedon	91
Figure 2.10.	X-ray diffractograms of clay fraction ($<2\mu\text{m}$) of the Kinross pedon in Cheboygan hydrosequence	92
Figure 2.11.	X-ray diffractograms of fine clay fraction ($<0.2\mu\text{m}$) of the E horizons in Chippewa hydrosequence.	93
Figure 2.12.	X-ray diffractograms of fine clay fraction ($<0.2\mu\text{m}$) of the E horizons in Cheboygan hydrosequence	94
Figure 3.1.	X-ray diffractograms of the Spodosol E and Mollisol Btg horizons ($<0.2\mu\text{m}$; treatments specified at right)	104
Figure 3.2.	XRD patterns of the fine clays from E and Btg horizons of Spodosol and Mollisol respectively (treatments are specified at right)	106
Figure 3.3.	XRD of the fine clays from E and Btg horizons of the Spodosol and Mollisol respectively. Re-expansion properties of clays (treatments specified at right)	107
Figure 3.4.	X-ray patterns of the $<0.2\mu\text{m}$ soil clay separated from the E and Btg horizons of the Spodosol and Mollisol pedons and treated with various alkylammonium hydrochlorides (carbon chain length specified at right)	108
Figure 3.5.	Basal plane spacings of alkylammonium complexes with the E and Btg fine clay Spodosol and Mollisol, respectively, and the corresponding layer charge distribution	109

INTRODUCTION

The study of weathering of primary and secondary minerals in soil hydrosequences in relation to the soil forming factors (parent material, climate, vegetation, and time) provides valuable information as to soil mineral distribution, kind and amount of secondary clay minerals formed and its variability with depth. The study of soil sequences will increase our understanding of soil distribution in a landscape and hence enable us to predict soil occurrences in different areas where similar soil forming factors are present.

Clay minerals, which are the most important products of weathering, are instrumental in controlling the physical and chemical characteristics of soil. Water permeability, aeration, profile development, and cation exchange capacity of soils depend on the amount and kind of clay minerals present. These properties of clay minerals affect the growth of plants and soil fertilization.

The kind and amount of primary and secondary minerals present in sand, silt, and clay size affects the general nutrient reserve status of soils and also soil fertility studies.

In Soil Taxonomy, sand silt and clay mineralogy data are used in soil classification at the family level and it is also used together with other features, to differentiate taxa at other categorical levels.

Theoretically, internal drainage of soils is one of the major intensity factors controlling the rate of chemical weathering reactions. However, studies of the influence of drainage on weathering in soil hydrosequences and its relation to the formation of different clay minerals have been few and contradictory. Detailed study of sand, silt, and clay mineralogy of soils from the same parent material in a topographic hydrosequence occurring in a young glacial landscape and their relationship to the degree of internal drainage will increase our understanding of soil mineral distribution and genesis.

The objectives of this study were to:

- (1) determine and compare the mineralogy of the total clay, fine silt, coarse silt, and dominant sand fraction with depth in soils of fine-loamy and sandy hydrosequences.
- (2) To characterize smectite present in the fine-loamy and sandy hydrosequences.

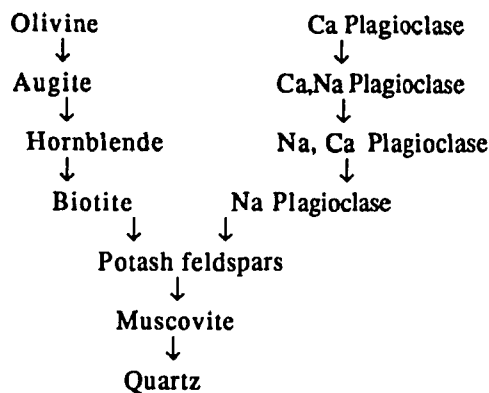
In order to accomplish these objectives, two texturally different hydrosequences (fine-loamy and sandy) in replicate were selected. These topographic hydrosequences were selected in forested land to minimize disturbances due to cultivation, artificial drainage and accelerated erosion. Sampling sites (profiles) were selected according to drainage variation in each hydrosequence.

LITERATURE REVIEW

Mineral weathering sequences

Different weathering sequences of minerals have been postulated for different categories of minerals. Weathering sequences have been worked out for coarse-grained minerals, with heavy specific gravity, colloidal minerals and combinations of these categories.

A weathering sequence of coarse-grained minerals was established by Goldich (1938). Goldich's double sequence of common minerals in the order of their decreasing vulnerabilities downwards was:



Graham (1949) also found experimentally the same kind of vulnerability sequence as observed in nature by Goldich (1938). This sequence is a generalization and may have many variations depending on weathering conditions. For instance, the weathering of plagioclase was thought to be much faster and stronger than that of alkaline feldspars in temperate climates (Millot, 1970) and tropical humid climates (Leneuf, 1959). However, in arid areas Rondeau (1958, see Millot, 1970) found strong weathering of alkaline feldspars and freshness of plagioclases. This difference was attributed to the composition of intergranular solutions which were not the same in arid areas and in humid areas, and which inverted the rates of hydrolysis. Various granular rocks reacted to different climates in different ways. Alkaline rocks were more vulnerable under humid climates and as a result acid rocks dominate the topography. However, under an arid climate the opposite holds true.

In the weathering sequence of heavy minerals, the less stable minerals of high specific gravity were found to occur in decreasing amounts in rocks of increasing age. In rocks older than Pleistocene olivine was absent (Pettijohn, 1941). Augite was rare or

absent in rocks of pre-Cambrian age but became more common in younger rocks.

Pettijohn's weathering sequence with most stable listed first was as follows:

(-3) Anatase (-2) Muscovite (-1) Rutile (1) Zircon (2) Tourmaline (3) Monazite
 (4) Garnet (5) Biotite (6) Apatite (7) Ilmenite (8) Magnetite (9) Staurolite
 (10) Kyanite (11) Epidote (12) Hornblende (13) Andalusite (14) Topaz (15) Sphene
 (16) Zoisite (17) Augite (18) Sillimanite (19) Hypersthene (20) Diopside (21) Actinolite
 (22) Olivine

The negative numbers on the first minerals were to indicate their tendency of formation rather than disappearance during long periods of burial.

Weyl (see Jackson and Sherman, 1952) suggested grouping heavy minerals in four categories of stability:

<u>Extremely Unstable</u>	<u>Slightly Stable</u>	<u>Stable</u>	<u>Very Stable</u>
Olivine	Garnet	Staurolite	Tourmaline
Hornblende	Epidote	Kyanite	Zircon
Augite		Sillimanite	Rutile
		Andalusite	Titanite
		Magnetite	

The relative stability of heavy minerals was employed to establish the age of the rock formation from which soils were derived (Buckhannan and Ham, 1942).

Allen (1948) found one to five fold decreases in the amounts of heavy minerals towards the top of weathering profile. Graham (1949) utilized the presence of plagioclase feldspars as an index to determine the stage attained in soil weathering.

Resistant species increased in relative abundance while less resistant ones decreased in abundance or disappeared completely (Pettijohn, 1941; Dryden and Dryden, 1946). A change in relative abundance of the minerals was used to measure their resistance to weathering.

A weathering sequence of clay-size materials in soils and sediments consisted of 13 stages according to Jackson et al. (1948).

1/ Gypsum (also halite etc.)

2/ Calcite (also dolomite, aragonite, etc.)

3/ Olivine-hornblende (also diopside, etc.)

4/ Biotite (also glauconite, chlorite, antigorite, nontronite, etc.)

5/ Albite (also anorthite, microcline, stilbite, etc.)

6/ Quartz (also cristobalite, etc.)

- 7/ Illite (also muscovite, sericite, etc.)
- 8/ Hydrous mica-intermediates
- 9/ Montmorillonite (also beidellite, etc.)
- 10/Kaolinite (also halloyite, etc.)
- 11/Gibbsite (also boehmite, etc.)
- 12/Hematite (also goethite, limonite, etc.)
- 13/Antase (also rutile, ilmenite, corundum, etc.)

The authors also suggested one mineral may be the parent material of others in successive stages of the weathering sequence and the weathering reactions were reversible in nature. The weathering sequence proposed by Jackson et al. (1948) and Jackson and Sherman (1952) involved the transition:

Mica → Mica intermediate → Aluminous chlorite → Kaolinite → Gibbsite

This weathering trend was supported in another study by White et al. (1957). Mica weathering to kaolinite through vermiculite and Al-vermiculite was also observed in humid tropical regions (Tardy, 1971). Under more extreme weathering conditions mica can be converted to kaolinite without a preceeding sequence of mineralogical changes involving vermiculization (Wilson, 1974).

Rice et al. (1985) proposed a weathering sequence of biotite to hydroxy-interlayered vermiculite through vermiculite and the formation of smectite from ferromagnesian minerals in soils with metagabbro and gabbro parent materials. Smectite formation from chlorite intermediates in soils developed from metagabbro parent material was also indicated. The formation of smectite from ferromagnesian minerals and from chlorite intermediates implies two kinds of smectite: transformation smectite from chlorite and neogenetic smectite formed from ions supplied by other ferromagnesian minerals (Borchardt, 1977).

Transformation of micas and chlorite under beech forest and tussock grassland in New Zealand soils was observed by Churchman (1980). Alteration of chlorite follows the sequence chlorite → interlayered hydrous mica → chlorite-swelling chlorite → chlorite-vermiculite, with increased weathering leading to destruction of the chloritic layers. The weathering of micas (muscovite) apparently occurred by either one of two distinct major pathways, both leading to beidellite: (1) mica → mica - vermiculite → mica-beidellite → beidellite and (2) mica → vermiculite → beidellite with pedogenic chlorite as a possible intermediate which might be formed from either mica or vermiculite but which gives vermiculite on de-alumination at pH less than 4.5. Both pathways appeared to be followed concurrently in the weathering of micas in soils under beech forest, while the first pathway

was the sole course followed in soils in tussock grasslands. This study suggested that the sensitivity of the transformation from pedogenic chlorite to vermiculite at this pH is consistent with the suggestion of workers (Gjems, 1970; Kapoor, 1973) that 4.5 is the critical pH for the de-alumination of pedogenic chlorite.

Droste and Tharin (1958) found illite weathering through an intermediate stage of illite-smectite mixed layers to smectite in soils derived from Illinoian aged tills.

Bhattacharya (1962) proposed a similar weathering sequence for dioctahedral illites but trioctahedral illites weathered to smectite through intermediate stages of illite-vermiculite and vermiculite-smectite mixed layers. Dioctahedral illites are altered to smectite by exchange of potassium from interlayer position with hydronium ions. Trioctahedral illites alter in the same way but go through intermediate stages.

The minerals that result from the weathering of micas and/or chlorites depend on the environment in which the reactions occur and the time elapsed.

Smectite formation in acidic environments

Many soil mineralogists believe that smectite is unstable in acidic environments and restrict its formation mainly to basic environments. However, others (Brown and Jackson, 1958; Gjems, 1960; Franzmeier and Whiteside, 1963; McKeague, 1965; Ross and Mortland, 1966; Brydon et al., 1968; Malcolm et al., 1969; Coen and Arnold, 1972; Kapoor, 1972; Douglas, 1967, 1987) among others, have reported the weathering of mica and chlorite through vermiculite, to smectite in eluvial or albic horizons of Spodosols. Ross and Mortland (1966) reported beidellite to be the smectite variety in their study.

Gjems (1970) postulated the formation of smectite from hydroxy-aluminium interlayered smectite, and probably also from illite in two Yugoslavian Spodosols. The strong acidity of the eluvial horizons promoted the dealumination of hydroxy-interlayered species. Gjems believed the process was further enhanced by the formation of aluminium-humus complexes and subsequent translocation from the eluvial horizon to the B horizon.

In Scandinavian Spodosols a weathering sequence of biotite --> mixed layer mineral and vermiculite (C and B horizons) → hydrobiotite → vermiculite → smectite (in the eluvial horizon) was found (Kapoor, 1972). The initiating mechanism for the change from biotite to smectite under humid-temperate climates was attributed to the oxidation of Fe^{++} in the lattice with subsequent removal of ions both from the octahedral and interlayer positions.

Coen and Arnold (1972) attributed the presence of smectite in an eluvial horizon to eolian addition. Chlorite added to the soil by dust weathered to amorphous material and

translocated to the spodic horizon. Mica weathered to smectite in the eluvial horizon to vermiculite in the Bh horizon, and to chloritized vermiculite in the Bs horizon.

In well drained Scottish soils developed from glacial drift, a weathering sequence of biotite → hydrobiotite (C horizon) → vermiculite-chlorite (B horizon) → vermiculite (A horizon) was observed (Wilson, 1970). In the more acid surface horizon, vermiculite-chlorite interlayers tend to break down yielding more vermiculite products. The absence of smectite in soils derived from biotite-hornblende rock in the above weathering sequence might suggest that the changes mica → mica-vermiculite → mica-smectite probably follows a time sequence as well as a precipitation sequence (Churchman, 1980).

Malcolm et al. (1969) and Douglas (1987) have attributed the formation of smectite in Spodosols to high soil organic matter and low pH levels. At low pH the aluminium is complexed by organic matter and becomes unavailable for the formation of aluminium polymers. At pH below 4.5 the aluminium polymer is thermodynamically unstable and protonation of the interlayer aluminium polymer would result in the formation of exchangeable aluminium species, subject to leaching, and an expansible aluminosilicate.

Ross and Mortland (1966) and Gjems (1970) have considered the presence of smectite or smectitic layers as an indication of an advanced stage of weathering in soils. In spite of many reports of the presence of smectite in Spodosols of U.S.A. and Europe, the present state of knowledge regarding its formation in acidic environment remains controversial. Most believe it is a low charge vermiculite with smectite characteristics (glycerol expansion).

Mechanism of mica weathering

The weathering of mica in general was thought to proceed by at least two processes (Sparks and Huang, 1985): "simple transformation" of the K bearing mica to an expandable 2:1 layer silicates by exchanging the K ions from the interlayer cation sites with hydrated exchangeable cations, and dissolution of the mica followed by the precipitation of weathering products. The relative importance of these two processes depended on the stability of the mica and the nature of the soil environment.

In the simple transformation reaction a considerable portion of the primary mica structure (the 2:1 layer) was retained intact as a transformation product (Velbel, 1984; Fanning and Keramidas, 1977). This was understood mainly as the loss of interlayer K which was compensated for by replacement with hydrated exchangeable cations. In this way expandable 2:1 clay minerals such as vermiculite and smectite were formed.

This simple transformation took place in two ways: (1) by edge weathering (Mortland, 1958; Scott and Smith, 1967) and (2) by layer weathering or weathering along preferential planes in the mica structure (Fanning and Keramidas, 1977).

Edge weathering resulted when the mica grains were initially opened along cleavage traces and fractures. The expanded interlayers were not continuous throughout the grain but terminated in wedges toward the interior of the crystal. The core of the grain was initially unaffected. When K was released from many layers simultaneously the resultant particle had frayed, curled and expanded edges surrounding an unaltered mica core. It was by this process that intergrades of mica and expandable 2:1 phyllosilicates such as hydrobiotite and mica-smectite intergrades were thought to form.

In layer weathering the interlayers were opened or expanded throughout the crystal. If all of the interlayers were not expanded then various types of mixed layer or interstratified minerals were formed (e.g. biotite-vermiculite, biotite-smectite; Bisdom et al., 1982). If all the interlayers were expanded then the biotite was completely transformed into an expandable 2:1 clay mineral. If the layer charge of the transformed mineral was greater than 1.2 per unit then the secondary mineral was a vermiculite and if it was less than 1.2 the weathering product was a smectite (Bisdom et al., 1982).

Clay mineral weathering in relation to drainage

Topography influences infiltration rate, run off and run on, temperature, and evapotranspiration. Each of these subfactors, in turn, influences soil development through such processes as leaching, weathering, erosion, sedimentation, and biosphere development. The relative water table position can have an effect on the magnitude of weathering and thus on the formation of different clay minerals in the soil. The rate and nature of chemical weathering were found to be influenced by the pH and the time of contact between rock and water (Drever, 1982). Weathering intensity increased as acidity and oxidation increased (Jackson et al., 1948). Well drained soils had short contact times and tended to have kaolinitic soils, whereas poorly drained soils had longer contact times and tended to have smectite as the soil clay mineral (Drever, 1982).

The study of the influences of parent material and topography on soil genesis in the midwest by White et al. (1960) indicated the dominant clay mineral in the glacial tills and fine textured sedimentary rocks was mica. The influence of topography and drainage was reflected in the proportion and distribution of the vermiculite and smectite resulting from the weathering of mica.

Weathering of mica to vermiculite in well drained and moderately well drained soils and alteration to smectite in poorly drained soils has been reported (Thorp et al., 1959; Smith and Wilding, 1972; McKeague et al., 1973; Ritchie et al., 1974; Schouten, 1974; Smeck et al., 1981). Differences in clay mineralogy on basic rocks were less obvious, but on the poorly drained sites the intensity of the smectite reflections were much stronger than on the well drained sites. In recent weathering products no differences in clay mineralogical composition due to differences in profile drainage status were observed (Schouten, 1974). Smeck et al.(1981) pointed out that the somewhat poorly drained soils were subjected to more severe weathering and leaching than the better drained members. The formation of smectite in the fine clays through weathering of vermiculite and or a synthesis reaction was more significant under somewhat poorly drained soils (Gleysolic) than under the well drained soils (Chernozemic). Illitization was apparent in the fine clay fraction of the solum of the well drained soils (Huang and Lee, 1969).

Bidwell and Page (1951) and Martin and Russel (1952) found little difference in type of clay minerals produced between different members of a toposequence as a result of internal drainage differences. There was slight evidence of more smectite in the B horizons of the poorly drained members. Otherwise the clays had not sufficiently weathered to alter the original clay inherited from the parent materials. Johnson and Jefferies (1957) in the Allenwood catena of Pennsylvania and Sawhney (1960) in Connecticut observed a weathering sequence of mica → mica intermediate → vermiculite → chlorite like material. The weathering sequence in both poorly and well drained members of the Allenwood catena was the same, however, the degree of expression of the weathering sequences was apparently controlled by drainage conditions. The extent of weathering of mica was more pronounced in the well drained member. The poor drainage condition inhibited the transformation of vermiculite in the lower horizons of the Pennsylvania catena while it inhibited the formation of the Al interlayers in the Connecticut catena. The restricted formation of Al interlayers in these soils was probably due to less weathering associated with poor drainage.

Biswas and Das (1960) and Iniguez and Scoppa (1973) found smectite contents increased and illite contents decreased in descending from well drained to the poorly drained soils. Kaolinite was only present in the well drained soils. Millot (1970), and Tardy (1971) have indicated kaolinite was the dominant weathering product in rapid leaching environments, whereas smectite was the dominant clay mineral in impervious soils even with high amounts of precipitation.

Drainage influenced the mica weathering product in several French soils (Millot and Gamez, 1963). Mica weathered to vermiculite through a mica-vermiculite intermediate stage in soils with open drainage, whereas in poorly drained soils it weathered to smectite.

Having similar soil forming factors (time, climate, vegetation, parent material) in a hydrosequence, topography produces local differences (internal drainage) among soils and as a result the soil profile development, the type and the amount of clay minerals forming in a hydrosequence varies accordingly.

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CHAPTER 1

SAND, SILT, AND CLAY MINERALOGY OF TWO MICHIGAN
FINE-LOAMY HYDROSEQUENCES

ABSTRACT

This study was conducted to determine the effect of natural drainage on sand, silt and clay mineral distributions in two fine-loamy hydrosequences. Piezometers were installed to monitor differences in water table levels. The dominant sand fraction was used for identification of minerals by petrographic microscope. X-ray diffractograms of the silt and clay fractions were obtained to determine the distribution of minerals.

The predominant sand minerals are quartz, K-feldspars, plagioclase, sericite and dolomite. The silt fraction is dominantly quartz with small amounts of feldspars and dolomites. The clay fraction is composed of mica, vermiculite, chlorite, kaolinite, smectite, quartz and feldspars.

Weathering of dioctahedral mica/sericite to smectite through interstratified vermiculite-smectite is the dominant trend in the poorly drained Brookston pedon, whereas direct transformation to vermiculite is the prevalent weathering mechanism in the other drainage classes. Except for the smectite in the Brookston pedon, the fine-loamy soils in this study do not have significant differences in the sand, silt, and clay mineralogies with respect to natural drainage.

INTRODUCTION

Few studies have been conducted to evaluate variation in clay minerals due to differences in natural drainage. These studies are contradictory and suggest further study. Bidwell and Page (1950) in Ohio, Martin and Russel (1952) in New York, and Arneman et al. (1958) in Minnesota found little or no variation in clay mineral distributions in their soil hydrosequences. Other studies however, have indicated differential clay mineral distributions with natural drainage, Johnson and Jeffries (1957) in Pennsylvania, Hutcheson et al. (1959) in Kentucky, and Allen and Fanning (1983). Recent studies of fine clays in two Michigan hydrosequences by Cremeens and Mokma (1987) have shown differential weathering intensity and translocation of fine clay minerals.

Mineralogical studies of sand and silt fractions are also few. Yassoglou and Whiteside (1960), Cady (1960), and Sidhu and Gilkes (1977) studied individual soil series. Arneman et al. (1958) determined the mineralogical composition of all size fractions in a Mollisol catena. All of these studies found little evidence of alteration of sand and silt sized minerals.

The objective of this study was to determine the effect of natural drainage on sand, silt, and clay mineral distribution of two fine-loamy hydrosequences in south-central Michigan.

MATERIAL AND METHODS

Two replicated fine-loamy hydrosequences were selected in Clinton and Ionia Counties in Michigan (Figure 1.1). The soils in each hydrosequence occurred in adjacent mapping units, so as to keep the other soil forming factors relatively constant. The hydrosequences occur on forested land where disturbances due to cultivation, artificial drainage and extensive erosion are absent or minimal.

The parent material of the Clinton County hydrosequence is loamy glacial till which occurs on a till plain near the Flint moraine of the Lake Border morainic system (Bretz, 1951; Ward, 1979). The Ionia County hydrosequence which also has loamy glacial till, occurs on a till plain approximately 1.5 miles north of the northern tip of the Ionia moraine of the Lake Border morainic system (Bretz, 1951).

The hydrosequences are composed of moderately well drained (pedon M1) and well drained (pedon M2) Marlette soils (Glossoboric Hapludalfs; fine-loamy, mixed, mesic), somewhat poorly drained Capac soils (Pedons C1 and C2) (Aeric Ochraqualfs; fine-loamy, mixed, mesic), and poorly drained Parkhill soils (Pedon P1) (Mollic Haplaquepts; fine-loamy, mixed, mesic) in the Clinton County hydrosequence and Brookston soils (Pedon B2) (Typic Argiaquolls; fine-loamy, mixed, mesic) in the Ionia County hydrosequence.

Pedons were described according to Soil Survey Manual (Soil Survey Staff, 1951) and sampled by major horizons (A, B, and C). Pedon locations are given in the pedon descriptions in Appendix A. Piezometers were installed near each of the sampled pedons to monitor the apparent depth of water table. Water table levels were monitored biweekly for the period 1 January 1984 through 31 December 1987.

Particle size distribution was determined by the pipette method (Soil Survey Staff, 1984), after removal of cementing agents according to Jackson (1979). The pH of each sample was determined using a 1:1 soil-solution ratio, both in water and 0.1N KCl.

Sands were separated from the silts and clays of each horizon by sieving and the dominant sand fraction was considered for identification of minerals. The dominant sand fraction was impregnated with a 3M Scotchcast and #3 Resin in a test tube. Thin blocks were cut, lightly polished to make one side flat and mounted on glass slides. The mounted slides were thin sectioned to approximately 30 μ thickness (Carver, 1970).

Quantitative determination of feldspar was made by etching the slides with hydrofluoric acid and staining with sodium cobaltinitrite, barium chloride and rhodizonate reagent as described by Bailey and Stephens (1960). Percentages of the various minerals present were determined by point counting (Galehouse, 1971) of approximately 900 grains per thin section using a standard petrographic microscope.

Cation exchange capacity (CEC) and exchangeable bases of each sample were determined using ammonium acetate at pH 7 (Soil Survey Staff, 1984). Calcium carbonate equivalent (CCE) was calculated from the inorganic carbon determined using the method of Bundy and Bremner (1972). Total elemental analysis of clay samples were measured by direct analysis of clay suspensions in water using direct current plasma (DCP) emission spectrophotometry according to Spiers et al.(1983).

All X-ray analyses (XRD) were performed with a Philips APD 3720 Automated X-ray Diffractometer system using CuK α radiation at 35KV and 20mA, a theta compensating slit, and diffracted beam monochromator with a graphite crystal. Diffractograms were obtained over a total scan range of 2° 2 θ to 40° 2 θ for the Mg saturated clays, coarse and fine silt at room temperature and from 2° 2 θ to 30° 2 θ for all other cation and heat treatments. All samples were scanned at a rate of 0.02°/second. Integrated peak intensities were used to semiquantitatively estimate the clay minerals present.

Random powder X-ray diffraction of the coarse and fine silt was obtained by placing them in a sample holder. X-ray diffractograms of the clay fractions were obtained from basally oriented specimens by transferring clays from membrane filters to glass slides (Drever, 1973), which had been: (a) Mg-saturated and glycerol solvated, (b) K-saturated and heated to 300°C or (c) K-saturated and heated to 550°C. Minerals were identified for XRD patterns using diffracting criteria outlined by Whitting and Allardice (1986).

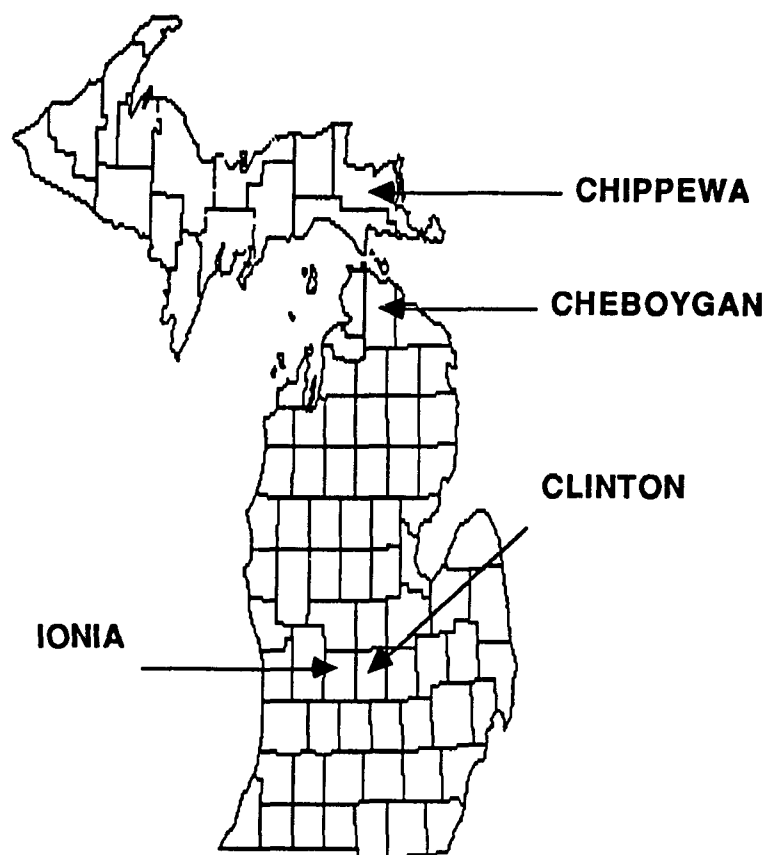


Fig. 1.1. Location of the study area in Michigan.

RESULTS AND DISCUSSION

Water Table Depth

Having similar soil forming factors (time, climate, vegetation, and parent material) in the study area, topography produces local differences in depth of water table among soils. Differences in the depth of water table can bring variations in weathering, soil development, and type and amount of clay minerals. With this in mind, depths of water table in two hydrosequences were monitored for four years to see the differences within and among hydrosequences.

Average monthly depths to water tables and average monthly precipitation in the two hydrosequences are presented in Figures 1.2 and 1.3. Except for the well drained M2 pedon, all pedons showed significant changes in the average monthly depths to water table during the four years. The high water table was observed during the months of March and April in response to snow melt and spring rains. During the active growing season (May through September), when evapotranspiration and precipitation is high, the water table drops and reaches the lowest at the end of the growing season, during August and September, even though this period is one of high precipitation. On average water tables were deepest during July through September. Water tables start rising during early fall and winter due to minimum evapotranspiration, plant senescence, and moderate precipitation. Fluctuations of water tables seem to be controlled by precipitation and evapotranspiration.

Well-drained (M2) and moderately well drained (M1) pedons are characterized by a deeper subsoil zone of saturation. Moderately well drained M1 pedon has a zone of saturation at the base of the solum during the middle of winter and early spring (February-May) whereas the well-drained M2 pedon was not saturated within the solum at any time of the year. When the soil is dry, dispersion upon wetting is favored (Arnold, 1965 and Daniels et al., 1967). As a consequence, the moisture fronts that result from any rainfall events will be capable of translocating suspended clay particles through the solum without the water table acting as a physical barrier. On the other hand, somewhat-poorly drained pedons (C1 and C2) had persistent water tables where the B horizons are saturated throughout the year except for the period of summer and early fall (June-October). In poorly drained pedons (P1 and B2) the B horizons are saturated throughout the year except for a brief period during August and September in the B2 pedon and during July through October in the P1 pedon. The water table in pedon B2 was higher than that in pedon P1 throughout the study period except during the month of September where the water tables

were at similar levels. Thus, except for this short period when the soil is dry, the throughflow of moisture fronts were restricted and as a result illuviation of suspended clay particles to the B horizon is limited. Pedons P1 and B2 do differ in respect to the extent of leaching, and duration of saturation (Figure 1.4). The B horizons of the Brookston pedon was saturated longer than the Parkhill B horizon (approximately 20% longer than the B horizon of the Parkhill pedon). Both pedons are characterized by the lack of throughflow moisture fronts because of shallow depths to saturation (Figure 1.5). However, they differ by the presence of argillans and smectite in pedon B2 and their absence in pedon P1. Cremeens and Mokma (1986) attributed the development of the Bt horizon in this pedon to relatively higher pH and presence of smectite. Smectite possibly inherited from the parent material was thought to be responsible for the argillic horizon. According to this study the high hydration condition of smectite in the natural settings, allows for its relatively easy dispersion, and its translocation with the fall rain to the zone of saturation. Base saturation and pH (Table 1.1 and 1.2; Figure 1.6) indicate these pedons are relatively unleached. The pH values of P1 and B2 pedons are in the range where smectite is stable.

Depths and durations of saturation were consistent with soil drainage classes as determined by profile morphology. Duration of saturation increased with depth within drainage classes and with decreasing drainage at similar depths (Figure 1.7 and 1.8). Depths and durations of saturation were similar for soils with the same natural drainage class. Patterns of average monthly depths of water tables and durations of saturation were similar to that observed by other researchers (Thorp et al., 1972; and Mackintosh et al. 1978) on similar soils formed on glacial till materials.

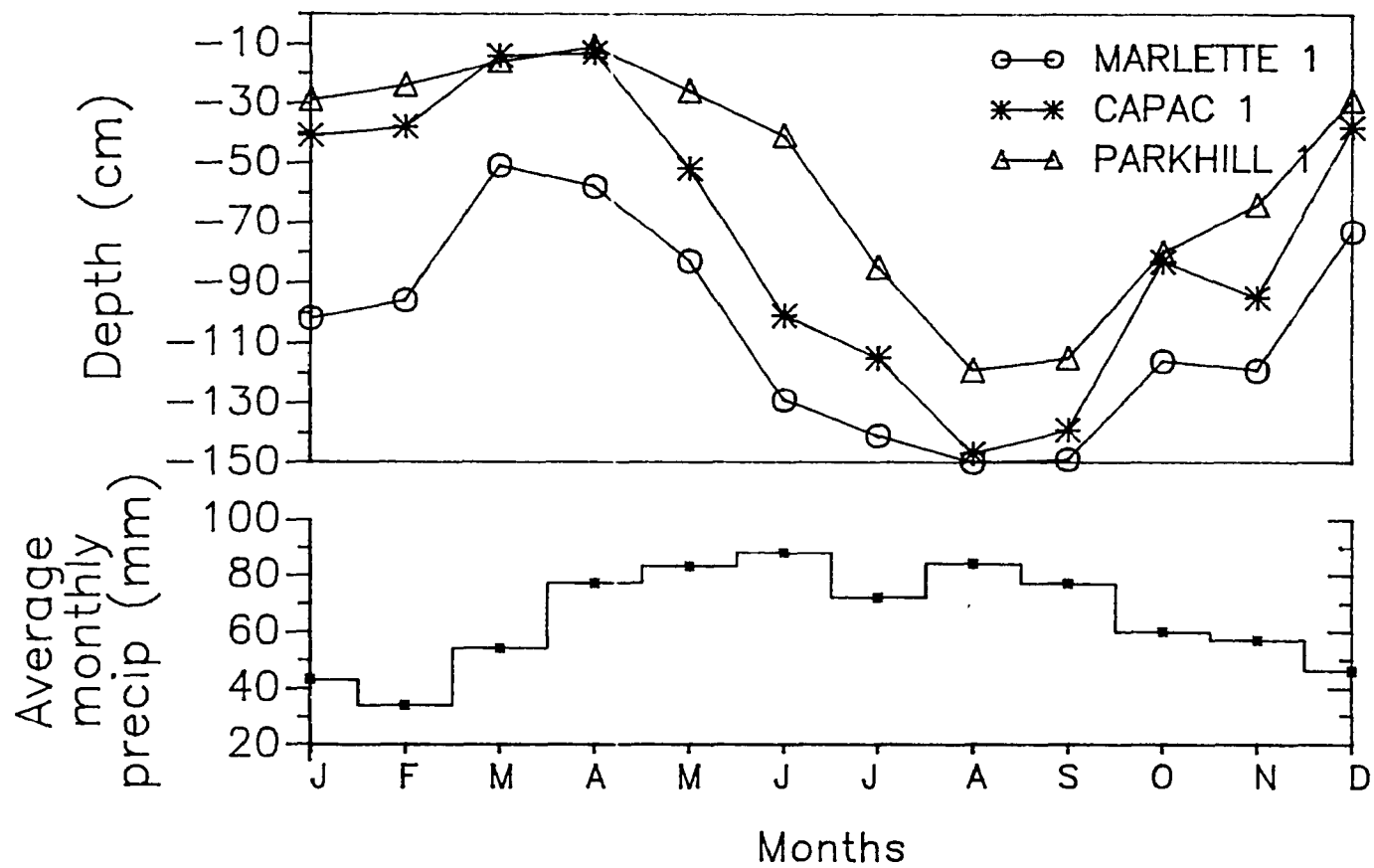


Figure 1.2 Average monthly depths to water tables and average monthly precipitation of hydrosequence 1, in Clinton County.

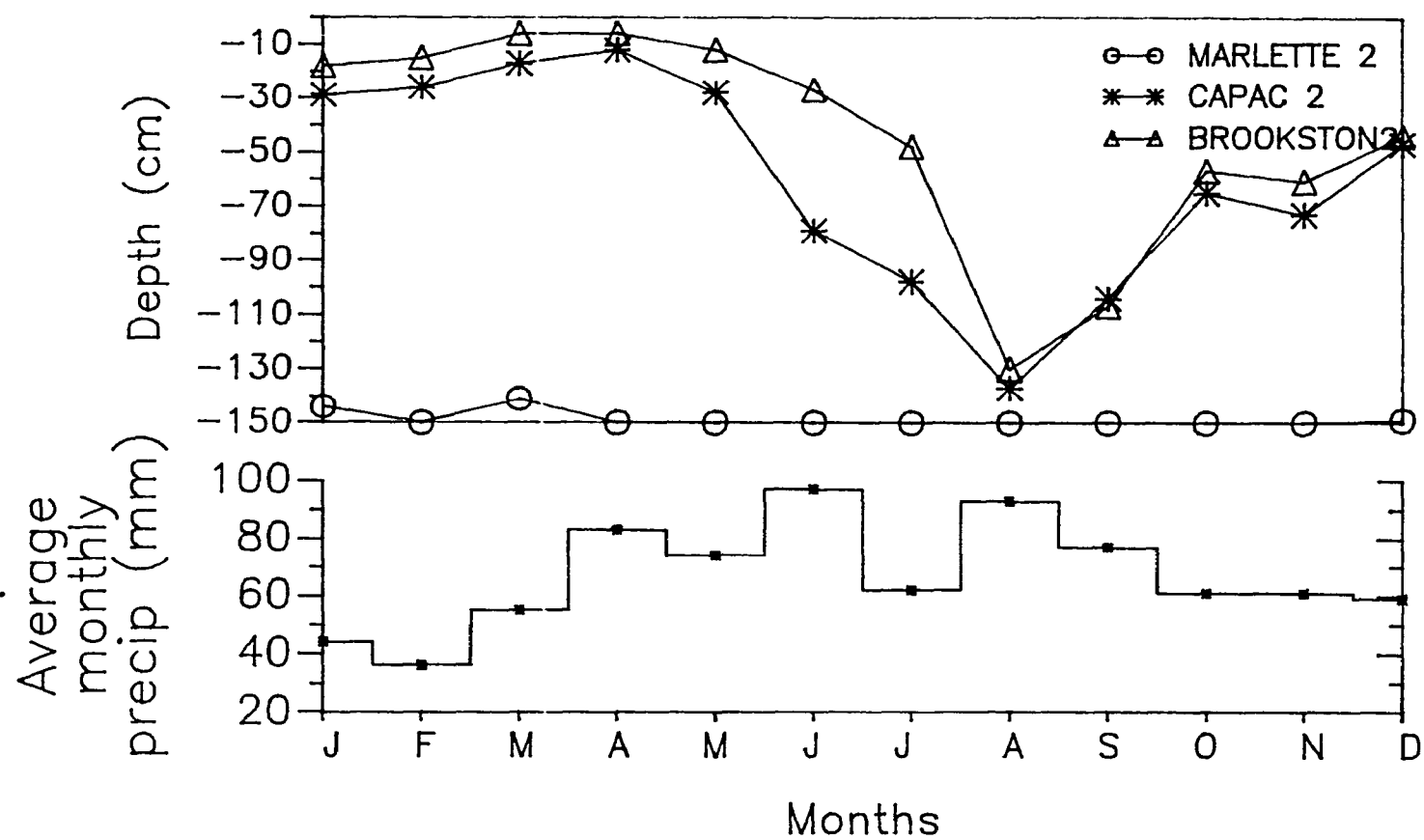


Figure 1.3 Average monthly depths to water tables and average monthly precipitation of hydrosequence 2, in Ionia County.

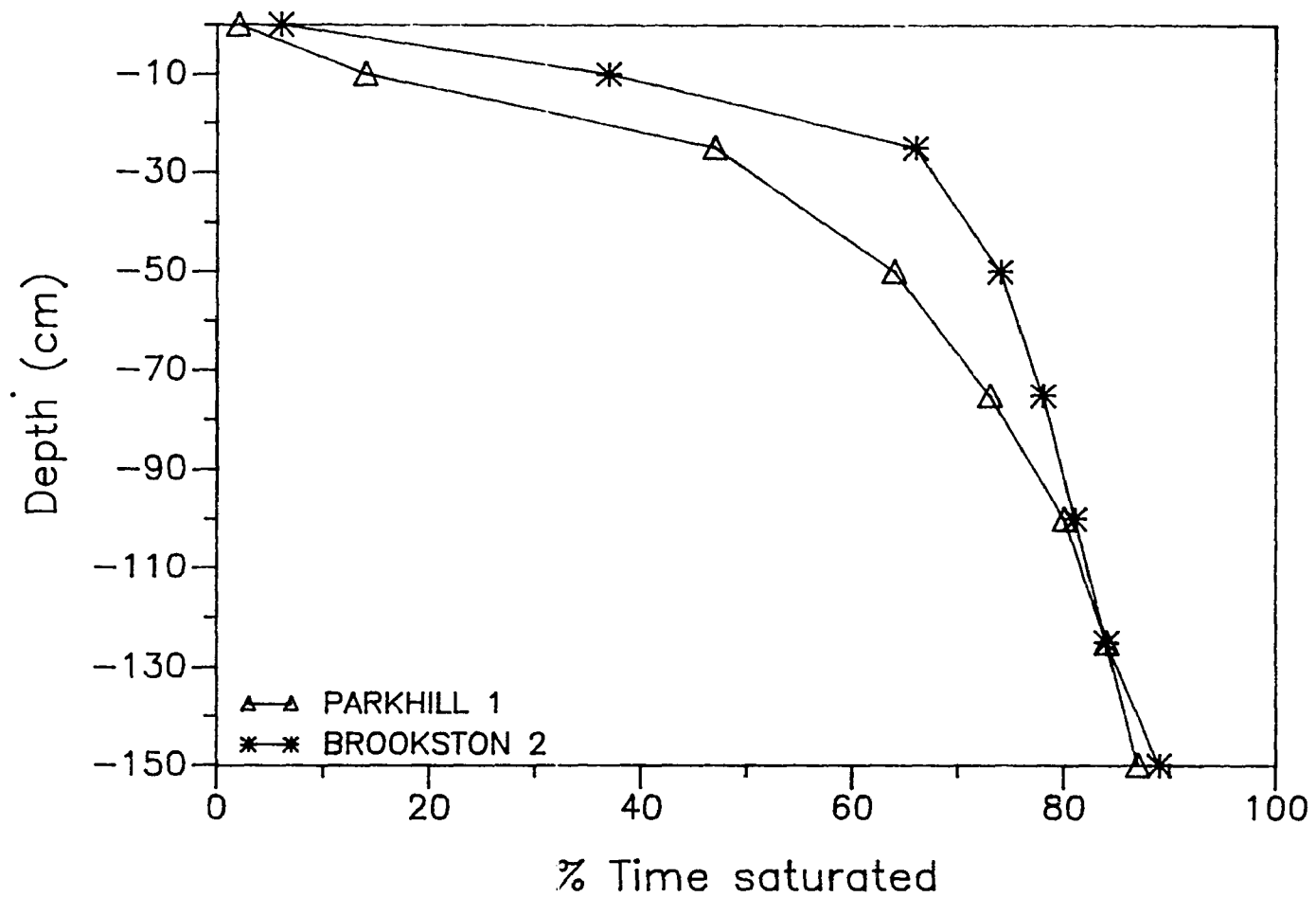


Figure 1.4. Percent total time saturated at given depth in poorly drained pedons, 1 Jan. 1984 – 31 Dec. 1987.

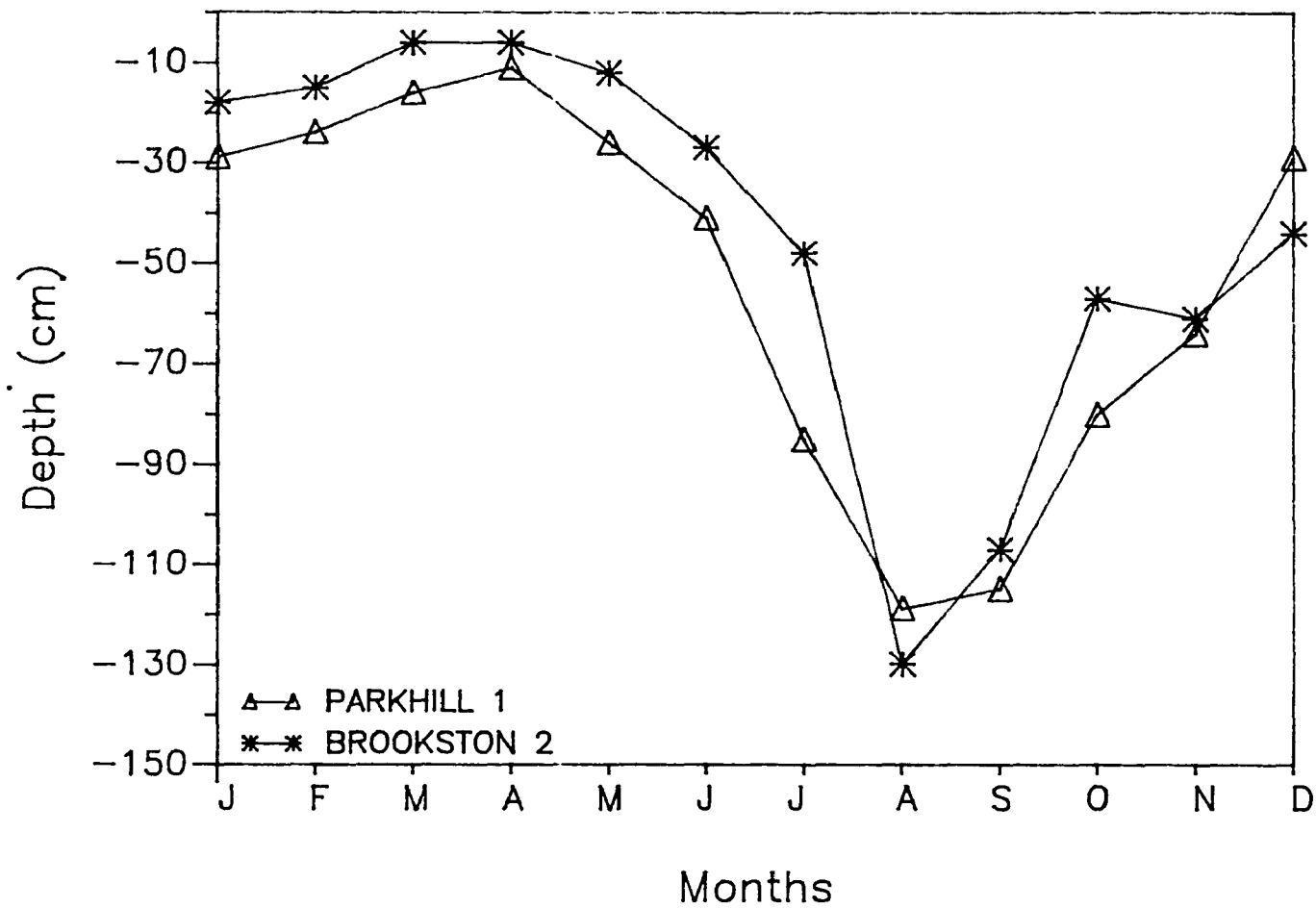


Figure 1.5. Average monthly depths to water tables in poorly drained pedons.

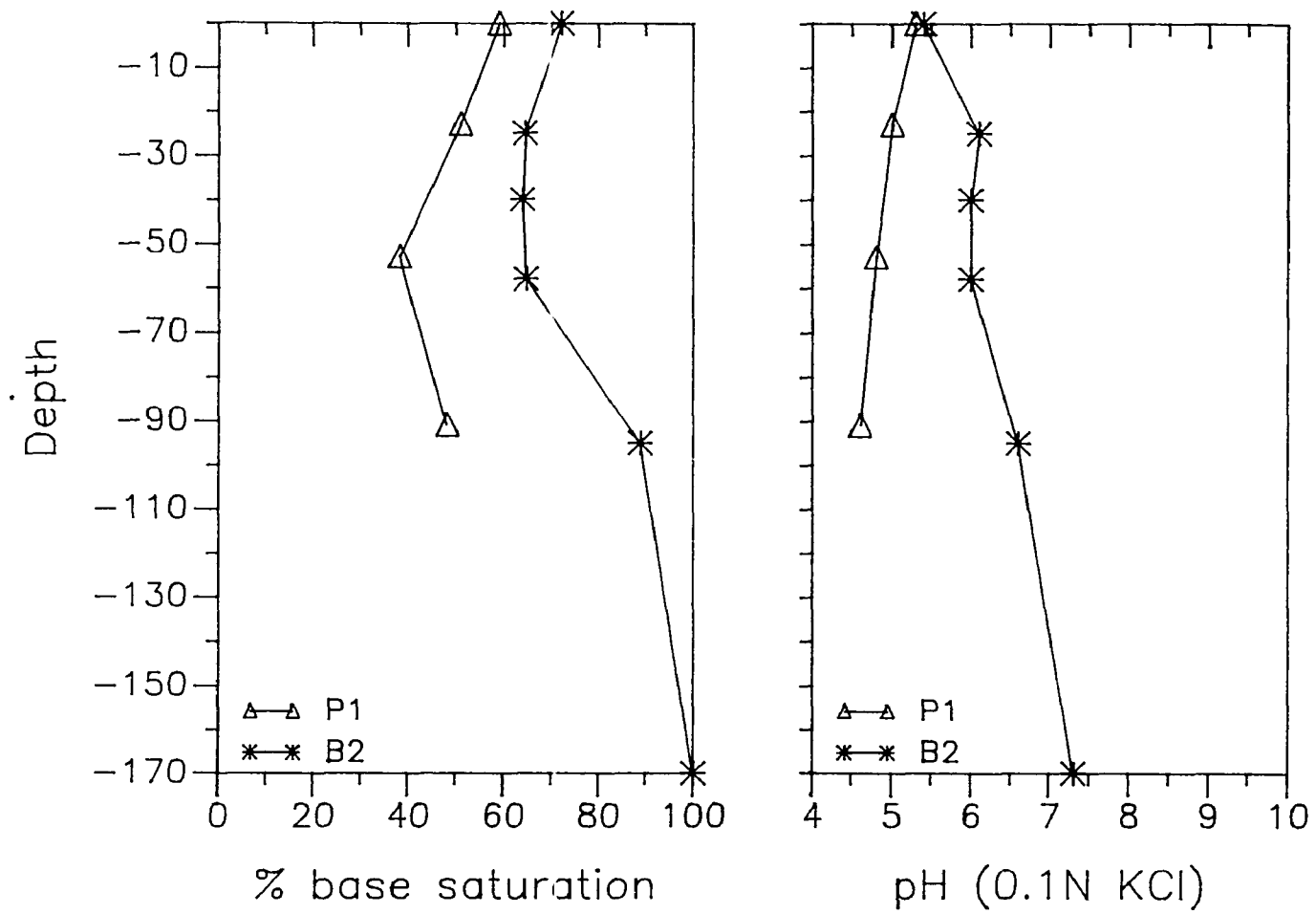


Figure 1.6. Base saturation and pH(0.1N KCl) in poorly drained pedons.

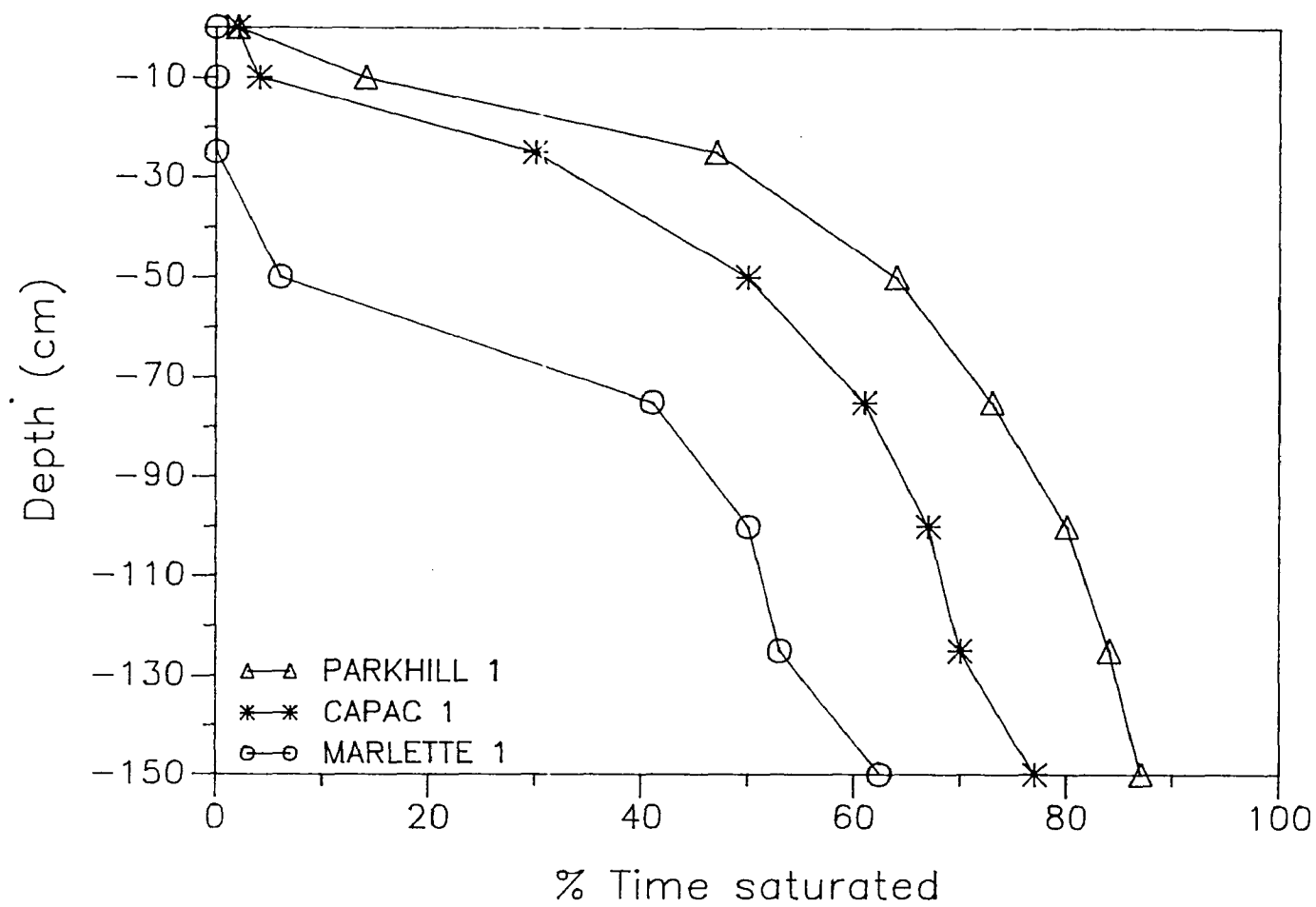


Figure 1.7. Percent total time saturated at given depth in hydrosequence 1.

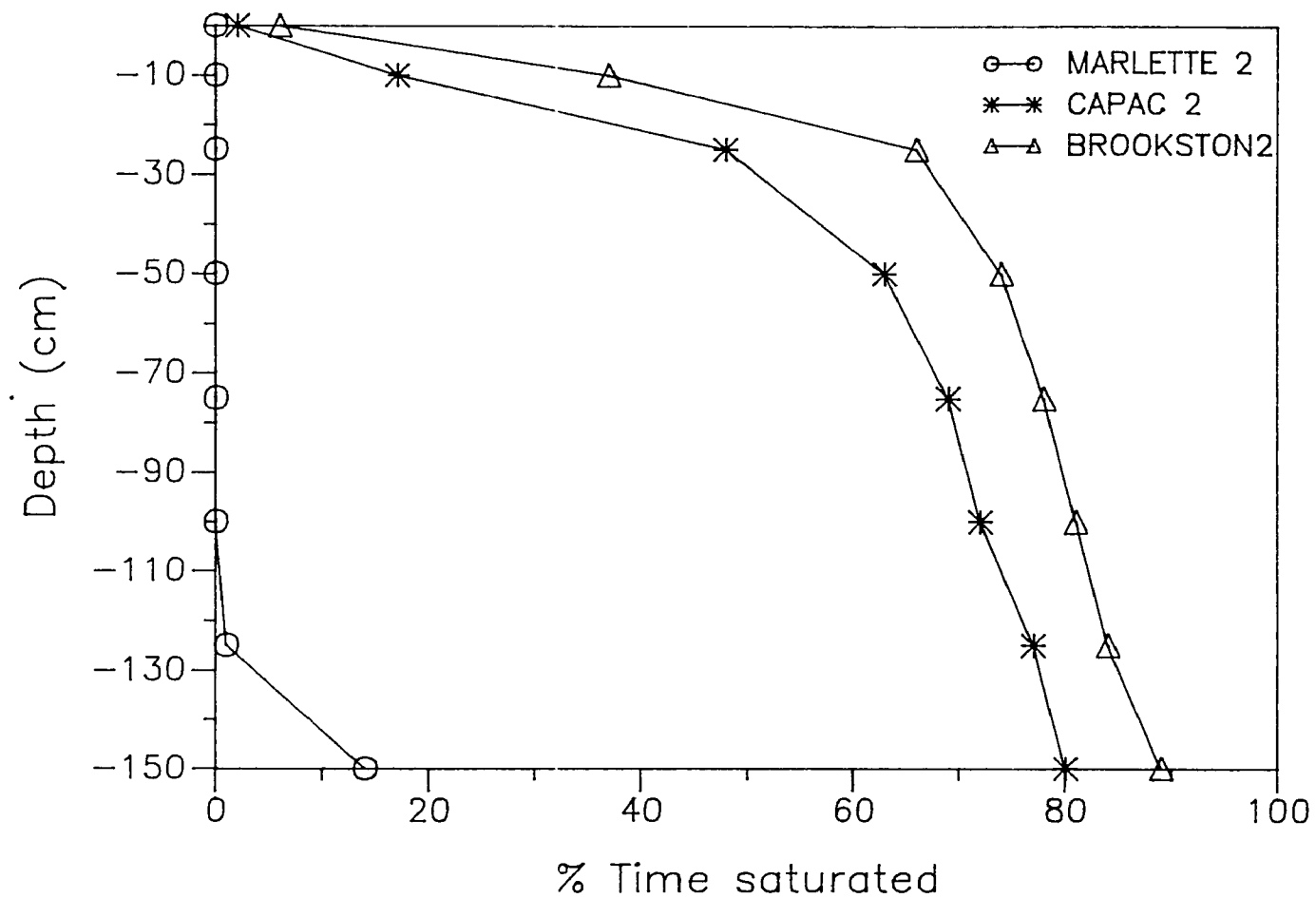


Figure 1.8. Percent total time saturated at given depth in hydrosequence 2.

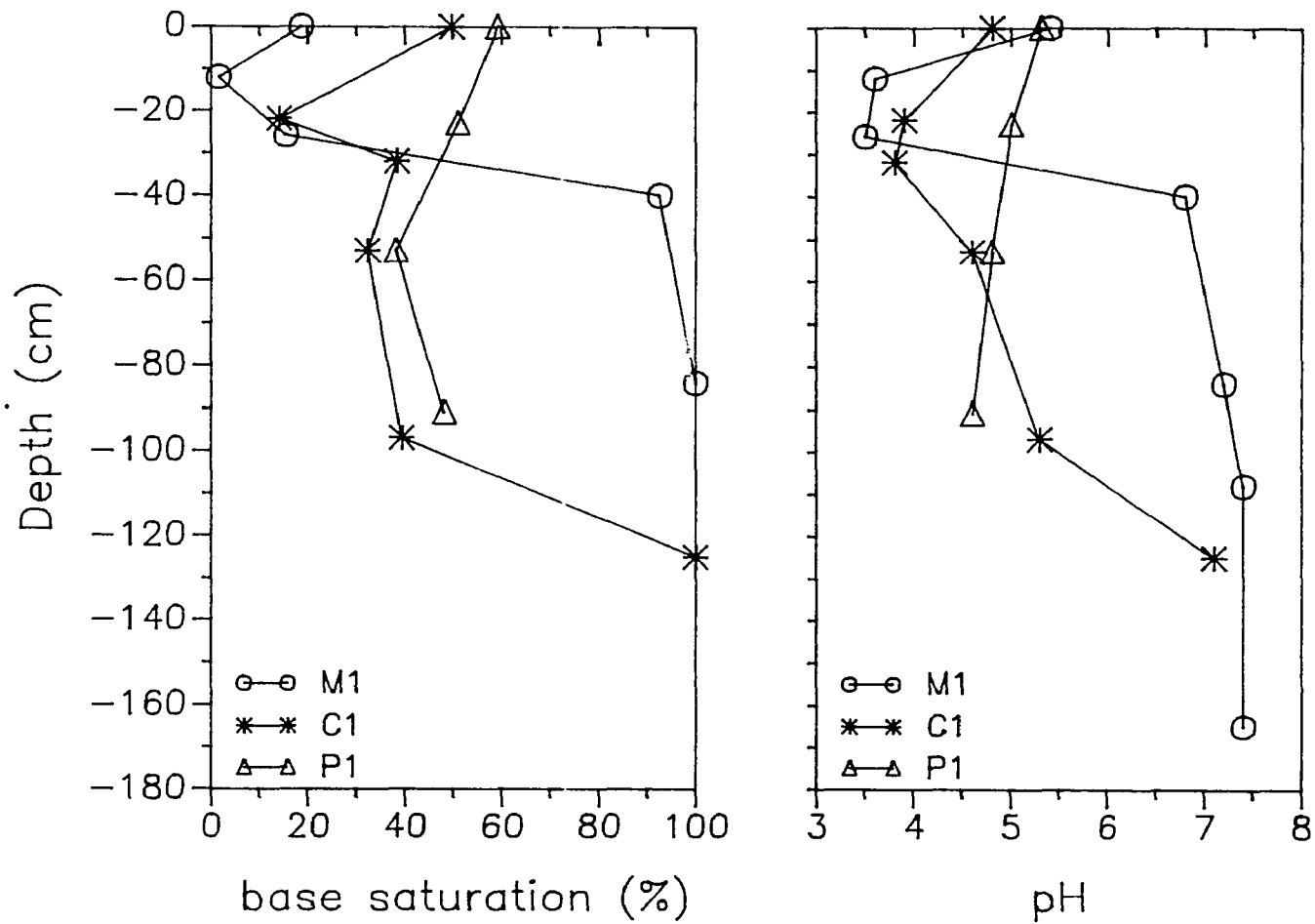


Figure 1.9. Base saturation and pH (0.1N KCl) in pedons of hydrosequence 1.

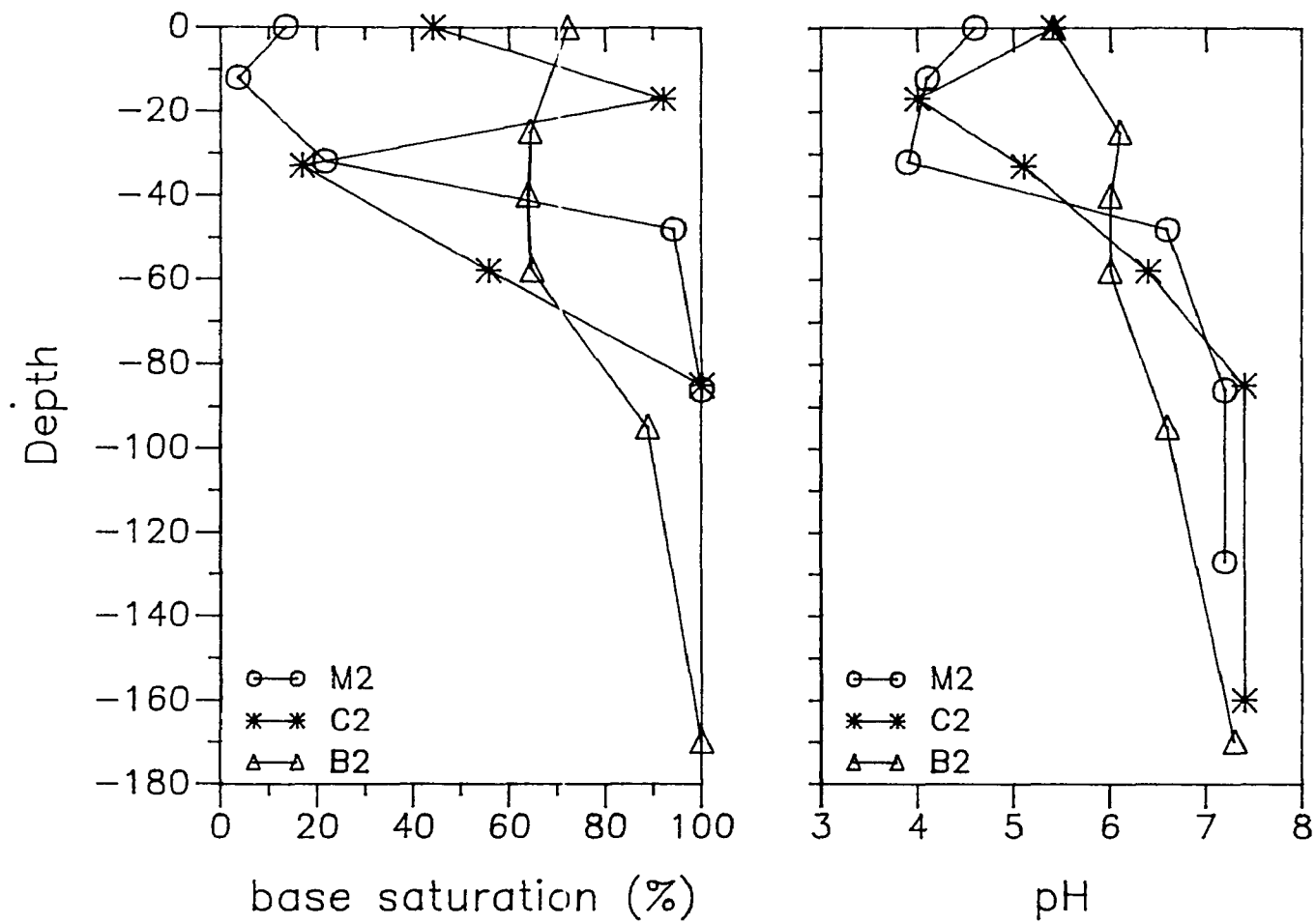


Figure 1.10. Base saturation and pH (0.1N KCl) in pedons of hydrosequence 2.

Table 1.1 SELECTED CHEMICAL PROPERTIES OF SOILS IN HYDROSEQUENCE 1

Horizon	Base Saturation Status								Dithionite- Citrate Ext.		Carbon	
	pH		CEC	Base Sat.	Exchangeable Bases				Fe	Al	Inorganic Ca CO ₃	Organic C.M.
	0 N											
	H ₂ O	KCl										
	meq/100g											
			%	meq/100g						%		
MARLETTE1												
A 0-12	6.1	5.4	22.1	45.7	0.3	7.9	1.9	10.1	0.37	0.06	-	5.8
E/B 12-26	4.8	3.6	12.0	1.5	0.2	*	-	0.18	0.42	0.06	-	1.1
Bt1 26-40	4.8	3.5	19.4	15.5	0.3	0.6	2.1	3.0	0.81	0.12	-	0.7
Bt2 40-84	7.6	6.8	21.3		0.4	16.1	6.2	22.7	0.84	0.10	0.5	0.7
BC 84-108	7.8	7.2	15.8		0.3	+	4.4		0.58	0.06	2.2	0.6
C1 108-165	8.0	7.4	12.4		0.3	+	3.7		0.53	0.04	2.1	0.5
C2 165+	8.1	7.4	10.9		0.3	+	6.6		0.53	0.04	2.5	0.4
CAPAC 1												
A 0-22	5.4	4.8	38.1	49.6	0.5	13.6	4.8	18.9	0.62	0.09	-	6.9
B/E 22-32	5.1	3.9	9.3	14.0	0.3	-	1.0	1.3	0.34	0.03	-	0.6
Bt1 32-53	5.1	3.8	14.1	38.3	0.2	2.0	3.2	5.4	0.63	0.05	-	0.4
Bt2 53-97	6.0	4.6	12.7	32.3	0.2	0.8	3.1	4.1	0.68	0.05	-	0.4
BC 97-125	6.6	5.3	10.4	39.4	0.2	1.4	2.5	4.1	0.64	0.05	0.01	0.4
2C 125+	7.9	7.1	11.0		0.2	+	3.8		0.66	0.04	1.9	0.3
PARKHILL1												
A 0-23	6.1	5.3	30.0	59.0	0.6	12.4	4.7	17.7	0.63	0.10	-	3.7
Bg1 23-53	5.9	5.0	22.8	50.9	0.4	7.3	3.9	11.6	0.45	0.07	-	2.6
Bg2 53-91	5.9	4.8	16.8	38.1	0.3	2.9	3.2	6.4	0.89	0.07	-	1.0
C 91+	5.9	4.6	15.8	48.1	0.4	3.4	3.8	7.6	0.63	0.07	0.3	0.6

* = negligible quantity
+ = free CaCO₃

Table 1.2. Selected chemical properties of soils in hydrosequence 2.

Base Saturation Status														
Horizon		pH		Exchangeable Bases							Dithionite		Carbon	
		0.1N		Base	CEC	Sat.	K	Ca	Mg	Sum	Citrate Ext.		Inorganic as CaCO ₃	Organic as O.M.
		H ₂ O	KCL								Fe	Al		
		meq/100g									%	meq/100g		
MARLETTE 2														
A	0-12	5.1	4.6	12.6	13.5	0.28	1.4	*	1.7	0.21	0.04	*	3.8	
B/E	12-32	5.2	4.1	6.4	3.6	0.23	*	*	0.23	0.28	0.04	*	0.8	
Bt1	32-48	5.1	3.9	13.4	21.6	0.41	1.5	1.0	2.9	0.61	0.09	*	0.5	
Bt2	48-86	7.2	6.6	15.5	94.2	0.45	7.5	6.6	14.6	0.69	0.09	0.6	0.5	
BC	86-127	7.9	7.2	7.9		0.24	+	2.3		0.38	0.04	2.2	0.4	
C	127+	8.0	7.2	9.9		0.24	+	2.7		0.38	0.04	2.3	0.3	
CAPAC 2														
A	0-17	6.0	5.4	20.8	44.2	0.21	7.6	1.4	9.2	0.31	0.05	*	4.0	
B/E	17-33	5.3	4.0	12.5	92.0	0.26	9.0	2.2	11.5	0.44	0.05	*	0.6	
Bt	33-58	6.4	5.1	16.1	16.8	0.21	0.8	1.7	2.7	0.50	0.08	*	0.5	
Btg	58-85	7.2	6.4	14.0	55.7	0.28	4.2	3.3	7.8	0.45	0.06	*	0.4	
BC	85-160	8.0	7.4	6.1		0.28	4.8	3.4	8.5	0.32	0.03	3.8	0.2	
C	160+	8.0	7.4	5.8		0.19	+	2.4		0.32	0.03	2.2	0.2	
BROOKSTON 2														
A	0-25	6.1	5.4	43.7	72.1	0.32	26.1	5.1	31.5	0.16	0.05	*	8.3	
BA	25-40	7.0	6.1	18.8	64.4	0.37	8.1	3.6	12.1	0.21	0.07	*	0.8	
Btg1	40-58	7.1	6.0	17.2	63.9	0.36	7.3	3.3	11.0	0.24	0.07	*	0.5	
Btg2	58-95	7.1	6.0	18.7	64.7	0.37	8.1	3.6	12.1	0.29	0.08	*	0.4	
BC	95-170	7.4	6.6	16.9	88.8	0.34	9.2	5.5	15.0	0.55	0.05	0.6	0.4	
C	170+	7.9	7.3	8.3		0.21	+	4.3		0.34	0.05	3.6	0.3	
* = negligible quantity														
+ = free CaCO ₃ present														

Parent Material Homogeneity

The initial step, before any soil development and mineral weathering studies, is to ascertain that the soils formed from relatively similar parent material and are not affected by the action of erosion and deposition. Glacial till is the most heterogeneous sediment (Flint, 1971) and as a consequence detection of subtle lithologic discontinuities is difficult. Methods used for differentiating parent materials include soil morphology, micromorphology, particle size distribution with depth, and depth distribution of heavy minerals (zircon, rutile, etc.) which are resistant to weathering and are considered to be stable. Cremeens and Mokma (1986), modifying Asady and Whiteside's (1982) methods, calculated the ratio of silt plus very fine sand to total sand minus very fine sand for each horizon to identify lithologic discontinuities. The ratio of an overlying horizon was divided by that of the underlying horizon and one is subtracted from the resultant ratio. A value of ± 0.60 was chosen by the investigators to identify lithologic discontinuities. Ratios between these values indicate uniformity whereas greater deviation from these values indicates nonuniformity of the parent material. Particle size data are presented in Tables 1.3 and 1.4. Lithologic discontinuities were found in pedons C1 and P1 but not in the other pedons. Pedon C1 has a lithologic discontinuity between the BC horizon to the 2C horizon. In pedon P1 a discontinuity was identified between the A and Bg horizon. The A horizon could be deposition of erosion products from the surrounding upland soils. Hydrosequence 1, being on the edge of the Flint moraine, may have had more influence from the melting process as the glacier retreated (Cremeens, 1983). Ice contact slightly stratified drift, including flowtill phenomenon, has been described by Flint (1971). Hydrosequence 2 appears to have been developed in relatively uniform material of somewhat coarser texture than hydrosequence 1.

Table 1.3 Particle size analysis and bulk density of soils in hydrosequence 1.

Particle Size Analysis (%)														
Horizon	TOTAL			SAND					SILT		CLAY		BULK DENS.	
	SAND	SILT	CLAY	VCS	CS	MS	FS	VFS	CSi	FSi	CC	FC		
	—	—	—	—	—	—	%	—	—	—	—	—	g/cc	
MARLETTE1														
A 0-12	26	60	14	1	1	5	10	8	27	33	11	3	1.43	
E/B 12-26	22	60	18	1	1	4	8	8	34	26	14	4	1.91	
Bt1 26-40	13	56	31	0	1	2	5	5	25	31	20	11	1.87	
Bt2 40-84	15	54	31	1	1	2	6	5	31	23	19	12	1.86	
BC 84-108	17	57	26	1	1	3	6	6	38	19	15	11	1.93	
C1 108-165	16	62	22	1	2	2	6	5	42	20	14	8	2.04	
C2 165+	15	62	23	1	1	2	6	5	41	21	17	6	2.01	
CAPAC 1														
A 0-22	42	39	19	1	3	10	18	10	25	14	10	9	1.44	
B/E 22-32	54	33	13	2	3	10	24	14	17	16	8	5	1.87	
Bt1 32-53	49	33	18	2	2	10	22	13	18	15	9	9	1.91	
Bt2 53-97	48	36	16	1	2	9	22	14	20	16	9	7	1.86	
BC 97-125 **	57	29	14	2	3	13	26	13	15	14	7	7	1.88	
2C 125+	28	53	19	1	2	5	11	9	48	5	11	8	2.1	
PARKHILL 1														
A 0-23 **	18	57	25	1	2	4	6	5	29	28	14	11	1.68	
Bg1 23-53	36	43	21	1	3	10	15	7	22	21	12	9	1.78	
Bg2 53-91	36	41	21	0	3	11	16	8	21	20	12	9	1.99	
C 91+	39	37	24	1	2	12	16	8	17	20	14	10	1.92	

** = Lithologic discontinuity at lower boundary of horizon;
uniformity value exceeded ± 0.60
 $(Si+vfs)/(s-vfs)$ for overlying horizon — 1
 $(Si+vfs)/(s-vfs)$ for underlying horizon

Table 1.4. Particle size analysis of soils in hydrosequence 2.

Particle Size Analysis (%)													
Horizon	TOTAL				SAND				SILT		CLAY		BULK
	SAND	SILT	CLAY	VCS	CS	MS	FS	VFS	FSI	CSI	CC	FC	DENS.
	—	—	—	—	—	—	%	—	—	—	—	—	g/cc
MARLETTE 2													
A 0-12	50	40	10	0	4	14	21	8	17	23	6	4	1.5
B/E 12-32	49	40	11	1	3	13	21	9	16	24	8	3	1.9
Bt1 32-48	44	37	19	1	3	12	19	8	19	18	11	8	1.96
Bt2 48-86	35	42	23	1	2	10	15	6	22	20	12	11	1.9
BC 86-127	31	56	13	1	2	8	13	7	46	10	7	6	1.97
C 127+	38	46	16	1	3	10	16	8	31	15	9	7	2.05
CAPAC 2													
A 0-17	63	31	6	2	5	19	27	10	17	14	4	2	1.49
B/E 17-33	45	42	13	2	4	12	18	8	21	21	9	4	2.05
Bt 33-58	48	38	14	1	4	13	20	9	22	16	8	6	1.91
Btg 58-85	51	35	14	2	4	14	22	11	28	10	9	5	1.86
BC 85-160	54	35	14	2	4	14	22	11	28	10	4	4	2.03
C 160+	51	41	8	1	3	13	22	10	29	12	5	3	2.09
BROOKSTON 2													
A 0-25	61	30	9	5	5	19	23	8	16	14	5	4	1.46
BA 25-40	56	28	16	2	4	17	24	9	12	16	6	10	1.92
Btg1 40-58	50	31	19	2	4	16	20	8	13	18	8	11	1.87
Btg2 58-95	47	33	20	1	4	15	19	8	15	18	9	11	1.82
BC 95-170	56	31	13	2	4	20	22	8	14	17	6	7	1.83
C 170+	46	38	16	2	4	15	20	6	33	5	9	7	2.03

Sand Mineralogy

Preliminary mineral counts in triplicate samples indicated that good reproducibility could be obtained and as a result single samples were used for mineral counts. The single samples were counted three times and in each count 300 grains were counted and the average was considered. Previously established statistical computation indicates that probable error depends largely upon the number of grains counted, and is greatest for the rarer minerals and lowest for the abundant minerals (Galehouse, 1971). The mineralogy of the fine sand fraction is composed of quartz, K-feldspar, plagioclase, chert, pyroxene, amphibole, sericite, dolomite, altered minerals, and opaque minerals (Table 1.5). Quartz is the only mineral that accounts for more than 50% but less than 90% of the fine sand of these soils. Thus these soils are classified as having mixed, not siliceous, mineralogy at the family level according to Soil Taxonomy.

Eberl et al. (1987) have described sericite as a petrographic term used to indicate highly birefringent, fine-grained, micaceous material that is viewed under the optical microscope. Sericite is also described by others as a fine-grained white mica present in acidic intrusive rocks which have undergone hydrothermal alteration. Sericite forms in response to changes in the H⁺/alkali ratio in the rock-water system (Meunier et al., 1982). Sericite can cover many mineral types (Eberl et al., 1987). It has been described as being composed of muscovite, phengite, illite, hydromica, or mixed-layer illite/smectite, with fixed interlayer cation contents which are less than the structural limit of one equivalent per O₁₀(OH)₂ (Eberl et al., 1987).

Results of the petrographic analysis of the fine sand fraction indicates the following points.

- A/ The quartz content for the solum (A and B horizons) is always higher than the parent material (C horizon). The differences between the solum and the parent material values are less pronounced for the poorly drained profiles particularly for Pedon P1.
- B/ The amount of plagioclase in the solum increases with depth while the potassium feldspar decreases or remains relatively uniform with depth.
- C/ The quartz to plagioclase feldspar ratios tend to decrease with depth indicating the weathering of plagioclase relative to quartz (Table 1.6 and Figure 1.11). The A horizons show the highest ratios in all pedons except the A horizon of pedon M2.
- D/ The quartz/potassium feldspar ratios also tend to decrease with depth (Table 1.6 and Figure 1.12) but the ratios within a pedon are less than the quartz/plagioclase ratios for the same pedon. The differences in ratios may be due to different intensities of plagioclase and K-feldspar weathering. The relatively small increase in

quartz/K-feldspar ratios relative to the parent material indicate the less weathering of K-feldspar than the plagioclase feldspars. The relative similarity of the ratios in the C horizons indicates the mineral uniformity of the parent material (Table 1.6 and Figures 1.11, 1.12, 1.13). In pedon P1 the quartz/k-feldspar ratio is higher in the B horizon than the A horizon (Table 1.6 and Figure 1.12), suggesting variability in the mineralogical composition of the material from which the A and B horizons developed relative to that of the underlying material. Differences in the parent material were also observed based on the values calculated according to Cremeeens and Mokma (1986).

- E/ The ratios of quartz/feldspar decreased with increasing depth in all the pedons except pedon P1 (Figure 1.13) suggesting differences in parent material between A and B horizons and also indicates complementary covariance of other percentages.
- F/ The percentage of chert in all the profile is constant indicating the resistance of chert to chemical and physical weathering.
- G/ Dolomite is present only in C horizons except the Parkhill profile. The absence of dolomite in the C horizon of the pedon P1 could be due to the sampling depth of the C horizon 125 cm compared to 170 cm in pedon B2. Dolomite is present in C horizons of pedons M1 and C1 of hydrosequence 1. The three pedons are about 50 meters apart, therefore it is difficult to assume the lack of dolomite in the pedon P1 is due to parent material differences.
- H/ Pyroxenes, amphiboles, and opaque minerals are present in small amounts and are relatively uniform throughout the profile. Pyroxene and amphiboles tend to be lower in the solum than in C horizons. These minerals constitute a minor portion of the total minerals present (<5%).
- I/ Sericite is nearly uniformly distributed in the profile with a slight increasing tendency in the C horizon. Sericite viewed with a petrographic microscope was observed as shining, fine grained particles on K-feldspar and plagioclase grains and as well as a single grain. This suggests sericite may have formed, at least partially, from feldspars.
- J/ The similarity in mineral contents of C horizons suggest the relative uniformity of the parent materials in each hydrosequence (Table 1.5).

The decreasing quartz contents with depth indicate weatherable minerals have weathered in the solum. Plagioclase feldspar appeared to weather faster than potassium feldspar, a trend which agrees with similar results reported by other investigators

Table 1.5 Mineralogy of fine sand fractions.

HORIZON	Qz	K FELD.	SER.	Na/Ca FELD.	Rock FRAG	CHE.	OP. %	PYR.	AMP	ALT.	Dol.
MARLETTE1											
A	68	14	2	7	2	2	1	1	1	2	-
Bt	64	15	2	9	2	2	1	1	2	1	-
C	56	13	3	11	1	3	1	2	2	1	7
CAPAC 1											
A	68	13	3	7	2	2	1	1	1	2	-
Bt	65	13	3	10	1	2	1	1	2	2	-
2C	55	13	3	13	1	2	1	2	3	1	5
PARKHILL											
A	67	14	4	9	2	2	1	-	-	2	-
Bg	66	12	4	8	2	2	2	-	2	2	-
C	62	13	3	12	2	2	1	2	2	1	-
MARLETTE 2											
A	69	13	2	9	1	2	1	1	1	1	-
Bt	64	15	2	8	2	3	1	2	2	1	-
C	60	14	3	11	1	2	1	2	2	1	3
CAPAC 2											
A	70	11	2	8	1	2	2	1	1	2	-
Bt	68	12	3	9	1	2	1	1	2	1	-
C	58	13	3	11	1	2	1	1	3	1	6
BROOKSTON 2											
A	69	12	2	9	2	1	1	1	1	2	-
Btg	63	14	2	12	2	1	1	1	1	2	-
C	58	14	1	12	1	1	1	2	3	1	5

Qz=quartz; Op=opaque; Che=chert; Rock frag=rock fragment
k-feld=k-feldspar; Pyr=pyroxene; Amp=amphibole;
Na/Ca-feld=plagioclase; Alt=altered; Ser=sericite; Dol=dolomite;

(Franzmeier et al., 1963). According to Eberl et al. (1987) and Meunier et al. (1982) sericite formation is associated with K rich and acidic rock-water system as a retrograde metamorphic product. However, its association with K poor plagioclase is something that needs further study. The very small amounts of easily weatherable minerals in C horizons

of these soils indicate intense weathering either before deposition or during soil formation or low initial content in the parent rock.

Table 1.6 Mineral ratios for the fine sand fraction.

	Q/F	Q/K	Q/P		Q/F	Q/K	Q/P
MARLETTE 1				MARLETTE 2			
A	2.4	4.9	9.7	A	3.1	5.3	7.7
Bt	2.7	4.3	7.1	Bt	2.8	4.3	8
C	2.3	4.3	5.1	C	2.4	4.3	5.5
CAPAC 1				CAPAC 2			
A	3.4	5.2	9.7	A	3.7	6.4	8.8
Bt	2.8	5.0	6.5	Bt	3.2	5.7	7.6
2C	2.1	4.2	4.2	C	2.4	4.5	5.3
PARKHILL 1				BROOKSTON 2			
A	3.2	5.2	8.4	A	3.3	5.8	7.7
Bg	3.3	5.5	8.3	Btg	2.4	4.5	5.3
C	2.5	4.8	5.2	C	2.2	4.1	4.8

SILT MINERALOGY

Minerals identified in coarse (20-50 μm) and fine (2-20 μm) silt fractions are chlorite, mica, plagioclase, K-feldspar, quartz, and dolomite (Table 1.7). Generally, identification of minerals present in silt fractions was based on JCPDS (1974) powder diffraction data for standard minerals. The presence of chlorite and mica was based on $14\text{\AA}$ and $10\text{\AA}$ peaks in the x-ray diffractogram respectively. Plagioclase was identified using peaks with d-spacings of $4.03\text{\AA}$, $4.04\text{\AA}$, $3.68\text{\AA}$, $3.19\text{\AA}$, $3.18\text{\AA}$ and $3.15\text{\AA}$, whereas K-feldspars were identified from $4.21\text{\AA}$, $4.22\text{\AA}$, $3.47\text{\AA}$, $3.46\text{\AA}$, $3.31\text{\AA}$, $3.25\text{\AA}$, $3.03\text{\AA}$, $2.99\text{\AA}$, $2.96\text{\AA}$, $2.91\text{\AA}$, $2.90\text{\AA}$, $2.89\text{\AA}$ and $2.77\text{\AA}$ peaks. The presence of $4.26\text{\AA}$, $3.34\text{\AA}$, $2.46\text{\AA}$, and $2.28\text{\AA}$ peaks were indicative of quartz in the XRD. Dolomite was identified using the $2.89\text{\AA}$, $2.67\text{\AA}$, and $2.54\text{\AA}$ diagnostic peaks.

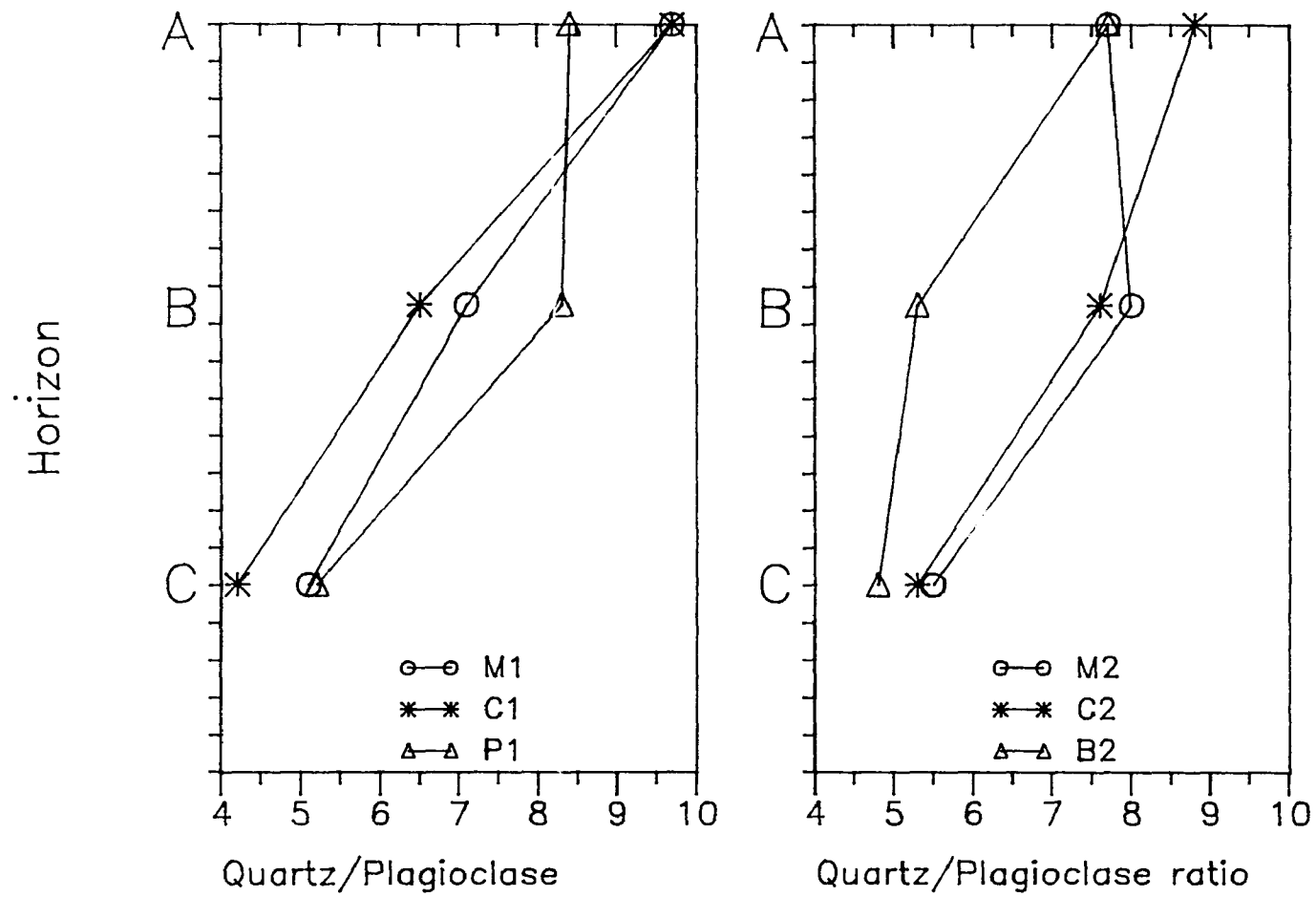


Figure 1.11. Quartz to plagioclase ratios.

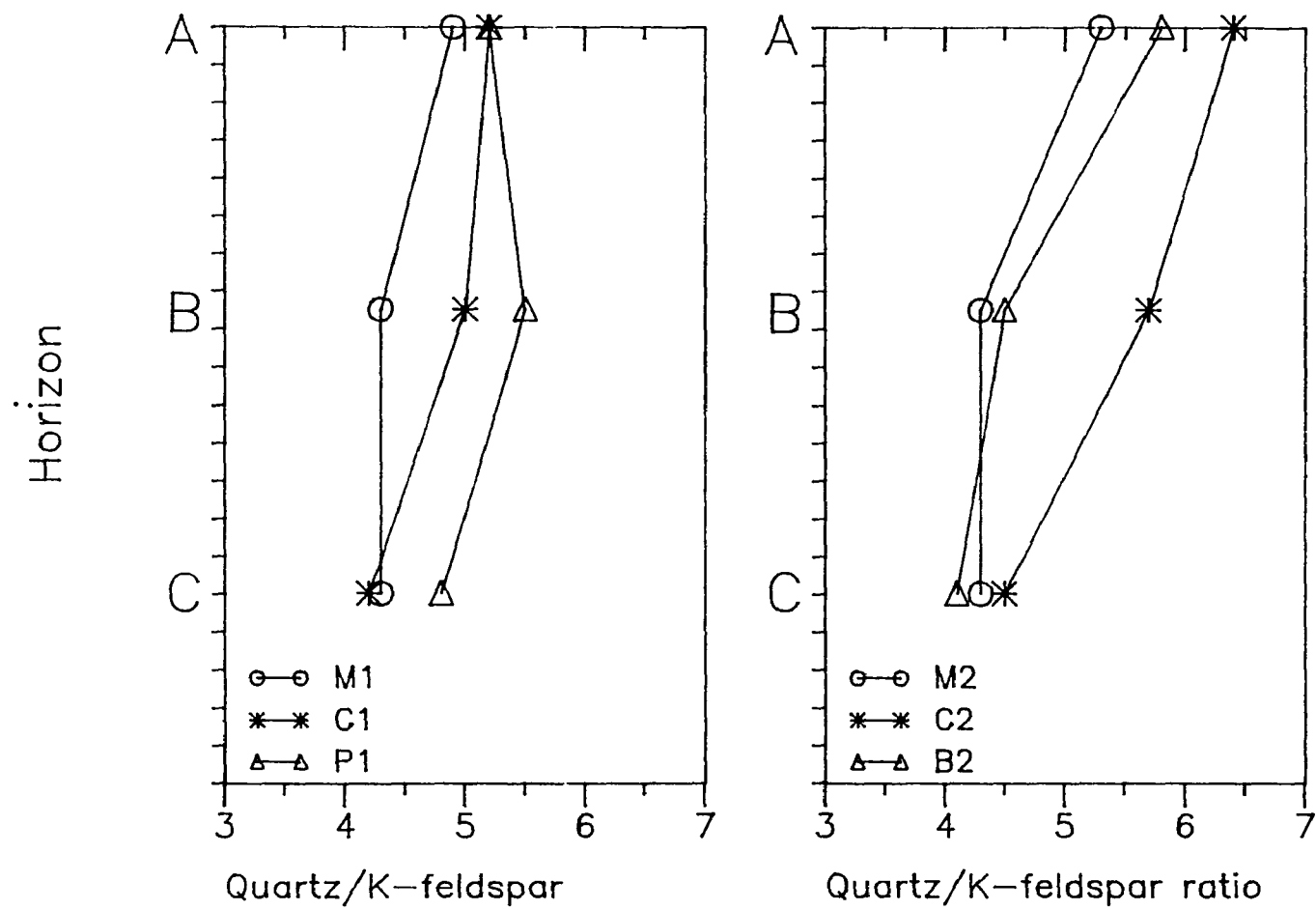


Figure 1.12. Quartz to K-feldspar ratios.

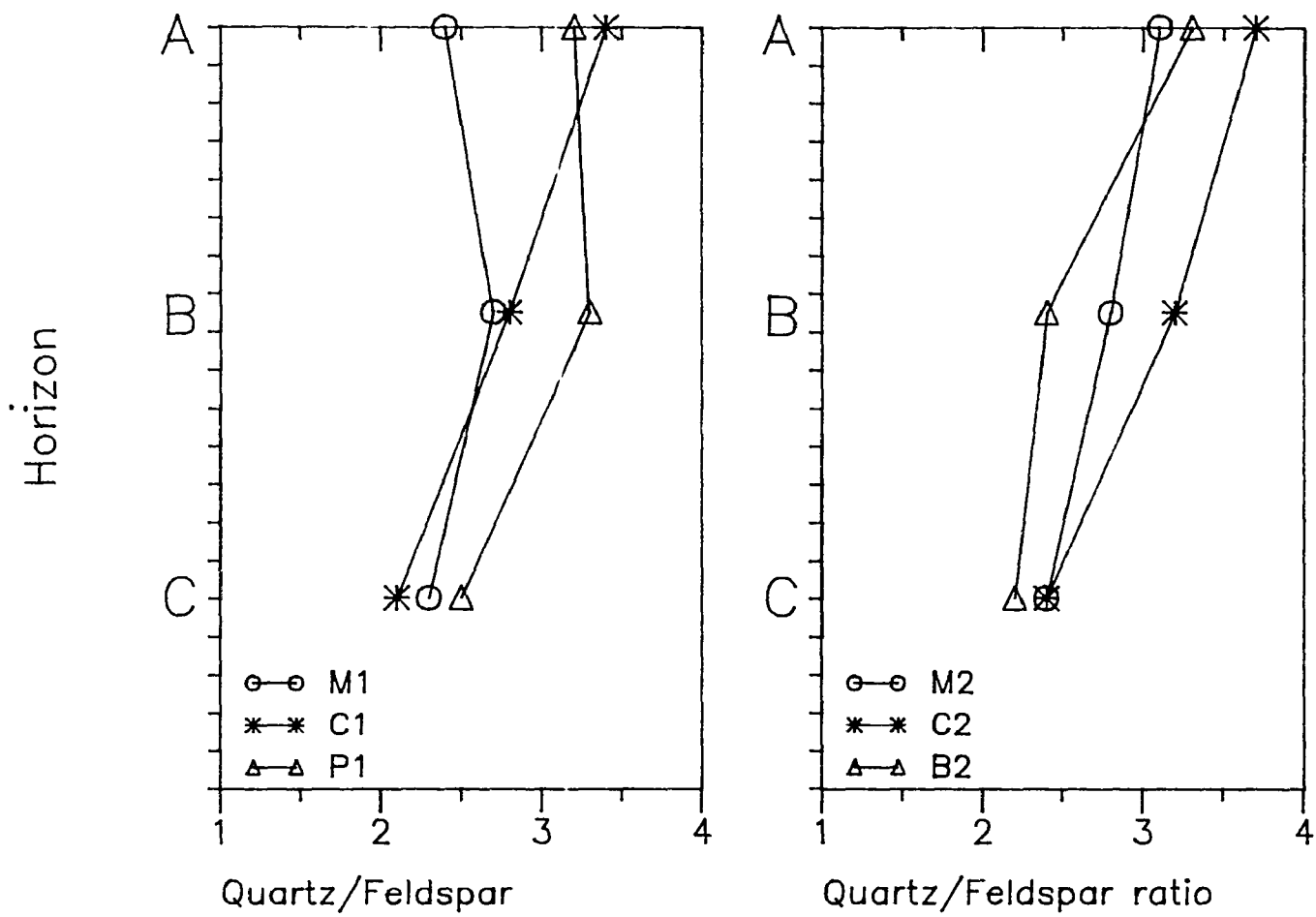


Figure 1.13. Quartz to feldspar ratios.

Quartz is the dominant mineral present in all horizons as it was in the fine sand fraction. Both silt fractions had more than 80% quartz. Chlorite and mica are present in small quantities mainly in the fine silt fraction of B and C horizons, suggesting their susceptibility to weathering in the surface. Nornberg (1980) indicated these minerals are easily weathered once they lose their protection in rock fragments and quickly reduced to finer particle sizes. Sericite was mainly observed on feldspar grains in the fine sand fraction. The low abundance of mica or sericite in the fine silt fraction indicates it is further comminuted to clay size fraction once it loses its protection on feldspar grains.

Dolomite in both silt fractions has completely weathered from the solum. It is present in equal quantities in the fine and coarse silt fractions in the parent materials except pedon P1. The absence of dolomite in this pedon could be for the same reason, depth sampling, as suggested above in the sand fraction. The presence of relatively high quantities of dolomite in C horizons indicates it is less soluble than calcite which is present in the clay fraction.

The amounts of plagioclase and K-feldspar are in relatively equal proportion in both silt fractions. Na-feldspar is the dominant feldspar in the silt fractions, indicating it is less susceptible to weathering than calcium feldspar. This also suggests, once the K and Na feldspars are comminuted their weathering intensities become similar.

The silt fraction is dominated by quartz comprising about 80%, followed by dolomite where present and followed by feldspars. Amphiboles and pyroxenes which were present in the fine sand fraction were not detected in the silt fraction. This could be due to their presence in very small quantities which might have limited their detection in the powder diffraction. The other explanation might be due to their high susceptibility to weathering, they might have dissolved chemically. It is evident from these data that the nutrient supply power of the silt fraction is very low. The productivity of the forest vegetation in these soils is maintained from the release of cations from the clay size fraction and as Miller et al. (1979) pointed out it is mostly due to "tight" cycling of available nutrients.

Table 1.7 Mineralogy of silt fractions.

PEDON	FINE-SILT						COARSE-SILT				
	CHL	MICA	PLAG	K-FELD	QZ	DOL %	PLAG	K-FELD	QZ	DOL	
MARLETTE 1											
A	-	-	L	L	H	-	L	L	H	-	
Bt	L	L	L	L+	H	-	L+	L	H	-	
C	L	L	L	L	H	H	L+	M	H	H	
CAPAC 1											
A	-	-	L	L	H	-	L+	L	H	-	
Bt	L	L	L	L	H	-	L	L	H	-	
2C	L	L	L	L	H	H	L	L	H	H	
PARKHILL 1											
A	L	L	L	L	H	-	L+	L+	H	-	
Bg	L	L	L	L	H	-	L	L	H	-	
C	L	L	L	L	H	-	L+	L	H	-	
MARLETTE 2											
A	-	-	L	L	H	-	M	L+	H	-	
Bt	L	L	L	L	H	-	L+	L	H	-	
C	L	-	L+	L+	H	H	L	L	H	M	
CAPAC 2											
A	-	-	L	L	H	-	L+	L	H	-	
Bt	-	-	L	L	H	-	L	L+	H	-	
C	L	L	M	L	H	H	L	L	H	H	
BROOKSTON 2											
A	-	-	L	L	H	-	L	L	H	-	
Btg	T	-	L	L	H	-	M	L	H	-	
C	T	-	L	L	H	H	L	L	H	H	
H-HIGH M-MEDIUM L-LOW T-TRACE											
CHL=chlorite; PLAG= plagioclase; K-FELD=f-feldspar; QZ=quartz; DOL= dolomite											

CLAY MINERALOGY

X-ray Diffraction Analysis

The clay minerals present in this study, based on XRD, are mica, kaolinite, vermiculite, smectite, chlorite, (interstratified vermiculite/chlorite) hydroxy-interlayered vermiculite (HIV), mica/smectite, vermiculite/smectite, hydroxy-interlayered smectite, quartz, and feldspar. These minerals were identified based on XRD patterns using Whittig and Allardice (1986) diffracting criteria. Mica was identified by its (001) d-spacing of about 10Å in all the treatments. Muscovite and biotite were differentiated based on the presence and intensity of the (002) peak. Presence of discrete kaolinite in all clay samples is indicated by 7.1Å (001) and 3.58Å (002) basal reflections which are not present after heating to 550°C due to dehydroxylation. Vermiculite is indicated by about 14.2Å peak that shifts to about 10Å peak upon K-saturation and heat treatments. Discrete chlorite is identified by the presence of 14.2Å peak that persists in all heat treatments. The presence of smectite is shown by about 18Å d-spacing when Mg-saturated and glycerol solvated. However, when the samples are K-saturated and heated, the 18Å peak collapses to about 10Å peak. The presence of HIV is indicated by partial collapse of 14.2Å to 10Å and the asymmetrical 10Å peak, when K-saturated and heated. The presence of a shoulder on the 14.2Å peak indicates interstratified mica/vermiculite. Quartz was identified based on 4.26Å and 3.34Å peaks that persists in all heat treatments.

Clay Mineral Distribution

The results of XRD analysis of the <2-µm clay from the six soils representing two hydrosequences are summarized in Table 1.8. Figures 1.14-1.21 contain the X-ray diffraction patterns obtained for these soils. Mica is the predominant mineral followed by kaolinite and vermiculite in the glacial till parent material of fine-loamy soils of Michigan. Similar mineralogical compositions of the C horizons suggest the uniformity of the parent material in which these soils have formed. All pedons in these two hydrosequences show the same kind of weathering trend but with variable intensities. The parent material of all pedons are rich in mica followed by abundant kaolinite and vermiculite, and small amounts of chlorite, and quartz (Table 1.8). Feldspars are present in very small quantities in all pedons indicating moderate weathering in these fine-loamy soils.

The most noticeable weathering trend observed is the decrease in amount of vermiculite with depth indicating higher weathering intensity in the A horizon than the B and C horizons. On the other hand the mica content increases with depth. This type of trend was also observed in the fine clay mineralogy by Cremeens and Mokma (1987). The clay mineral distribution in these two hydrosequences indicates mica has weathered to vermiculite with some subsequent illuviation of vermiculite into the B horizons as shown by fine clay mineralogy of clay films (Cremeens and Mokma, 1987). The intensity of weathering seems to be influenced by drainage as evidenced by peak intensities. Similar clay mineral distributions were reported by Klages et al. (1957) and Kodama (1979). The formation of vermiculite by weathering of mica and translocation of mixed mineral suites, either downward or by lateral movement are favored by a strong leaching environment, K loss from the interlayer, oxidation of iron in iron rich mica, substitution of hydroxyl for oxygen, and loss of octahedral iron and magnesium (Douglas, 1977; Newman, 1967). The loss of charge seems to be related to the oxidation of octahedral iron in iron rich micas and to protonation of structural oxygen anions to form new hydroxyls. Pedon P1, a poorly drained soil, has slight changes in vermiculite and mica contents within the profile.

Kaolinite does not show a particular trend, however in some of the pedons the solum is higher in kaolinite content than the parent material. The diffractograms do not indicate a presence of significant mixed-layer clays in all the pedons examined, although presence of minor amounts of hydroxy-interlayered vermiculite is indicated by the small shoulder in the 11 Å to 13 Å region and by the incomplete collapse of 14 Å peak that resulted in a broad peak towards a low angle upon K-saturation and heating to 300°C and 550°C. In the absence of interlayer contaminants, K-saturated vermiculite should collapse to 10 Å prior to heat treatment, but as indicated by April et al. (1986), the necessity to heat the sample to force K into the interlayer and to dehydroxylate the interlayer is characteristic of hydroxy-interlayered vermiculite. The amount of HIV is greatest in the surface horizons, where frequent wetting and drying cycles are crucial to the formation of the mineral (Rich, 1968) and also where pH and base saturation are somewhat lower than the parent material, (Figures 1.9 and 1.10), particularly in Marlette and Capac pedons.

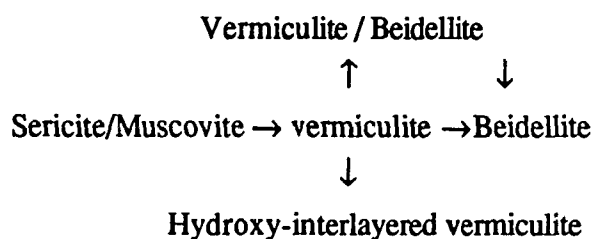
Chlorite contents are relatively higher in the C horizons than the A horizons. In well drained and moderately well drained pedons, chlorite is present in trace amounts in the surface horizon. In general the amount of chlorite decreases by half when you go from the parent material to the B horizon. The chlorite present in C horizons of these pedons may have weathered to vermiculite (Ross et al., 1982; Ross, 1975). The amount of chlorite increases with depth whereas vermiculite decreases. However, the chlorite present in the parent material is likely trioctahedral as shown by the 060 diffraction peak of 1.54 Å. The

060 diffraction peak of the B and A horizons indicate the clay minerals present are dioctahedral. The absence of trioctahedral peak of the 060 diffraction in the solum could be due to a low quantity of chlorite present in these horizons or more likely the trioctahedral chlorite has weathered to amorphous material and/or has decomposed to soluble products. In other words trioctahedral chlorite present in the parent material eventually disappears from the solum. This leads to the conclusion that the dioctahedral vermiculite present in the solum is a weathering product of muscovite/sericite or/and neoformation.

Smectite is present in the $<2 \mu\text{m}$ fraction of the Btg horizon and in the fine clay fraction of all horizons in pedon B2 (Fig. 1.20). The Green-Kelly test and the 060 spacing of the fine clay of the Btg horizon indicates the smectite phase is beidellite. Smectite however, is absent from all other pedons even in the fine clay fraction. The absence of smectite in pedon P1, the comparable drainage class in hydrosequence 1, where minimum leaching occurs, is possibly attributed to differences in parent material and higher total K content in the solum than in the pedon B2 (13-18 ppm Vs 9-11 ppm). The high water table through out most of the year (Figures 1.3, 1.4, and 1.5) inhibits the possibility of clay translocation in the C horizons deeper. The presence of smectite even in the deeper C horizon (250 cm) indicates it is inherited from the parent material. The distribution of smectite in the fine clay size fraction within the profile indicates this clay mineral is allogenic. The mineralogy of the clay films and the fine clay does not reflect monomineralic composition, therefore smectite is not likely the result of neoformation. The fine clay mineralogy as well as the mineralogy of the clay films (Cremeens and Mokma, 1986) of the Btg horizons indicated the existence of mixed mineral suites (mica, smectite, kaolinite, and vermiculite). In a soil where clay translocation, in situ weathering, and neoformation have occurred, it is difficult to attribute the presence of smectite (Btg) to a single mechanism.

Proposed Weathering Sequence

Sand, silt, and clay mineral distribution suggest the following weathering sequence:



Plagioclase $\rightarrow$ Dissolves

Chlorite $\rightarrow$ Dissolves

Chlorite → vermiculite

The evidence for this proposed sequence is primarily based on the depth distribution of various components. The trends of weathering observed in these hydrosequences of fine-loamy soils in Michigan is in agreement with the literature. The most important changes that occur in mica during the transformation process are (1) a reduction in layer charge and (2) a replacement of interlayer K with hydrated cations (Fanning et al., 1989; Robert, 1973). Fanning et al. (1989) reviewed the literature concerning possible mechanisms for the layer charge reduction and concluded that the most probable mechanisms were (1) the oxidation of structural Fe^{2+} to Fe^{3+} following the opening of the mica interlayer, (2) proton incorporation into the structure, and (3) Si replacement of Al and Fe in the tetrahedral sheets.

Vermiculite derived from mica is fast forming and unstable (Kittrick, 1973). Vermiculite is often abundant in soils because the rate at which interlayer K is removed from mica to form vermiculite is often more rapid than the rate at which the 2:1 layer is broken down (Kittrick, 1973; Fanning et al., 1989). Robert (1973) determined that some dioctahedral micas were transformed first to dioctahedral vermiculite and then to dioctahedral smectite whereas other dioctahedral micas were transformed only to either dioctahedral smectite or vermiculite. Stoch and Sikora (1976) observed that mica weathering consisted of gradual structural transformations with removal from the structure of Mg, Fe, and K. They thought that mica weathered according to the sequence of muscovite → regularly interstratified mica/montmorillonite → montmorillonite → kaolinite. The source of mica in this study is sericite which is a retrograde metamorphic product of feldspar and lithogenic muscovite. Sand mineralogy does not indicate the presence of muscovite or biotite, however the clay fraction indicates abundant dioctahedral mica in the glacial till parent material. In the present study no attempt was made to characterize or differentiate muscovite and sericite in the clay fraction. According to Eberl et al. (1987) and Meunier et al. (1982), particle thickness of sericite influences the mineral's properties. Petrographic microscope examination reveals sericite, whereas the TEM (Transmission electron microscope) shows individual mica particles and XRD gives patterns for mixed-layer illite/smectite or muscovite. In this study the dioctahedral mica in the clay fraction is assumed to be muscovite. Elemental analysis of the fine clay fraction indicates the weathering product, smectite, is iron rich.

Table 1.8 Clay mineralogy of total clay.

HORIZON	SMECTITE	CHLORITE	VERMICULITE	MICA	KAOLINITE	QUARTZ
	<u>%</u>					
MARLETTE 1						
A	-	T	XXX\	XXX	XXX	\
Bt	-	\	XX\	XXXX	XX\	\
C	-	X	X	XXXX	XXX	X
CAPAC 1						
A	-	\	XXXX	XX\	XX\	\
Bt	-	\	XX\	XXX\	XXX	\
2C	-	X	XX	XXXX	XX\	\
PARKHILL 1						
A	-	\	XXX	XXX	XXX	\
Bg	-	\	XX\	XXXX	XX\	\
C	-	\	XX\	XXXX	XX\	\
MARLETTE 2						
A	-	T	XXXX	XX\	XX\	X
Bt	-	X	XX	XXX\	XX\	X
C	-	X	XX	XXXX	XX	X
CAPAC 2						
A	-	\	XXX\	XX\	XX\	X
Bt	-	\	XX\	XXXX	XX\	\
C	-	X	XX	XXXX	XX	X
BROOKSTON 2						
A	-	\	XX\	XXX	XX\	X\
Btg	XXX	\	X\	XX\	XX	\
C	-	X	XX	XXXX	XX	X

\= APPROXIMATELY 5%
 X= APPROXIMATELY 10%
 -= ABSENT
 T= TRACE

SUMMARY AND CONCLUSIONS

The sand, silt, and clay mineralogy of the two fine-loamy hydrosequences of south-central Michigan suggest the glacial till parent material is relatively uniform. Depth and duration of water tables were similar for soils with the same natural drainage class. Having similar parent material, vegetation, climate, and time, topography has produced no significant differences in distribution of sand and silt size minerals within and among profiles.

Weathering of muscovite/sericite to smectite (beidellite) through interstratified vermiculite-smectite seems to be the dominant trend in the poorly drained Brookston pedon whereas direct transformation to vermiculite is the prevalent weathering mechanism in the other drainage classes. Except for the smectite in the Brookston pedon, the fine-loamy soils in this study do not show significant differences in sand, silt, and clay mineralogies with respect to natural drainage.

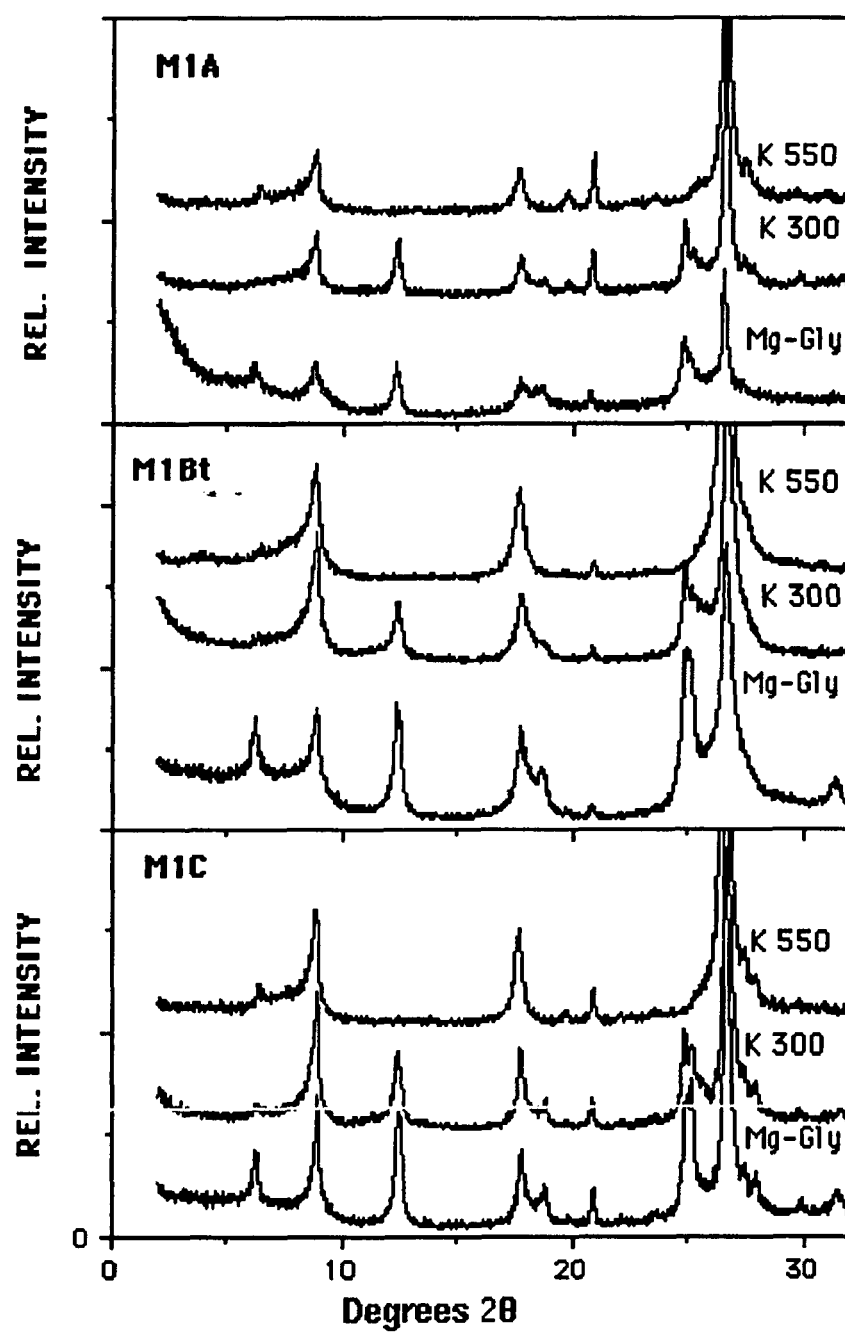


Fig. 1.14 X-ray diffractograms of clay fraction (<2μm) of pedon M1.

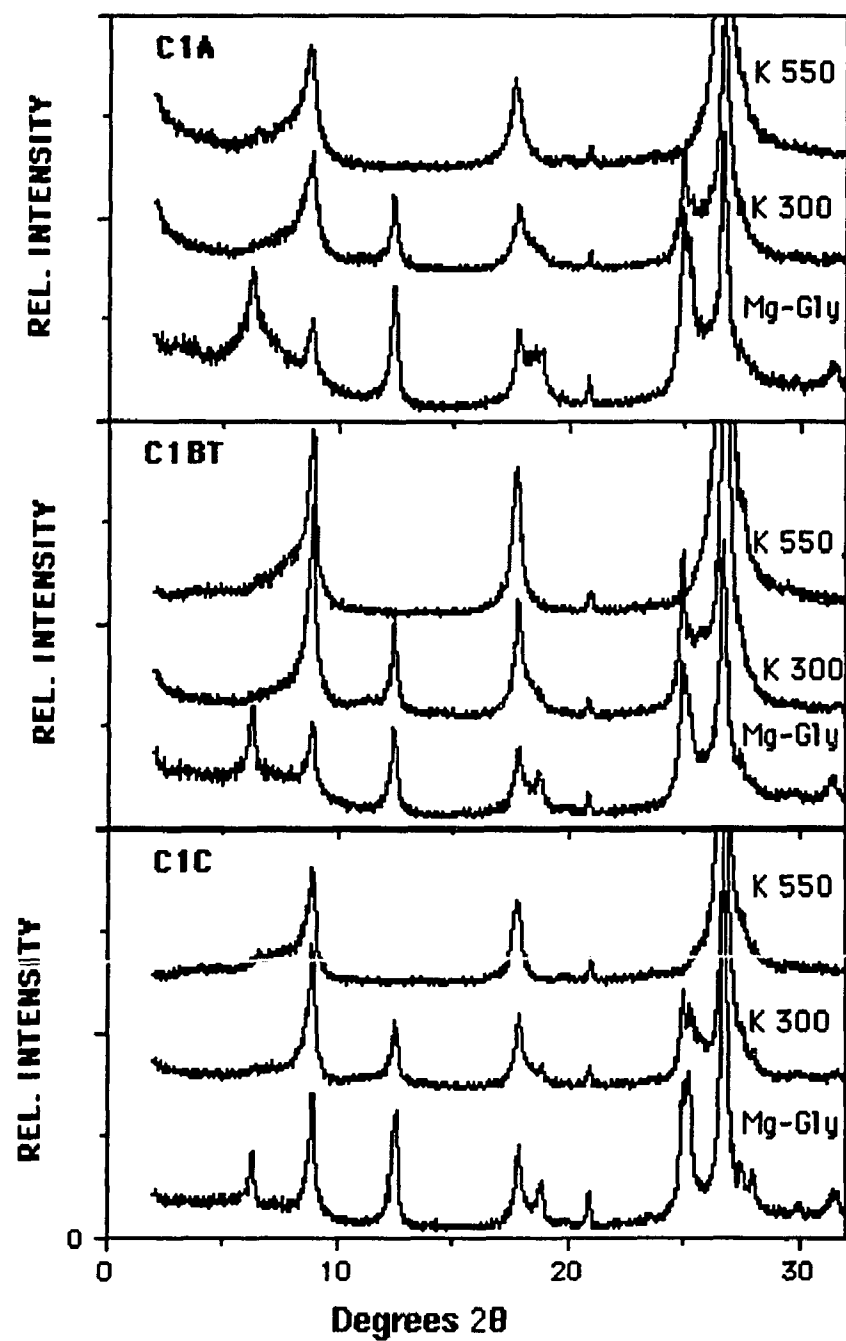


Fig. 1.15 X-ray diffractograms of clay fraction (<2μm) of pedon C1.

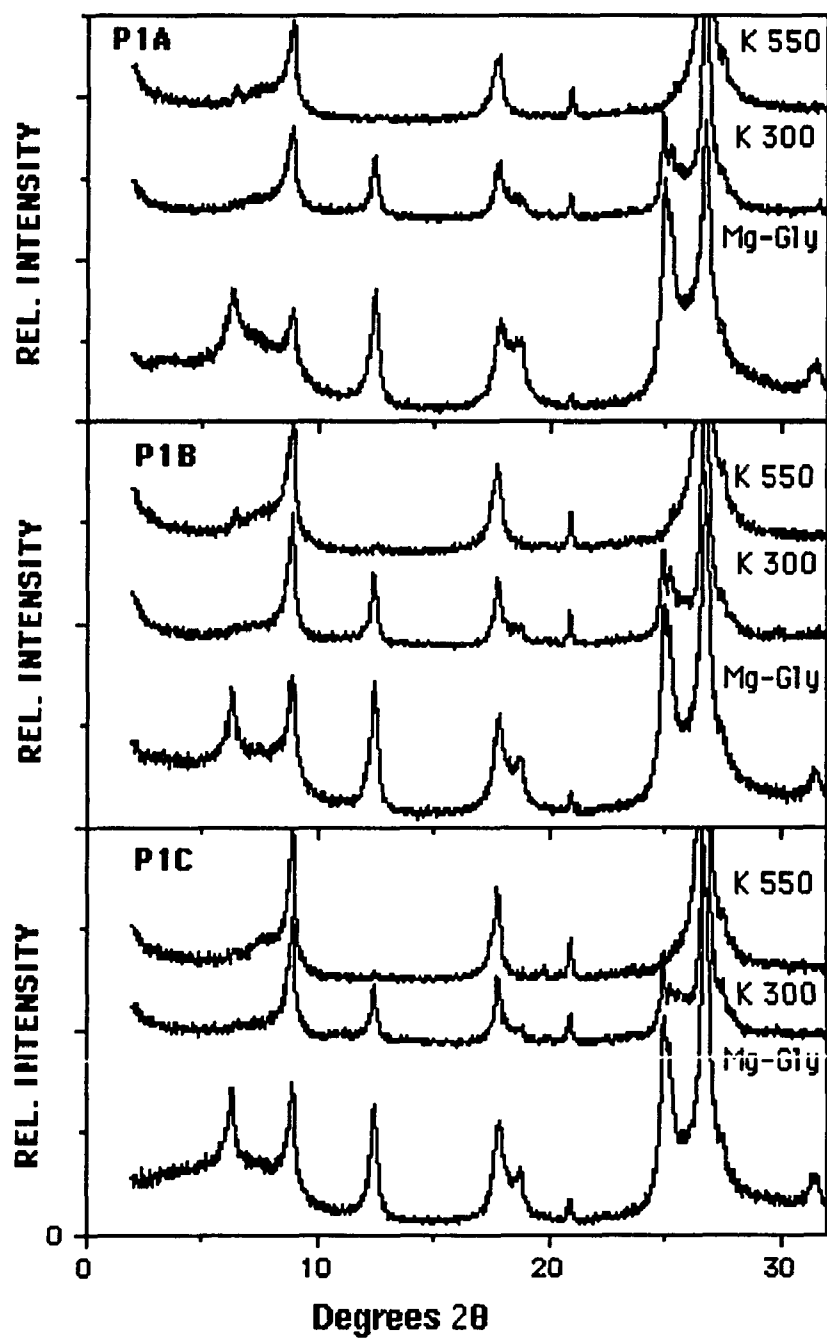


Fig. 1.16 X-ray diffractograms of clay fraction (<2μm) of pedon P1.

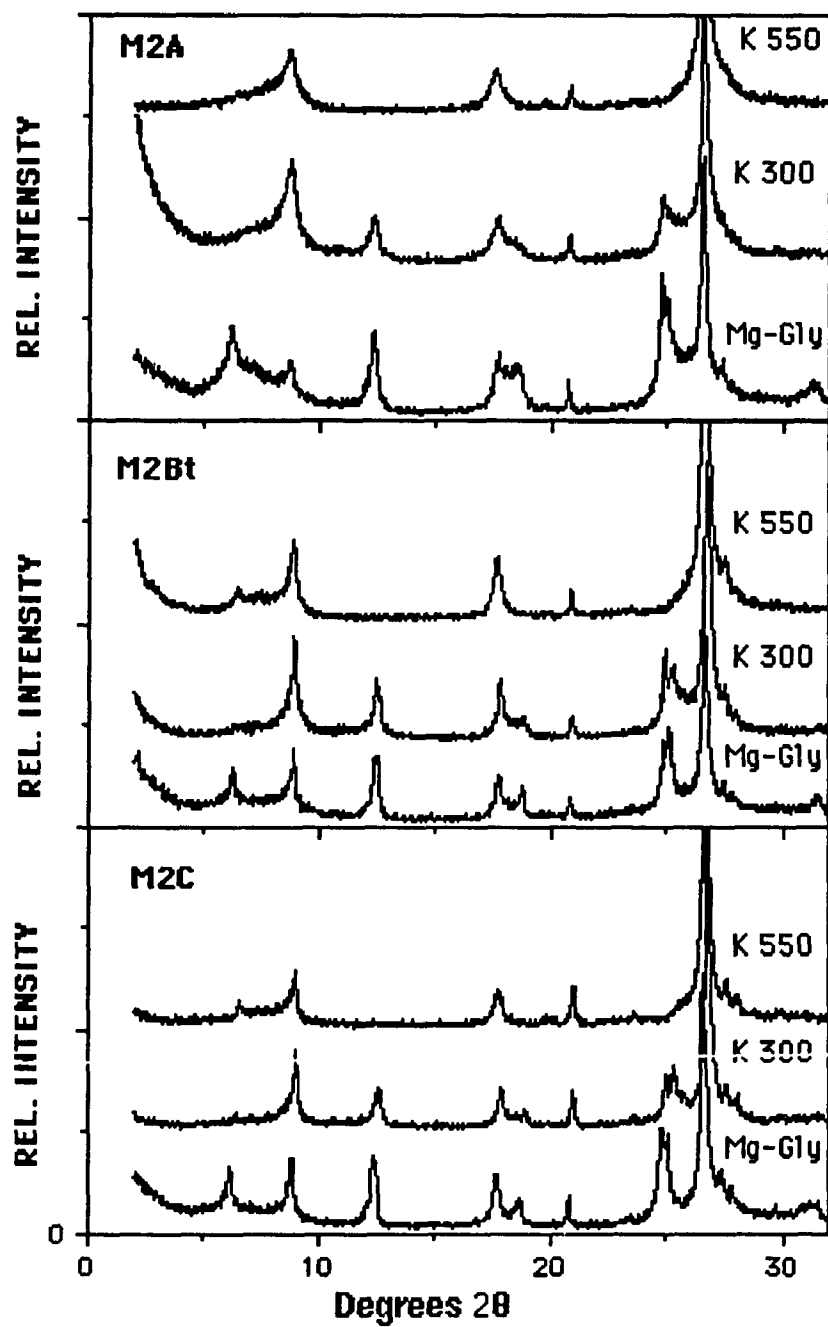


Fig. 1.17 X-ray diffractograms of clay fraction (<2μm) of pedon M2.

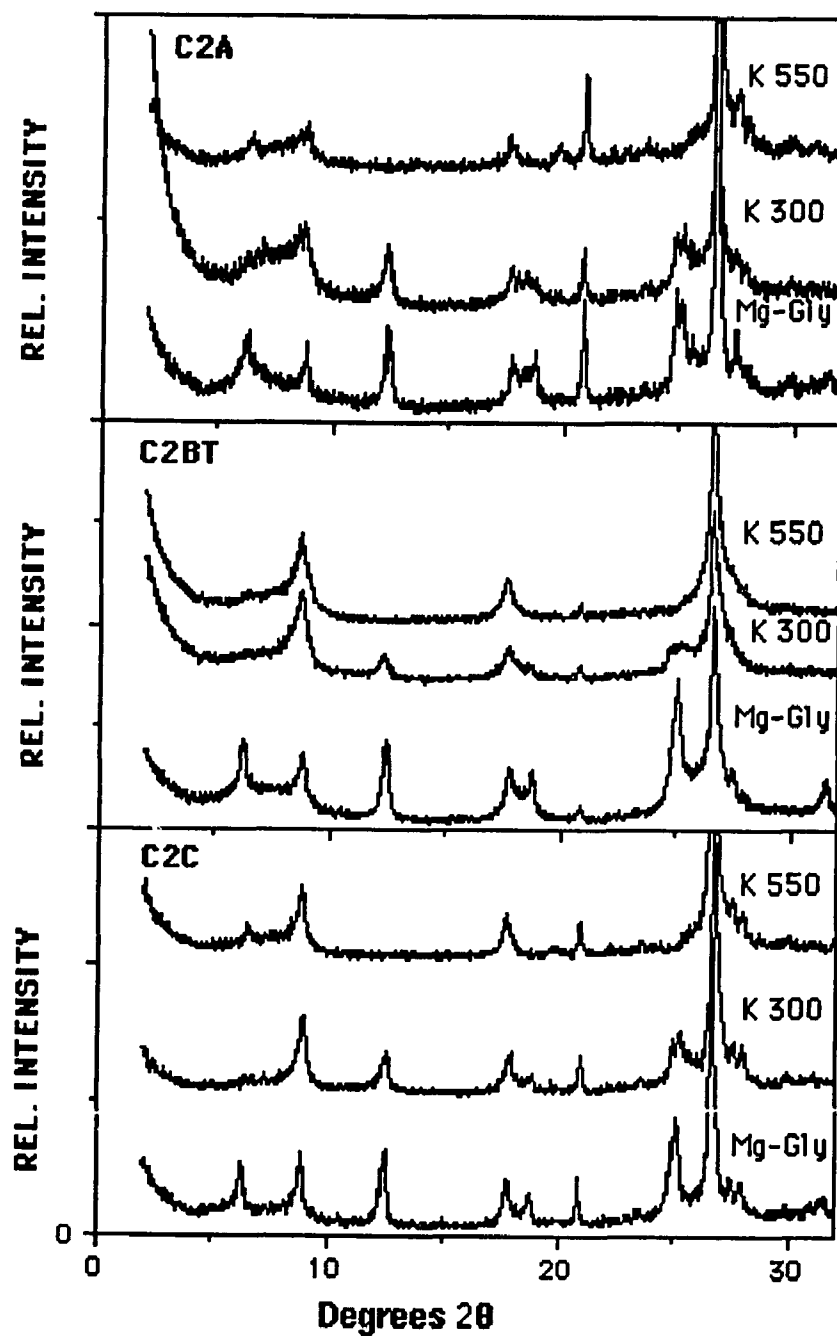


Fig. 1.18 X-ray diffractograms of clay fraction (<2μm) of pedon C2.

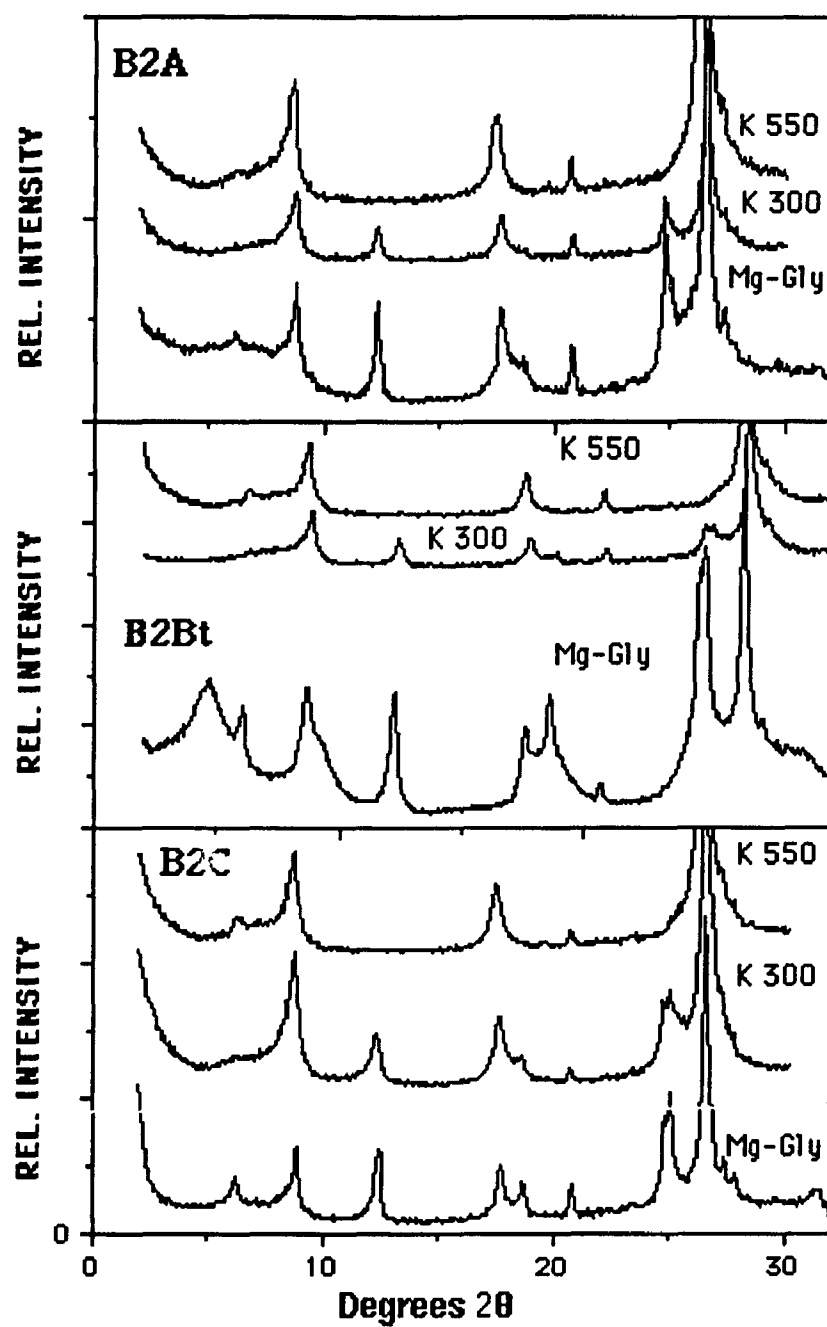


Fig. 1.19 X-ray diffractograms of clay fraction (<2μm) of pedon B2.

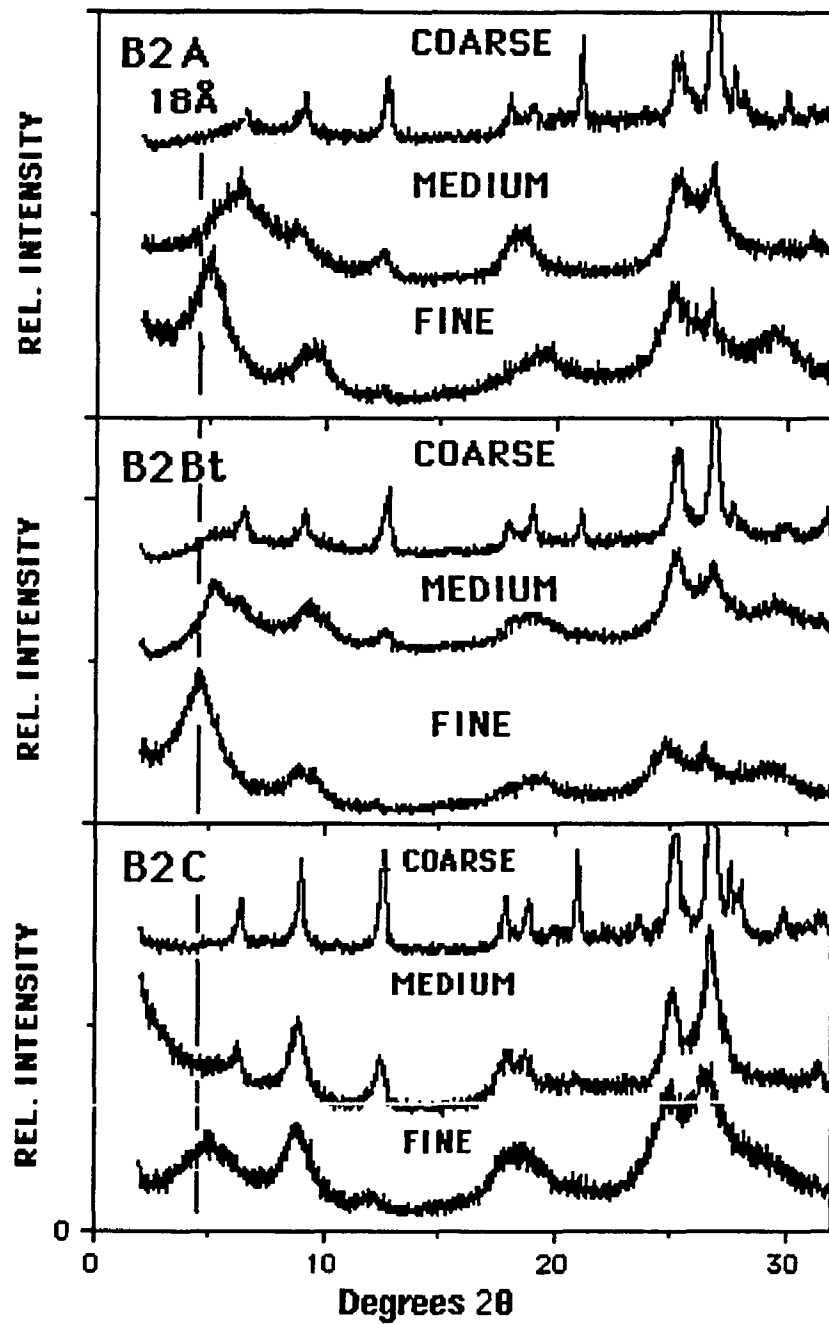


Fig. 1.20 X-ray diffractograms of pedon B2 fine, medium, and coarse clay fractions after Mg saturation and glycerol solvation.

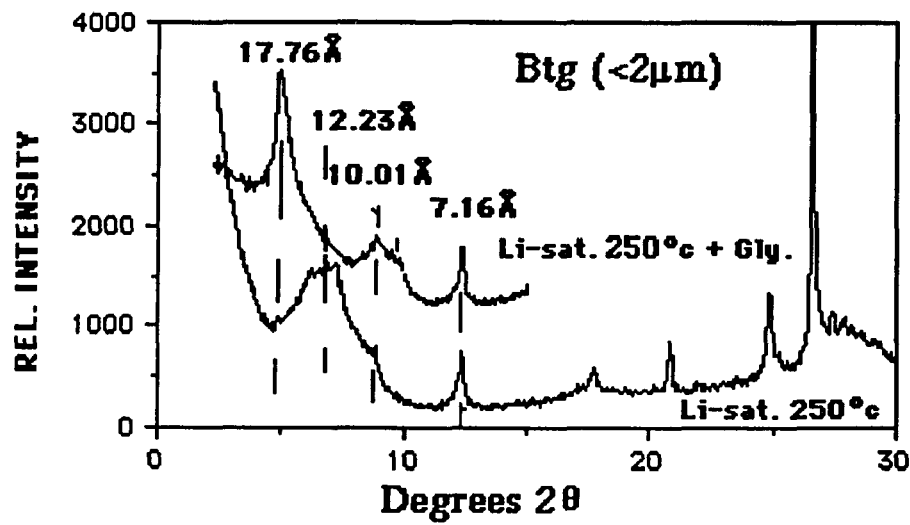


Fig. 1.21. X-ray diffractograms of the Bt horizon (<2-μm) clay fraction which has been Li-saturated and glycerated.

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CHAPTER 2

MINERALOGY OF TWO SANDY HYDROSEQUENCES IN MICHIGAN

ABSTRACT 2

The aim of this study is to examine the mineralogy of sand, silt, and clay size minerals in two sandy hydrosequences of Michigan. Apparent depth of water table was monitored using piezometers. The dominant sand fraction was considered for identification of minerals using petrographic microscope. X-ray diffraction was used to examine the silt and clay mineralogy.

The sand mineralogy is dominated by quartz followed by small amounts of feldspars and sericite. The silt fraction is dominantly composed of quartz and small amounts of feldspars. Differences in drainage do not indicate a particular distribution of sand and silt minerals. Chlorite, mica, kaolinite, vermiculite and quartz are the major minerals in the parent material of the clay fraction. The intensity of smectite peak and the presence and absence of vermiculite in the E horizons, indicates increasing weathering intensities from poorly drained to well drained soils in the these hydrosequences. The mineral distribution in these hydrosequences suggests the following weathering sequences: dioctahedral mica/sericite → vermiculite → smectite with or without mixed-layer formation.

INTRODUCTION

In earlier work by Franzmeier et al.(1963) and Ross and Mortland (1966) in Michigan Spodosols, smectite was found to be the dominant clay mineral present in the eluvial horizon (E). Those studies were conducted to see soil development in a chronosequence of Spodosols and to characterize smectite in the E horizon of well drained Spodosols in northern Michigan respectively. Other studies have also reported the presence of 18Å clay mineral in the acidic E horizon of Spodosols (Brown and Jackson, 1958; Gjems, 1960; McKeague, 1965; Coen and Arnold, 1972; and Douglas, 1982).

One of the major hinderances in Michigan as in other glaciated areas in the study of weathering sequences is the lack of precise knowledge of the original nature of the parent material (Rutherford and Debenham, 1981). The formation of smectite in this acidic environment was attributed by most researchers as the weathering product of mica and vermiculite-chlorite and by others as being added as dust (Coen and Arnold, 1972) or weathering product from minerals added as dust.

The aim of this study is to examine the mineralogy of sand, silt, and clay size minerals in two sandy hydrosequences of Michigan.

MATERIALS AND METHODS

FIELD METHODOLOGY

Two replicated hydrosequences in sandy outwash material were selected for this study. The sandy hydrosequences are located in Chippewa and Cheboygan Counties in Michigan (Figure 1.1). The soils in each hydrosequence occurred in adjacent mapping units (delineations), so as to keep the other soil forming factors relatively constant. These hydrosequences occur as true sequences as defined by Jenny (1941, 1980). The hydrosequences were located on forested lands where disturbances due to cultivation, artificial drainage and extensive erosion are absent or minimal.

Each drainage sequences consisted of three soils in the landscape with increasing heights above the local water table. According to drainage classes, these soils were classified as moderately well drained, somewhat poorly drained, and poorly drained soils and occupy, back slope, foot slope, and toe slope positions on the landscape, respectively. These hydrosequences occur as natural products of young glacial landscapes with immature drainage networks that develop on them.

The sandy hydrosequences have sandy glacial drift parent materials and are both located on glacial outwash plains. The soil series in the hydrosequences are shown in Table 2.1 and their classification and location in Table 2.2.

Piezometers were installed in the C horizon near each of the sampled pedons to monitor the apparent depth of water table. Water table levels were monitored bi-monthly for the period 1 October 1985 through 31 December 1987. Piezometer data were converted to profiles of depth versus duration of saturation.

Soil sampling pits were dug and soils described following standard conventions (Soil Survey Staff, 1951). Pedon descriptions are presented in Appendix 1. Approximately 10-20 kg of bulk samples were collected from each mineral horizon of each pedon along the faces described, for chemical and mineralogical analysis.

TABLE 2.1: Soils of the two sandy hydrosequences

SEQUENCE	MODERATELY WELL DRAINED	SOMEWHAT POORLY DRAINED	POORLY DRAINED
CHIPPEWA HYDROSEQUENCE	LIMINGA	WAINOLA	KINROSS 1
CHEBOYGAN HYDROSEQUENCE	RUBICON	AUGRES	KINROSS 2

TABLE 2.2: CLASSIFICATION OF SOILS IN THE TWO HYDROSEQUENCES

SOIL SERIES	CLASSIFICATION
HYDROSEQUENCE 1	
LIMINGA	SANDY, MIXED, FRIGID, TYPIC HAPLORTHOD
WAINOLA	SANDY, MIXED, FRIGID, TYPIC HAPLAQUOD
KINROSS 1	SANDY, MIXED, FRIGID, AERIC HAPLAQUOD
HYDROSEQUENCE 2	
RUBICON	SANDY, MIXED, FRIGID, ENTIC HAPLORTHOD
AUGRES	SANDY, MIXED, FRIGID, ENTIC HAPLAQUOD
KINROSS 2	SANDY, MIXED, FRIGID, ENTIC HAPLAQUOD

LABORATORY ANALYSIS

Soil samples were air dried, crushed and sieved using a 2 mm sieve to remove coarse fragments. These samples were stored and used for the following analysis. The following procedures were performed using methods of the Soil Survey Staff (1972, 1984): particle size distribution by pipette; pH in H₂O and 1N KCl; Fe, and Al extraction with pyrophosphate, oxalate and citrate-dithionite. Total C was determined by wet oxidation using the method of Snyder and Trofymow (1984).

SAND MINERALOGY

The dominant sand fraction was considered for identification of minerals. The dominant sand fraction was impregnated with a 3M Scotchcast and #3 Resin in a test tube. Thin blocks were cut, lightly polished to make one side flat and mounted on glass slides. The mounted slides were thin sectioned to approximately 30 μ thickness (Carver, 1970).

Quantitative determination of feldspar was made by etching the slides with hydrofluoric acid and staining with sodium cobaltinitrite, barium chloride and rhodizonate reagent as described by Bailey and Stevens (1960). Percentages of the various minerals

present were determined by point counting of approximately 900 grains using a standard petrographic microscope (Galehouse, 1971).

SILT AND CLAY MINERALOGY

XRD analysis were conducted using Philips APD 3720 automated X-ray diffractometer system. A theta compensating slit and diffracted beam monochromator with graphite crystal were used to maintain a constant area of irradiation and for monochromatization of the X-ray beam, respectively. All samples were scanned at a rate of 0.02°/second. Diffractograms were obtained over a total scan range of 2° 2 θ to 40° 2 θ for the Mg saturated clays, coarse and fine silt at room temperature and from 2° 2 θ to 30° 2 θ for all other cation and heat treatments.

X-ray diffraction was used to examine the silt and clay mineralogy (Jackson, 1979). Random powder X-ray diffraction of the coarse and fine silt was obtained by placing them in a sample holder. Total clays and fine clays were separated by the sedimentation and centrifugation, respectively. After removal of the cementing agents (organic carbon, and iron oxide) X-ray diffractograms of the clay fractions were obtained from basally oriented specimens (Drever, 1973) which had been: (a) Mg-saturated and glycerol solvated, (b) K-saturated and heated to 300°C or (c) K-saturated and heated to 550°C. The 060 spacing of the clays was measured using a random powder diffraction. Integrated peak intensities were used to semi quantitatively estimate the clay minerals present. Minerals were identified for XRD patterns using diffracting criteria outlined by Whittig and Allardice (1986).

RESULTS AND DISCUSSION

VARIATION IN THE DEPTHS TO THE WATER TABLE

Average monthly depths to water tables and average monthly precipitation in the two hydrosequences are presented in Figures 2.2 and 2.3. In the moderately and well drained pedons of both hydrosequences, the high water table was observed at a depth of 130cm during the month of April. During the rest of the year the water table was at or below 150cm. The high water table during April is associated with snow melting rather than one of high precipitation. In the somewhat poorly drained and poorly drained pedons the water table drops and reaches the lowest between June and September. It is during these months precipitation, evaporation and plant uptake of water are the highest.

The Kinross and Au Gres pedons in Cheboygan County show a higher water table during fall, winter and spring than the Kinross and Wainola pedons in Chippewa County. The Cheboygan hydrosequence seems wetter than the Chippewa hydrosequence as observed by the depth to water table and the amount of precipitation during these periods. The eluvial and the spodic horizon of the Kinross pedon and the spodic horizon of AuGres pedon in Cheboygan County were under high water table for at least six months (between December and May) of the year. On average the eluvial horizon of Kinross pedon in Chippewa County was above the high water table for most of the year whereas the lowest part of the spodic horizon was under water for four months (April, May, October and November). The water table was below the spodic horizon of Wainola pedon throughout the study period. As shown by Figures 2.4 and 2.5, the somewhat poorly drained and poorly drained pedons of Cheboygan County, the eluvial and the spodic horizons had a longer duration of saturation (40% time saturated) than the corresponding pedons in Chippewa County (<20% time saturated). Much of the variation in the depths to the water table can be accounted for by the amount and frequency of precipitation and evapotranspiration.

Due to higher specific position in the landscape and more percolation of water in well drained and moderately well drained soils, thicker eluvial horizons were thought to develop in sandy materials (Lag, 1970). The thickness of the eluvial and the spodic horizons of the somewhat poorly drained pedons in both hydrosequences are deeper than the other pedons in the hydrosequences. It seems there is no direct relationship between thickness of eluvial and spodic horizons to drainage classes. Deepening of these horizons seems to be controlled by some other soil forming processes other than drainage alone. If drainage affects the rate of weathering, the Chippewa pedons should indicate a relatively higher intensity of weathering than the Cheboygan pedons (AuGres and Kinross) that has been under water for a longer period of time.

Drainage is one of the most important factors in the formation of different type of soils in a landscape Jackson and Sherman (1953), Barshad (1959), Rich (1968), and Huang and Lee (1969) have discussed the relation of chemical weathering of minerals with drainage. Because drainage influences the moisture regime, seepage and redox potential, it is believed that the weathering of minerals and interlayer Al compounds would also be affected (Huang and Lee, 1969).

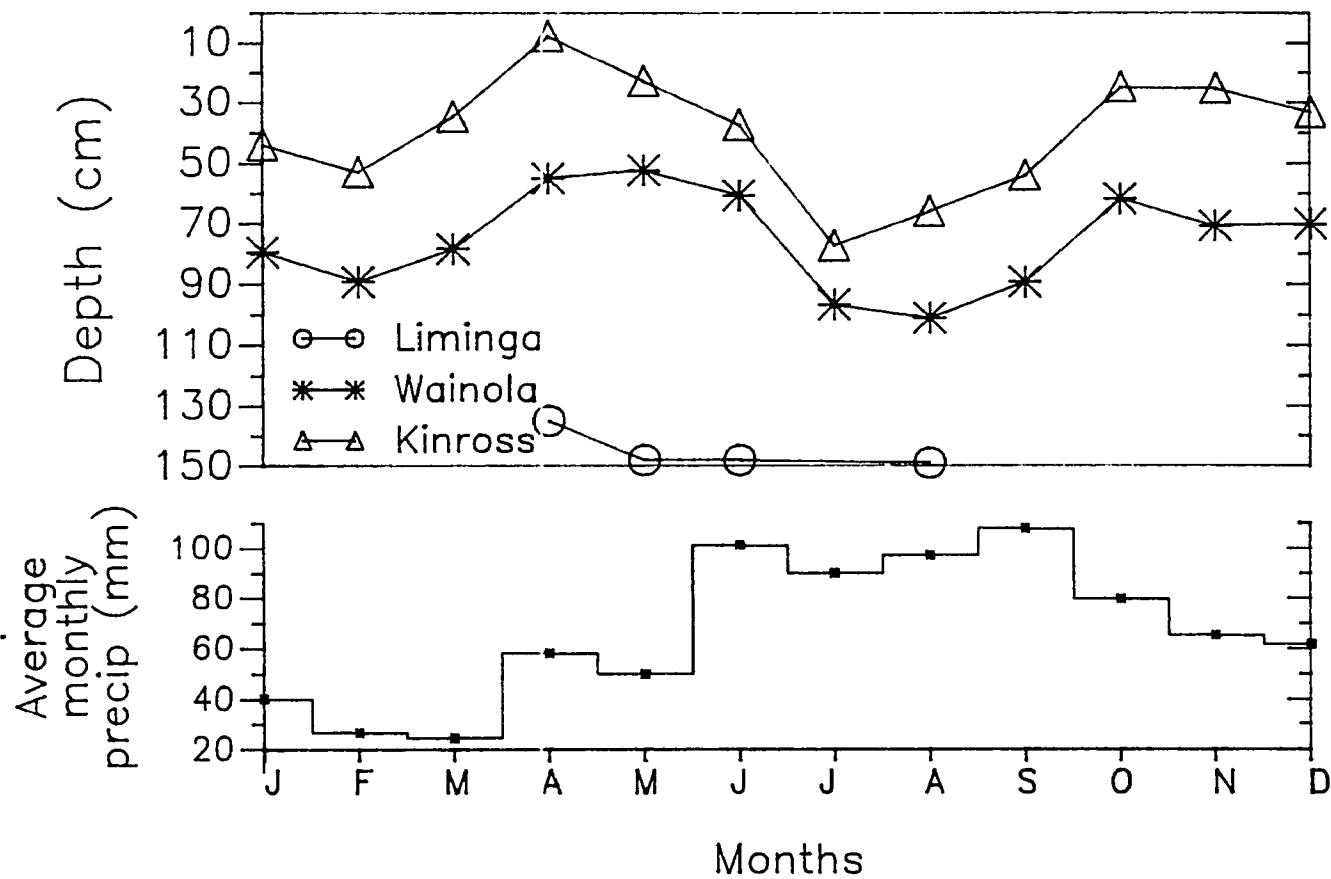


Figure 2.1. Average monthly depths to water tables and average monthly precipitation in hydrosequence 1, 1 Jan. 1985 – 31 Dec. 1987, Chippewa County.

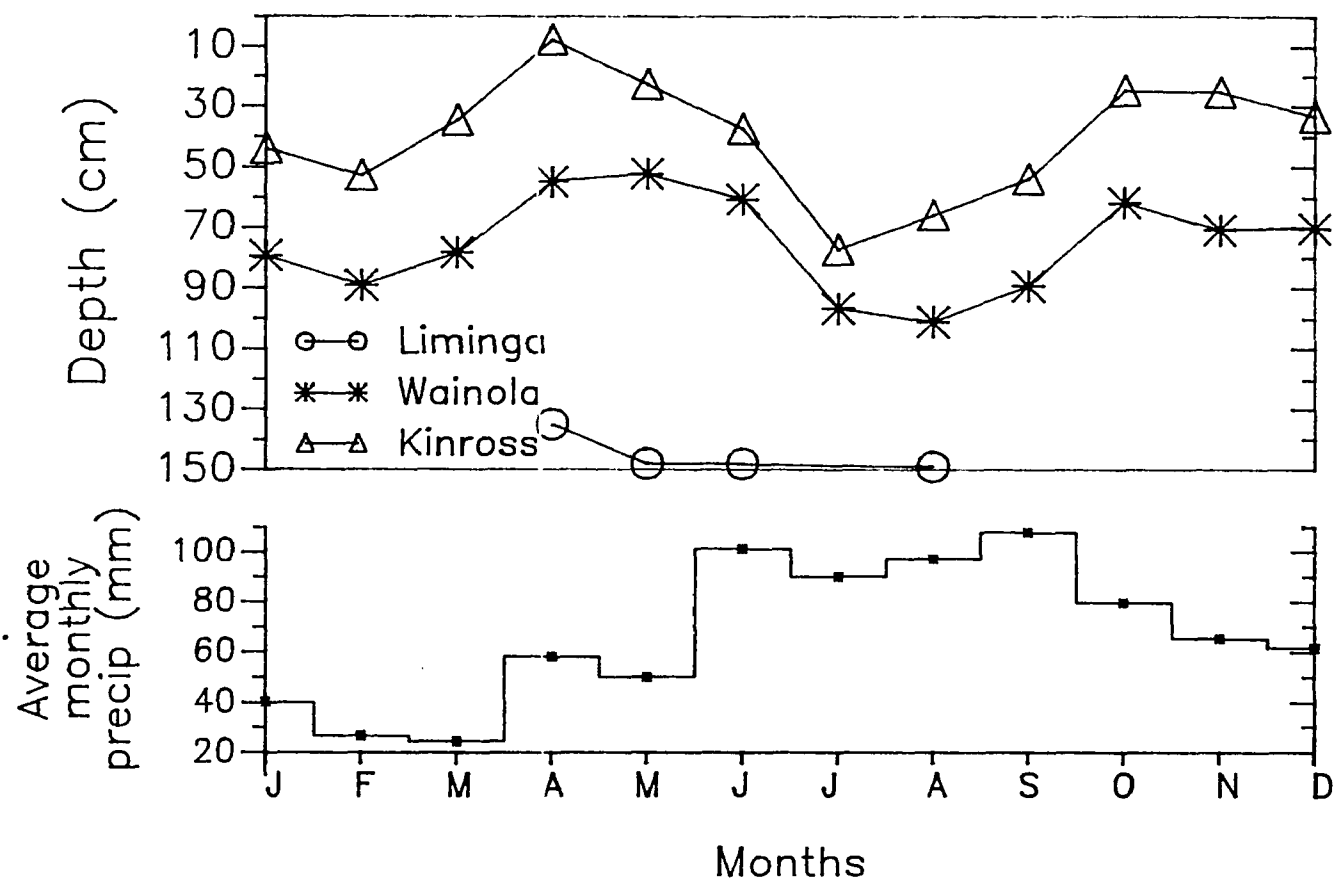


Figure 2.1. Average monthly depths to water tables and average monthly precipitation in hydrosequence 1, 1 Jan. 1985 – 31 Dec. 1987, Chippewa County.

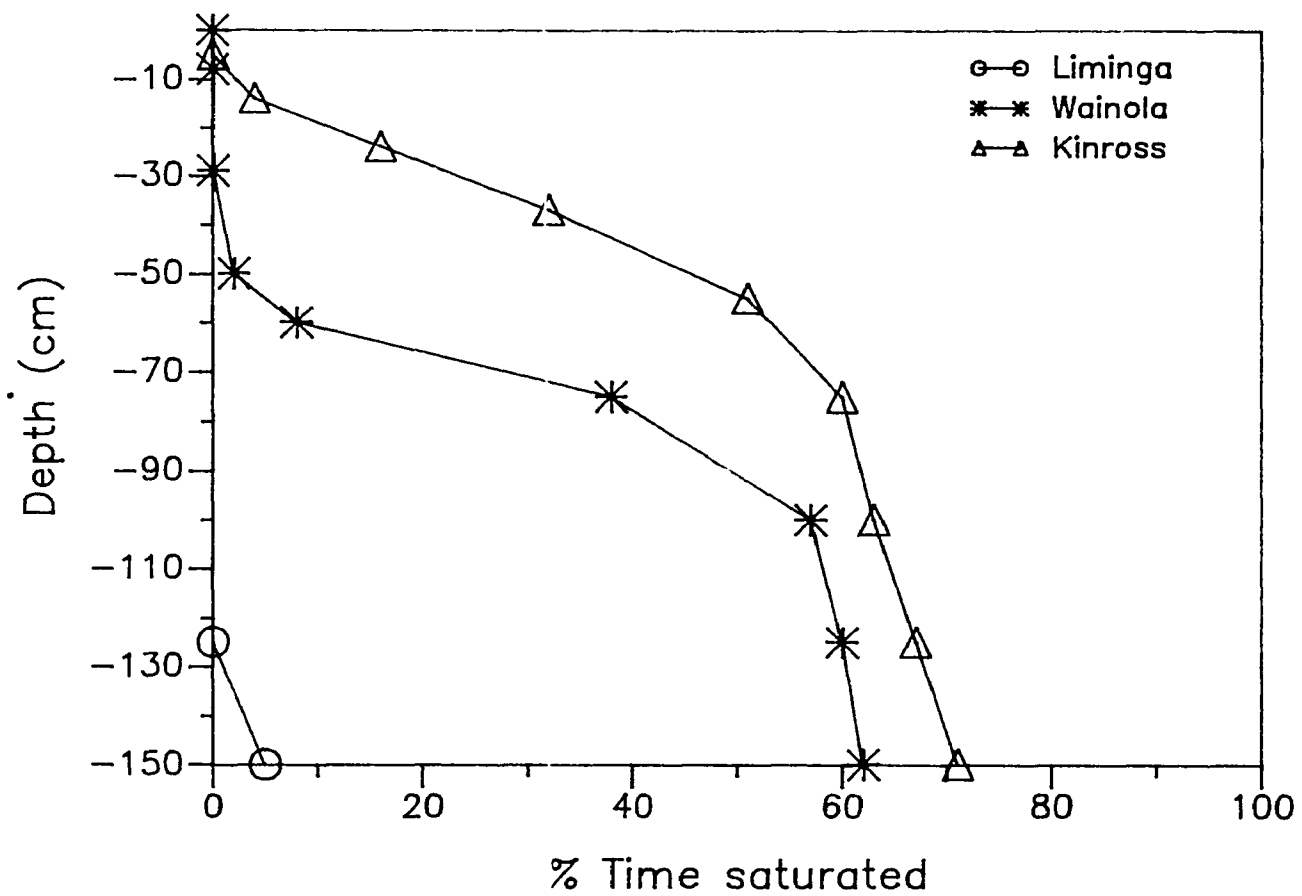


Figure 2.3. Percent total time saturated at given depth in hydrosequence 1, 1 Jan. 1985 – 31 Dec 1987, Chippewa County.

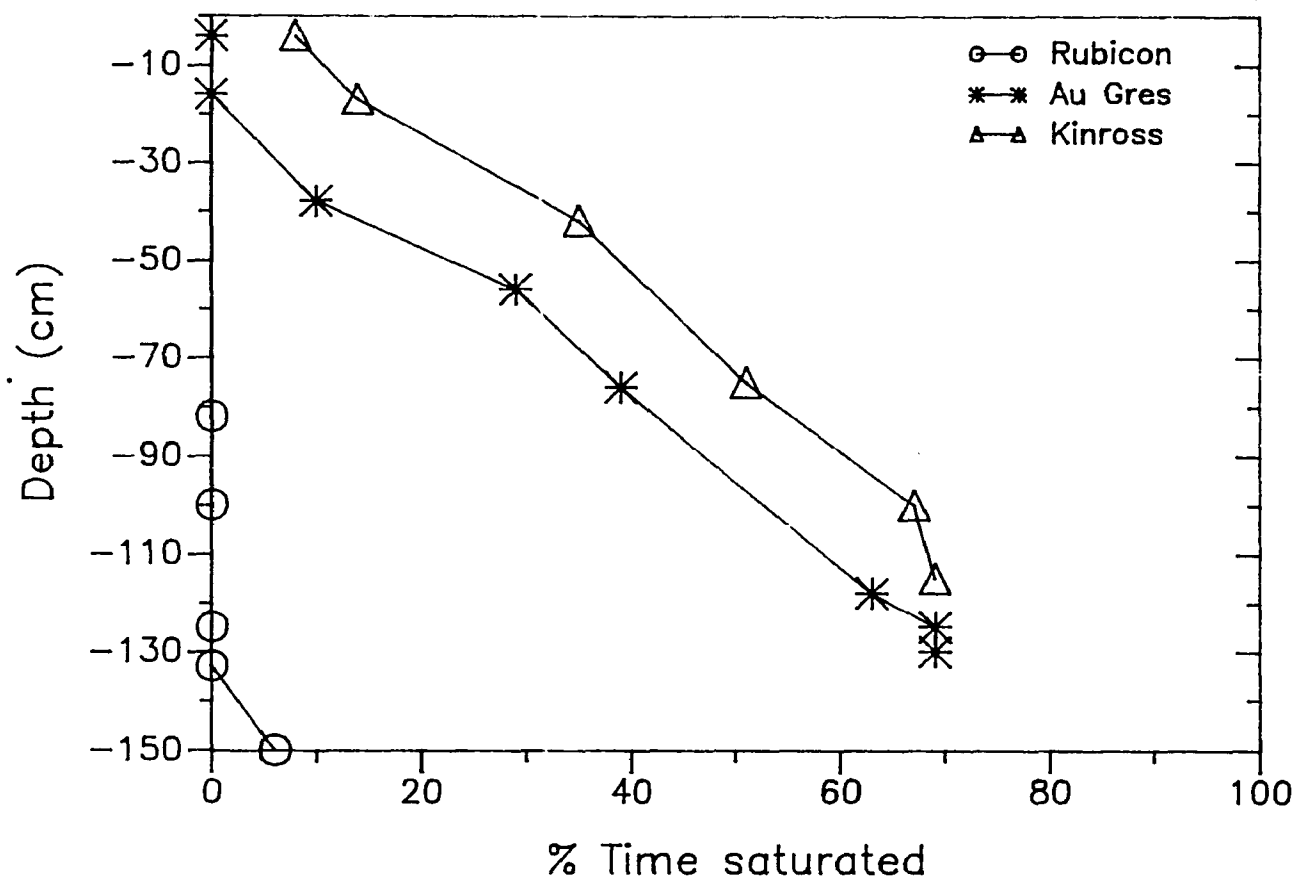


Figure 2.4. Percent total time saturated at given depth in hydrosequence 1, 1 Jan. 1985 – 31 Dec 1987, Cheboygan County.

PARTICLE SIZE DISTRIBUTION

The total sand percentages of these soils range from 81-98%, and these values generally attain their maxima in the C or lower B horizons (Tables 2.3 and 2.4). The Cheboygan hydrosequence has a relatively higher sand percentage (91-98%) than the Chippewa (81-98%). In most instances the eluvial horizons tend to have lower sand contents than the horizons below, suggesting some minerals in the sand fractions might have comminuted to the silt and clay fractions. The dominant sand fractions in Cheboygan and Chippewa hydrosequences are medium (39-55%) and fine (29-80%) sand fractions respectively.

The total silt percentages are usually highest in the eluvial and upper B horizons and tend to decrease in lower part of the profiles. Much of the silt may have weathered from the sand fraction, since its distribution in the profile follows the pattern of increasing intensity of weathering (increasing with proximity to soil surface). The presence of altered grains in the sand fraction of the solum also suggests it is a source of silt and clay in these horizons since they could easily be comminuted to a smaller size fractions. In all the horizons the clay content is less than 5%. The total percentages of very fine sand plus silt is higher in the Chippewa than in the Cheboygan hydrosequence. The kinross 1 pedon in Chippewa has the highest percentages of very fine sand plus silt. Very fine sand plus silt have big influence on moisture holding capacity.

TOTAL CARBON AND EXTRACTABLE IRON, AND ALUMINIUM

All pedons show a subsurface maximum of C, Fe, and Al. The Fe, Al and C maxima always occur in the spodic horizon (Tables 2.5 and 2.6).

TABLE 2.3. Particle size analysis of soils in Chippewa hydrosequence.

PARTICLE SIZE ANALYSIS (%)

		TOTAL			SAND					SILT	
Horizon		SAND	SILT	CLAY	VCS	CS	MS	FS	VFS	CSi	FSi
LIMINGA											
A	0-7	92	6	2	0	2	12	67	10	2	4
E	7-11	92	5	3	0	1	14	66	11	1	4
Bhs	11-22	94	3	3	0	1	13	69	11	3	0
Bs	22-63	94	4	2	0	0	10	75	10	4	0
C	63-192	98	2	0	0	0	12	75	12	2	0
WAINOLA											
Oi	7-0										
E	0-15	88	12	1	3	15	14	46	10	9	3
Bhs	15-43	94	6	0	2	7	7	67	11	5	1
BC	43-77	95	5	0	0	0	1	80	15	4	0
C	77-118	85	15	0	0	5	17	29	33	7	9
KINROSS 1											
Oa	10-0										
E	0-8	85	15	0	0	4	11	45	25	11	4
Bhs	8-19	86	14	0	1	4	13	48	20	12	6
Bg	19-34	81	19	0	1	3	13	49	16	10	10
C	34-56	91	7	2	1	3	11	44	31	7	0

Table 2.4. Particle size analysis of soils in Cheboygan hydrosequence.

PARTICLE SIZE ANALYSIS (%)										
Horizon	TOTAL				SAND				SILT	
	SAND	SILT	CLAY	VCS	CS	MS	FS	VFS	CSi	FSi
RUBICON										
A 0-10										
E 10-34	96	5	0	1	14	44	35	2	2	3
Bs1 34-50	95	2	3	1	18	46	29	1	0	2
Bs2 50-113	98	1	1	1	16	43	35	3	0	1
C1 113-153	97	2	1	0	16	55	26	0	1	1
C2 153-172	98	2	0	1	8	40	46	3	1	1
AU GRES										
Oi 8-0										
E 0-31	94	5	1	3	16	42	31	2	2	3
Bs1 31-45	91	8	1	1	15	40	32	2	8	0
Bs2 45-66	95	2	3	2	11	42	36	3	1	1
BC 66-85	94	4	2	3	11	39	38	3	3	1
C 85-150	98	2	1	0	2	42	51	3	2	0
KINROSS 2										
Oa 8-0										
E 0-18	96	4	0	1	14	47	31	2	3	2
Bs 18-50	95	1	4	1	10	44	36	4	1	0
C 50-125	96	4	0	0	3	36	51	7	4	0

Table 2.5. Selected chemical properties of soils in Chippewa hydrosequence.

Horizon	Fe			Al			pH		C
	PYR	OX	DITH	PYR	OX	DITH	KCl	H2O	
	—	—	—	g/kg	—	—			g/kg
LIMINGA									
A 0-7							4.2	4.2	
E 7-11	0.2	0.2	2.2	0.2	0.2	0.2	4.2	4.2	
Bhs 11-22	3.2	3.2	6.2	4.2	4.2	3.2	4.2	5.2	2.2
Bs 22-63	1.2	2.2	6.2	2.2	5.2	4.2	4.2	5.2	7.2
C 63-192	0.2	0.2	2.2	1.2	1.2	1.2	5.2	6.2	
WAINOLA									
Oi 7-0							5.2	5.2	
E 0-15	0.2	0.2	4.2	0.2	0.2	0.2	3.2	4.2	
Bhs 15-43	5.2	6.2	14.2	7.2	9.2	8.2	4.2	5.2	3.2
BC 43-77	1.2	1.2	3.2	1.2	2.2	1.2	5.2	5.2	
C 77-118	1.2	1.2	4.2	1.2	1.2	1.2	5.2	5.2	
KINROSS I									
Oa 10-0							4.2	4.2	
E 0-8	0.2	0.2	1.2	0.2	0.2	0.2	4.2	5.2	
Bhs 8-19	1.2	0.2	1.2	2.2	2.2	2.2	4.2	5.2	8.2
Bg 19-34	0.2	0.2	1.2	3.2	3.2	3.2	4.2	5.2	7.2
C 34-56	0.2	1.2	3.2	2.2	3.2	3.2	5.2	6.2	

PYR = pyrophosphate extraction OX = ammonium oxalate extraction
 DITH=sodium dithionite extraction
 pH: 1:1 1 N KCl:soil, 1:H2O:soil
 C = total carbon

Table 2.6. Selected chemical properties of soils in Cheboygan hydrosequence.

		Fe			Al			pH		C
Horizon		PYR	OX	DITH	PYR	OX	DITH	KCl	H2O	g/kg
		—	—	—	g/kg	—	—			
RUBICON										
A	0-10							5.3	5.9	
E	10-34	0.0	0.1	1.3	0.0	0.0	0.0	4.4	5.4	
Bs1	34-50	1.6	1.7	2.1	1.8	1.7	2.2	4.3	5.5	4.2
Bs2	50-113	0.3	0.5	1.5	1.1	1.6	0.9	4.5	5.5	1.5
C1	113-153	0.2	0.3	3.1	1.3	0.6	1.3	4.6	5.4	
C2	153-172	0.9	1.5	4.7	1.2	1.6	1.1			
AU GRES										
Oi	8-0							3.9	4.8	
E	0-31	0.0	0.0	0.2	0.2	0.1	0.2	4.0	4.9	
Bs1	31-45	0.1	0.1	0.4	2.0	1.7	2.5	4.2	4.9	2.8
Bs2	45-66	0.2	0.3	1.7	2.0	2.0	1.8	4.1	4.9	5.2
BC	66-85	0.2	0.2	1.4	1.2	2.1	1.3	4.3	5.1	
C	85-150	0.1	1.5	1.6	0.2	1.2	0.2	4.5	5.5	
KINROSS 2										
Oa	0-8							3.9	4.6	
E	0-18	0.1	0.1	0.4	0.2	0.1	0.2	4.0	5.0	
Bs	18-50	0.9	1.0	5.0	1.2	1.2	1.0	4.5	5.4	1.8
C	50-125	0.1	0.0	0.7	0.2	0.2	0.3	4.4	5.4	
PYR = pyrophosphate extraction OX = ammonium oxalate extraction DITH = sodium dithionite extraction pH: 1:1 1 N KCl:soil, 1:1 H2O:soil C = total carbon										

SAND AND SILT MINERALOGY

Medium sand and fine sand were the dominant sand size fractions in Cheboygan and Chippewa Counties, respectively. These sand fractions were used for mineralogical studies. Results of the petrographic analysis of the major sand fraction of the profiles under study are presented in Table 2.7. Examination of the data portrays the following points.

A/ Quartz accounts for more than 70% but less than 80% of the mineralogical composition

of these two hydrosequences. Hence, these soils are classified as having mixed, not siliceous, mineralogy at the family level (Soil Survey Staff, 1975). In all instances the solum quartz content is higher than the parent material. This could be due to a loss of weatherable minerals in the solum that causes an increase in the distribution of quartz. Another explanation is a physical break down of coarser fractions to finer size fractions.

- B/ The potassium feldspar(K-feldspar) distribution within a profile is somewhat uniform indicating resistance to physical and chemical weathering. The plagioclase feldspar contents, however, increase with depth indicating its susceptibility to weathering especially near the soil. This statement is supported by relatively equal amounts of these feldspars in the parent material of the Chippewa hydrosequence. Except in the well drained pedons, K-feldspar tends to be higher in the eluvial horizons than the horizons below. This may be explained in terms of weathering in the E horizons or due to physical breakdown of coarser fractions to finer fractions.
- C/ Chert and rock fragment contents tend to be slightly higher in the sola than in the parent materials. This could be due to high intensity of weathering (physical) at or near the surface.
- D/ Heavy minerals (pyroxene, hornblende and opaque) constitute 5-9% of the mineral composition in the parent materials. Their contents decrease to 3-5% in the surface due to weathering.
- E/ Altered (weathered) minerals are those which have aggregate extinction under strong light but which are almost opaque under normal light. These minerals were not identified as a specific mineral. These minerals are mainly identified in the solum as an alteration product of other weatherable minerals.
- F/ Sericite which is one of the abundant minerals next to quartz and K-feldspar shows the same distribution pattern as the weatherable minerals. As in the fine loamy hydrosequence, these minerals were observed under petrographic microscope as shiny, fine grained particles on feldspar grains and also as individual grains.
- G/ The distribution of the minerals identified in the parent material of each hydrosequence shows similar abundance indicating parent material uniformity within each hydrosequence.

Other minerals like mica, hematite and detrital chlorite were present in very small quantities (<1%). Separation of Na and Ca feldspars in the identification process was not attempted. Another study in Michigan (Franzmeier et al, 1963) found no evidence of K-feldspar weathering in the fine sand fraction, whereas chlorite and altered grains show the most evidence of weathering. Heavy minerals identified in their study constituted 0.5-6% of the total mineral composition. Collins (1971) found orthoclase and albite as a

predominant feldspars and heavy mineral contents of less than 7% in the fine sand fractions. The common results in all these studies are: 1/ K-feldspar shows little or no evidence of weathering, 2/ heavy minerals comprise a small percentage (<7%) of the total mineral assemblage and 3/ muscovite or biotite are less than 0.5% in the fine and medium sand fractions.

Identification of minerals present in the coarse (20-50 μ m) and fine (2-20 μ m) silt fractions was based on JCPDS (1974) powder diffraction data for standard minerals. Minerals identified in both silt fractions are mainly quartz, plagioclase, and K-feldspar (Fig. 2.8). Chlorite was present in low amounts mainly in the fine silt fraction of Cheboygan hydrosequence. Quartz is the only mineral found in high amount. Both feldspars are present in a relatively equal proportions but low amounts.

The productivity of the forest vegetation in these sandy soils is mainly maintained by "tight" cycling of available nutrients as Miller et al. (1979) pointed out in their study. Unlike the fine-loamy soils which has relatively higher silt and clay contents, these sandy soils mainly depend on the weathering of weatherable minerals and recycling of available nutrients.

MINERALOGY OF CLAY FRACTION

The results of XRD analyses of the <2 μ m clay fraction for the two hydrosequences are summarized in Table 2.9. Figures 2.6-2.11 depict the X-ray diffraction patterns obtained for these soils. Based on the X-ray diffraction patterns, the distribution of layer silicates shows the same pattern in all pedons. The non clay minerals identified were quartz and feldspars. Doublet peaks, 3.18Å - 3.21 Å, were the most intense part of the feldspar spectrum particularly in the parent material. The phyllosilicates of the parent material are chlorite, mica, kaolinite and small amount of vermiculite. XRDs of the C horizons show relatively high count level base lines, probably due to the presence of amorphous materials (Mehra and Jackson, 1960). Smectite is the dominant layer silicate found in the E horizons of all pedons. Other layer silicates present in this horizon are mica and kaolinite with the exception in the Kinross pedons that have vermiculite in addition to mica and kaolinite. The E horizon of Kinross pedon from the Chippewa hydrosequence has some random interstratification of smectite-vermiculite as shown by broadening towards the high angle of the 18Å peak.

The predominant clay mineral present in the spodic horizons is vermiculite. Other clay minerals present are mica, kaolinite, and chlorite. Random interstratification of vermiculite and mica in the spodic horizon of the Liminga pedon is shown by a broad

Table 2.7. Mineralogy of the sand fraction.

HORIZON	QZ	K	Na/Ca	ROC.						
		FEL.	FEL.	SER	FRA.	CHE.	OPA.	PY	AM	ALT
						%				
CHIPPEWA										
LIMINGA										
E	78	5	2	4	2	2	2	2	1	2
Bhs	77	5	2	4	2	2	2	2	2	2
C	71	5	5	6	1	1	3	3	3	2
WAINOLA										
E	78	7	2	4	2	2	2	1	1	1
Bhs	76	5	2	6	1	2	3	1	2	2
C1	73	6	5	8	1	1	2	2	2	*
C3	72	6	4	8	2	1	3	2	2	*
KINROSS 1										
E	75	7	2	6	1	2	2	1	2	2
Bhs	75	5	3	8	1	2	2	1	2	1
C	72	5	5	9	1	1	2	2	3	*
CHEBOYGAN										
RUBICON										
E	73	10	2	6	2	1	1	1	2	2
Bs	74	9	2	6	2	1	1	1	2	2
C2	70	10	5	7	1	1	1	2	3	*
AUGRES										
E	75	10	2	6	2	1	1	1	1	1
Bs	73	10	2	6	2	1	2	1	1	2
C	73	9	5	7	1	2	2	2	2	*
KINROSS 2										
E	73	10	3	6	2	1	1	1	1	2
Bs	74	9	3	6	1	1	2	1	1	2
C	72	9	5	7	1	1	2	2	1	*

QZ=Quartz; k Fel=K-feldspar; Ser=Sericite;
 Roc. Frag=Rock fragment; Che=chert; Opa=Opaque
 Py=Pyroxene; Am=Amphibole; Alt=Altered
 * = absent

Table 2.8. Relative amounts of minerals in silt fractions.

HORIZON	FINE SILT			COARSE SILT		
	PLAGIOCLASE	K-FELDSPAR	QUARTZ	PLAGIOCLAS E	K-FELDSPAR.	QUARTZ
CHIPPEWA						
LIMINGA						
E	L	L	H	L	M	H
Bhs	M	L	H	L	L+	H
C1	L+	L	H	L	L	H
C3	L	L	H	L+	L	H
WAINOLA						
E	L	L	H	L+	L+	H
Bhs	M	L	H	L	L+	H
C1	L	L	H	L+	L+	H
C3	L+	L+	H	L+	M	H
KINROSS 1						
E	L+	L	H	L	L	H
Bhs	L+	L	H	L+	L	H
C	M	M	H	L	L	H
CHEBOYGAN						
RUBICON						
E	L+	L	H	M	M	H
Bs	L+	L	H	L	L	H
C1	L	L	H	L	L	H
C3	L	L	H	L	L	H
AU GRES						
E	L	L	H	L+	L	H
Bs	L+	L	H	L+	M	H
C	*	*	*	L	L+	H
KINROSS 2						
E	L+	L	H	M	L+	H
Bs	M	L	H	L+	L+	H
C	L+	L	H	L	L	H
H-HIGH						
M-MEDIUM						
L-LOW						

* = ABSENT

Table 2.9. Relative amounts of clay minerals(<2μm).

HORIZON	SMECTITE	CHLORITE	VERMICULITE	MICA	KAOLINITE	QUARTZ
CHEBOYGAN						
RUBICON						
E	XXXXXX	-	-	XX	X/	X/
Bs	-	/	XXXXXX	XX	X/	X
C1	-	XXX	/	XXX	X/	XX
C3	-	XXX	/	XXX	X/	XX
AU GRES						
E	XXXXXX	-	/	X/	XX	X
Bs	-	-	XXXXXX	XX	XX	X
C	-	XX/	X	XXX	XX/	X
KINROSS 2						
E	XXXXX	/	XX/	X	X	X
Bs	-	XX	XXX/	X/	XX	X
C	-	XX/	X	XXX	XX/	X
CHIPPEWA						
LIMINGA						
E	XXXXXXX	-	-	XX	X/	/
Bhs	-	X	XXX/	XXX/	X/	/
C1	-	XX	X	XXX	XX/	X/
C3	-	XX/	X	XXX	XX/	X
WAINOLA						
E	XXXXXX	-	-	X/	XX/	X
Bhs	-	X	XXX/	XX	XX	X/
C1	-	XX	X/	XXX	XX	X/
C3	-	XX	X	XXX	XX/	X/
KINROSS 1						
E	XXXXXX	-	X	XX	X	X
Bhs	-	-	XXXXX	XX	XX/	X/
C	-	XX/	X	XX/	XX/	X/

- = not detectable
 /= Approximately 5%
 X = Approximately 10%

angle between 14Å and 10Å. This broad peak shifts to 10Å with 300°C heat treatment. This indicates moderately weathered muscovite initially produces mixed-layer muscovite-vermiculite and, as weathering proceeds, vermiculites and then smectite. Partial intergrade of 14Å and 10Å (chlorite and vermiculite or mica) with discrete chlorite appears in the Bs and C horizons of the Kinross pedon from the Cheboygan hydrosequence. Interstratification and hydroxy interlayering are relatively common especially in the spodic horizons. The presence of hydroxy-interlayering is evidenced by the fact that the vermiculite in the spodic horizons collapsed partially after K saturation at room temperature and shifted to 10Å with some broadening to the high angle after 300°C heat treatment. According to Barnhisel and Bertsch (1989), vermiculite containing little or no hydroxy-interlayering will collapse to 10Å upon K saturation at room temperature. As shown by April et al. (1986), the necessity to heat the sample to force K into the interlayer and to dehydroxylate the interlayer is characteristic of hydroxy-interlayered vermiculite. In addition to spodic horizons this phenomenon is also observed to some extent in the E horizon of the fine clay of all pedons (Fig 2.12 and 2.13).

Discrete mica occurs mostly in the C horizons of all pedons and in small amounts in the solum. The fact that the 10Å peaks tend to decrease in height and symmetry towards the surface horizon is further evidence of the alteration of mica in the more acid surface horizon. The chlorite and in some cases kaolinite peaks also tend to decrease in height and symmetry with decreasing depth. In fact, very little discrete chlorite occurs in the spodic horizons and is totally absent in the E horizons. This could be due to the alteration of these minerals, probably by the loss of structural Al and Fe and desilication (Ross et al., 1982; Ross and Mortland, 1966). The absence of the 1.54Å 060 diffraction peak in the spodic horizon indicates all clay minerals present are dioctahedral and the chlorite present is pedogenic. The trioctahedral chlorite present in the C horizon might have weathered to amorphous or decomposed to soluble products by the cheluviating action of organic acids (Kodama and Schnitzer, 1973), unless chlorite vermiculitization results in a change toward dioctahedral structure as found in New Brunswick Spodosol (Ross et al., 1982) and demonstrated in the laboratory by Ross (1975). Another explanation could be due to low concentration of trioctahedral chlorite and according to Barnhisel and Bertsch (1989), if the concentration is low, peak intensities of chlorite may not be sufficient for identification. Vermiculite is the predominant clay mineral in the spodic horizon. The intensity of vermiculite reaches the maximum in the spodic horizons and disappears in the eluvial horizons of all the pedons except in the Kinross pedons. Vermiculite is present as discrete and also as randomly interstratified smectite-vermiculite in the poorly drained pedons. This indicates alteration of vermiculite in the poorly drained pedons is still in progress and also

suggests intensity of pedogenic weathering processes increases from poorly drained to well drained soils. The alteration of mica to vermiculite depends on a strong leaching environment to remove solution K and mixed-layer muscovite/vermiculite is common and often dominate in the weathering sequence (Sawhney, 1989). The alteration sequence mica → vermiculite → smectite has been observed in Spodosols (Gjems, 1960; Ross and Mortland, 1966; Franzmeier et al., 1968; Douglas and Trela, 1979; among others). These same authors and Komarneni et al. (1985), among others, have attributed the transformation of smectite from mica due to: loss of K as in vermiculite formation; dealumination of the tetrahedral sheet; and silication of the tetrahedral sheet. Those workers mentioned above have considered the presence of smectite in the Spodosols as an advanced stage of weathering.

The mineral distribution within a profile in these hydrosequences suggest the following weathering sequence:

sericite/muscovite → vermiculite → smectite with or without mixed-layer formation. Trioctahedral chlorite in this study is assumed to decompose while pedogenic chlorite could have formed by neoformation which might have weathered to vermiculite in the surface horizons.

CONCLUSIONS

These Spodosol hydrosequences in Michigan are low in weatherable minerals. The sand mineralogy is dominated by quartz followed by small amounts of feldspar and sericite. The silt fraction is devoid of weatherable minerals including sericite. It is dominantly composed of quartz and small amounts of feldspar. Differences in drainage do not indicate a particular distribution of sand and silt minerals.

The clay mineral distribution indicates the parent material is composed of chlorite, mica, kaolinite and small amounts of vermiculite. Smectite, dioctahedral beidellite, is the dominant layer silicate found in the E horizons of all pedons. The intensity of smectite peak and the presence and absence of vermiculite in the E horizons, suggest increasing weathering intensities from poorly drained to well drained soils in these hydrosequences. Based on the clay mineral distribution of the total clay fraction the following weathering sequence is observed: Sericite/muscovite → vermiculite → smectite with or without mixed-layer formation.

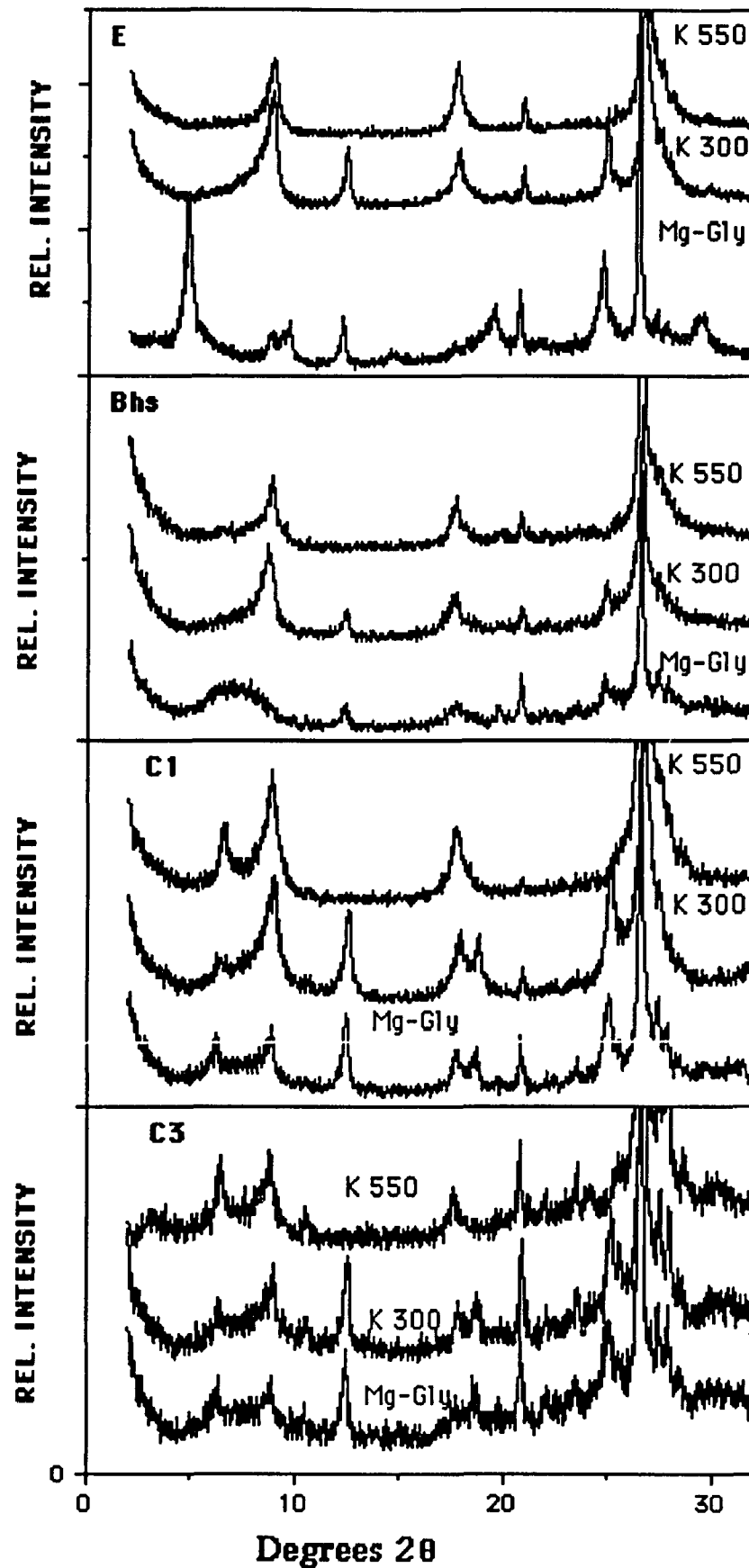


Fig. 2.5. X-ray diffractograms of clay fraction ($<2\mu\text{m}$) of the liminga pedon.

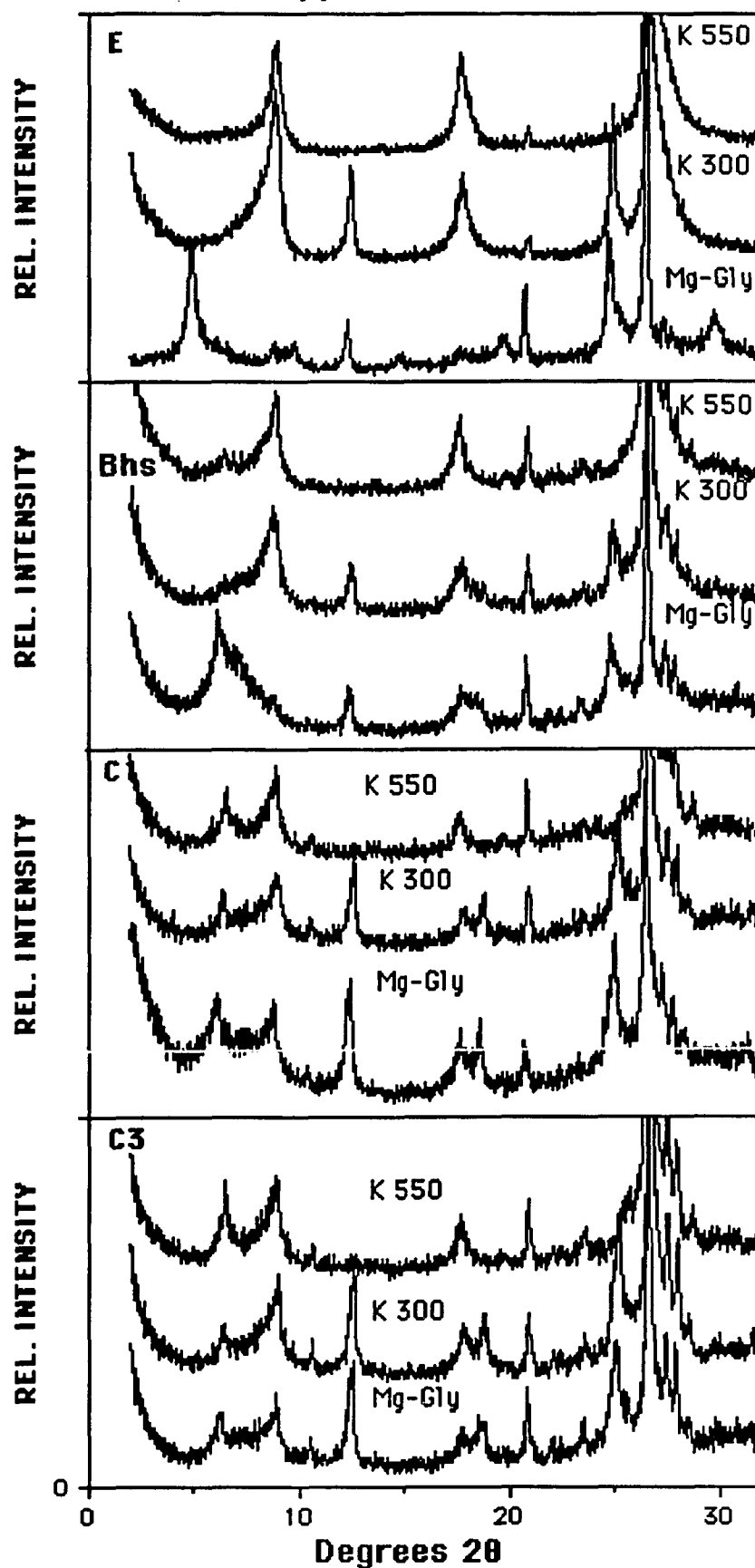


Fig. 2.6. X-ray diffractograms of clay fraction ($<2\mu\text{m}$) of the Wainola pedon.

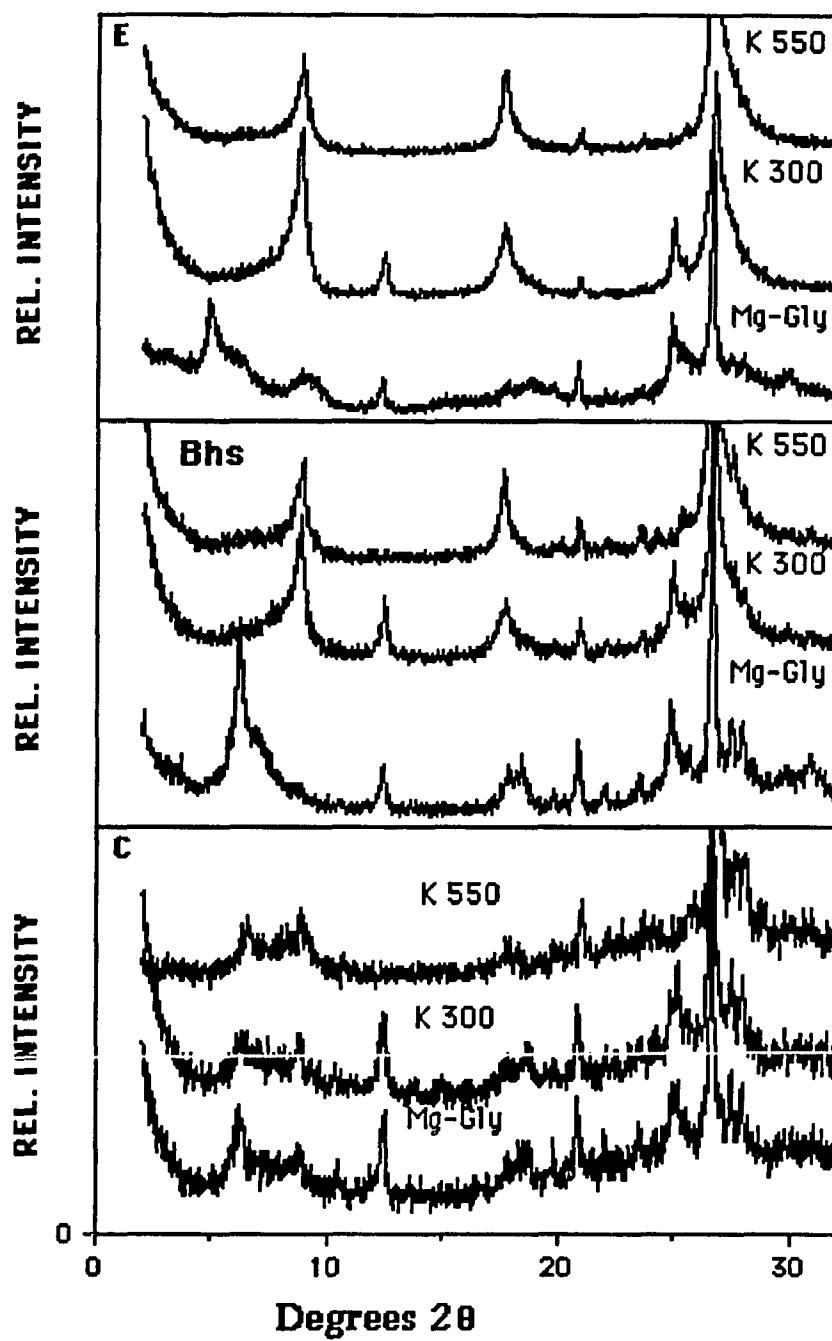


Fig. 2.7. X-ray diffractograms of clay fraction (<2μm) of the Kinross pedon in Chippewa hydrosequence.

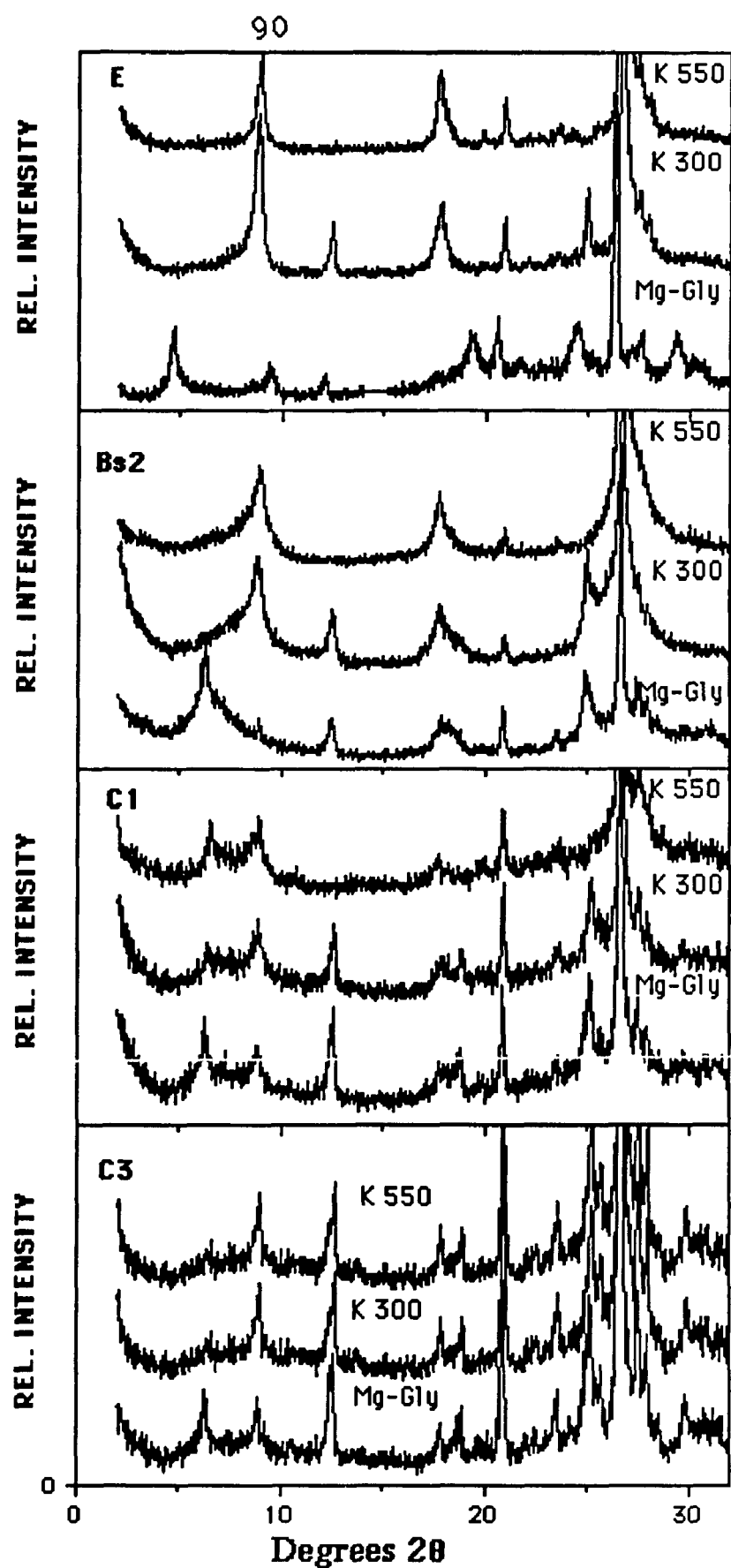


Fig. 2.8. X-ray diffractograms of clay fraction (<2μm) of the Rubicon pedon.

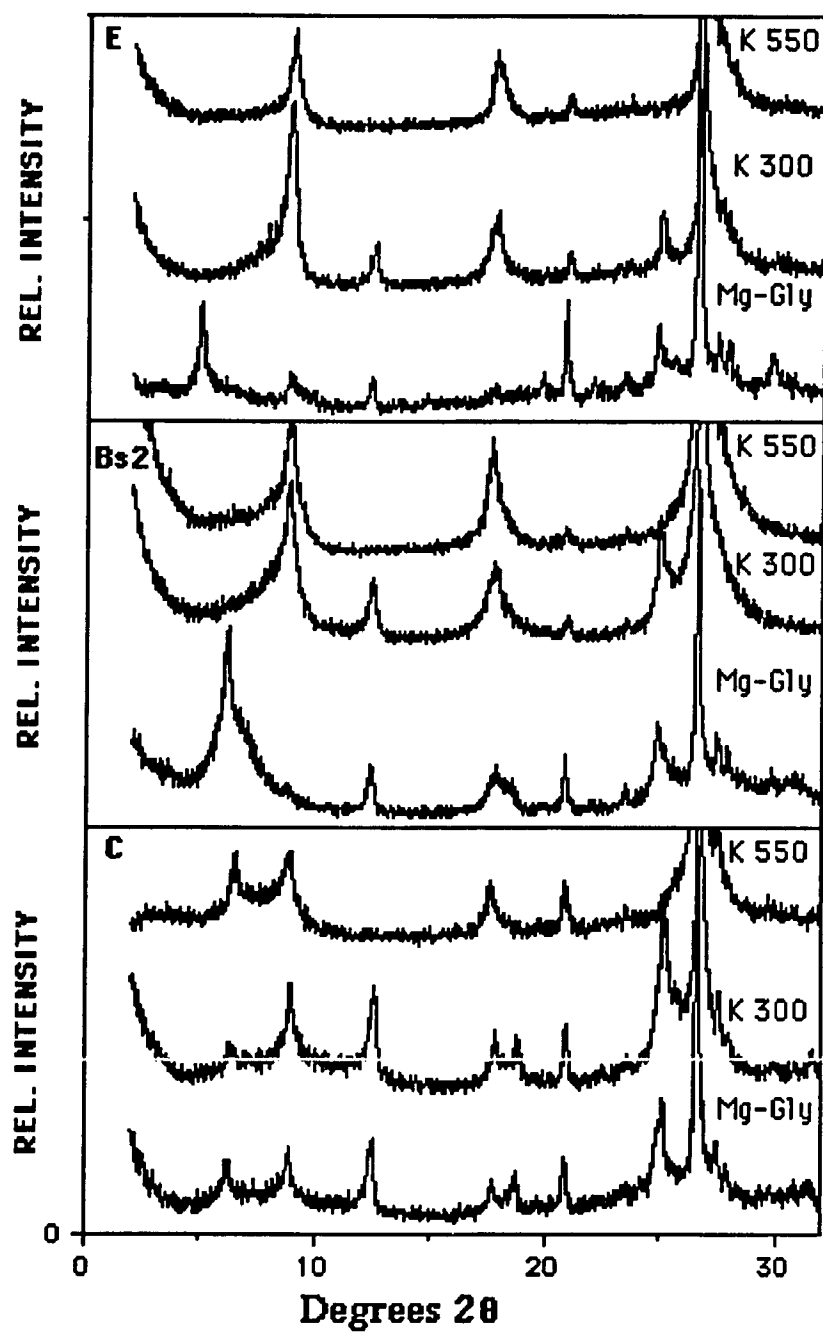


Fig. 2.9. X-ray diffractograms of clay fraction (<2 μ m) of the AuGres pedon.

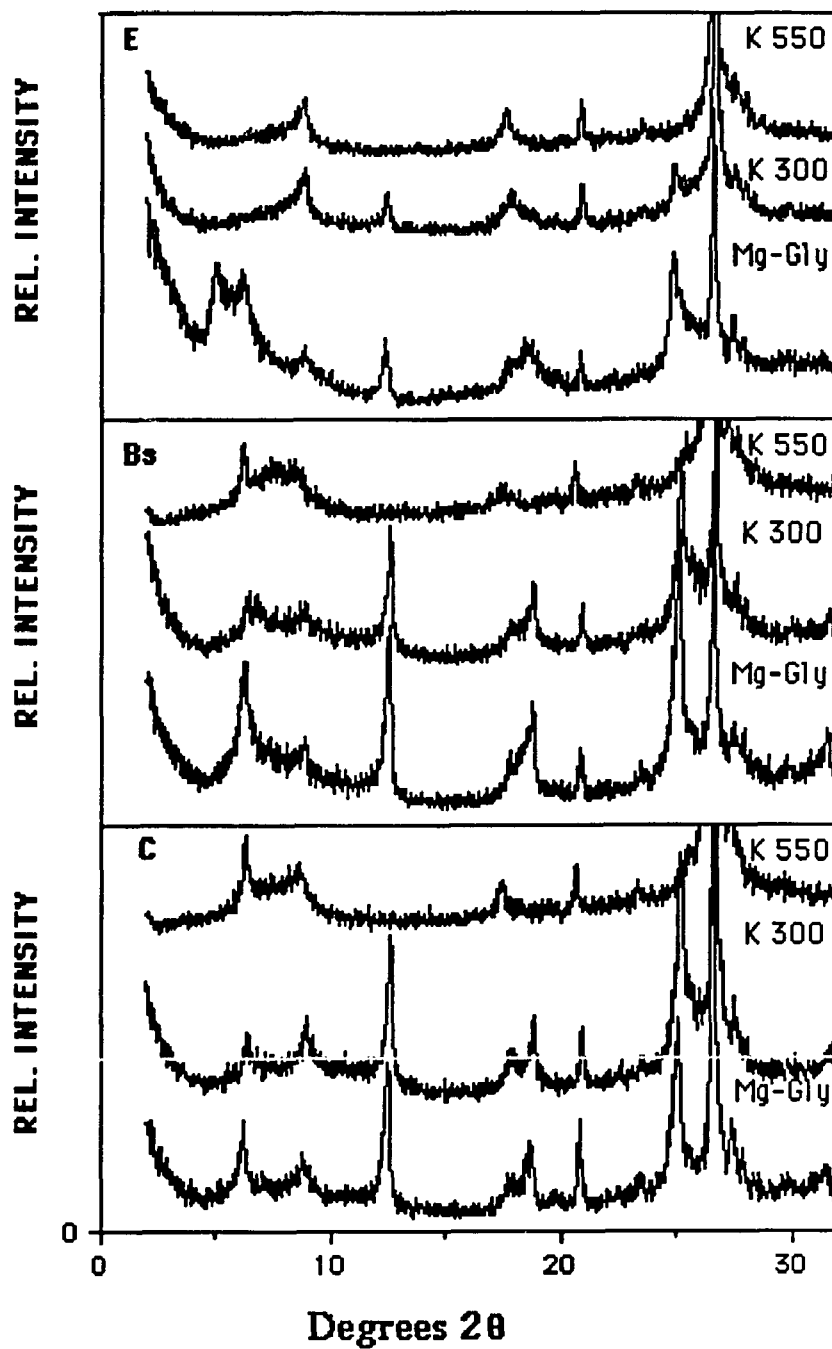


Fig. 2.10. X-ray diffractograms of clay fraction ($<2\mu\text{m}$) of the Kinross pedon in Cheboygan hydrosequence.

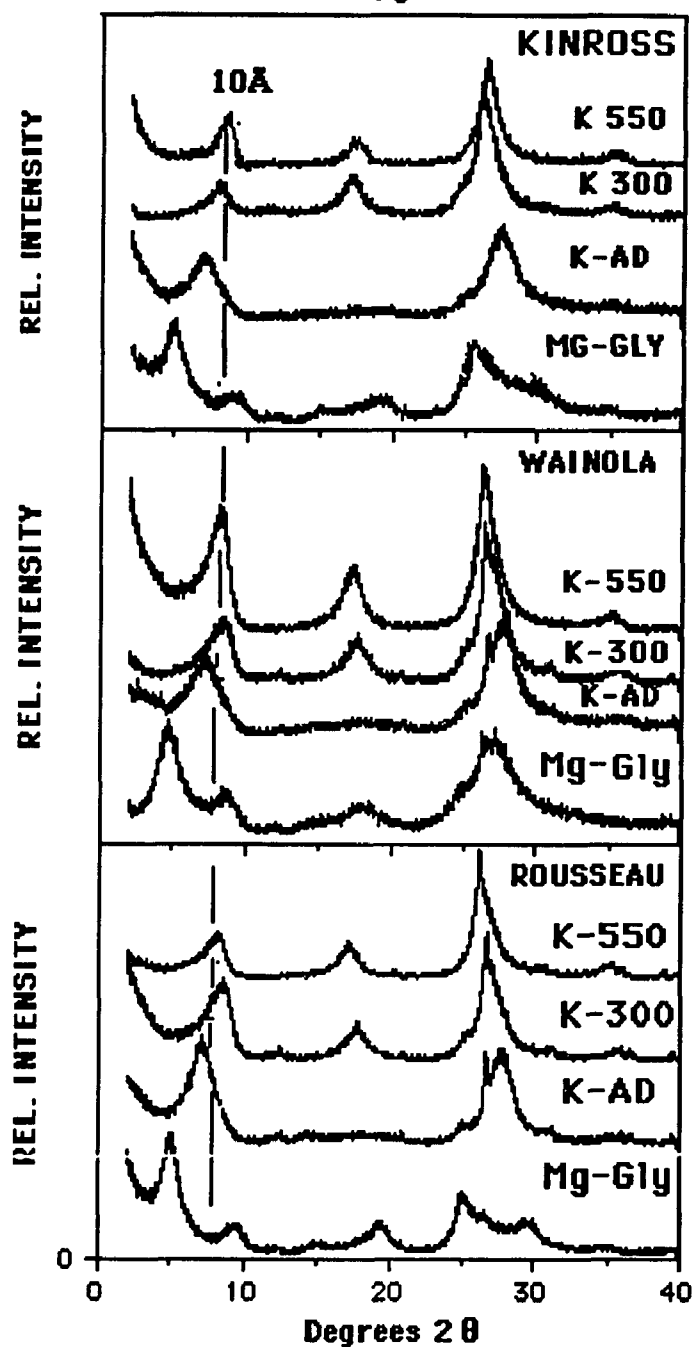


Fig. 2.11. X-ray diffractograms of fine clay fraction (<0.2 μ m) of the E horizons in Chippewa hydrosequence.

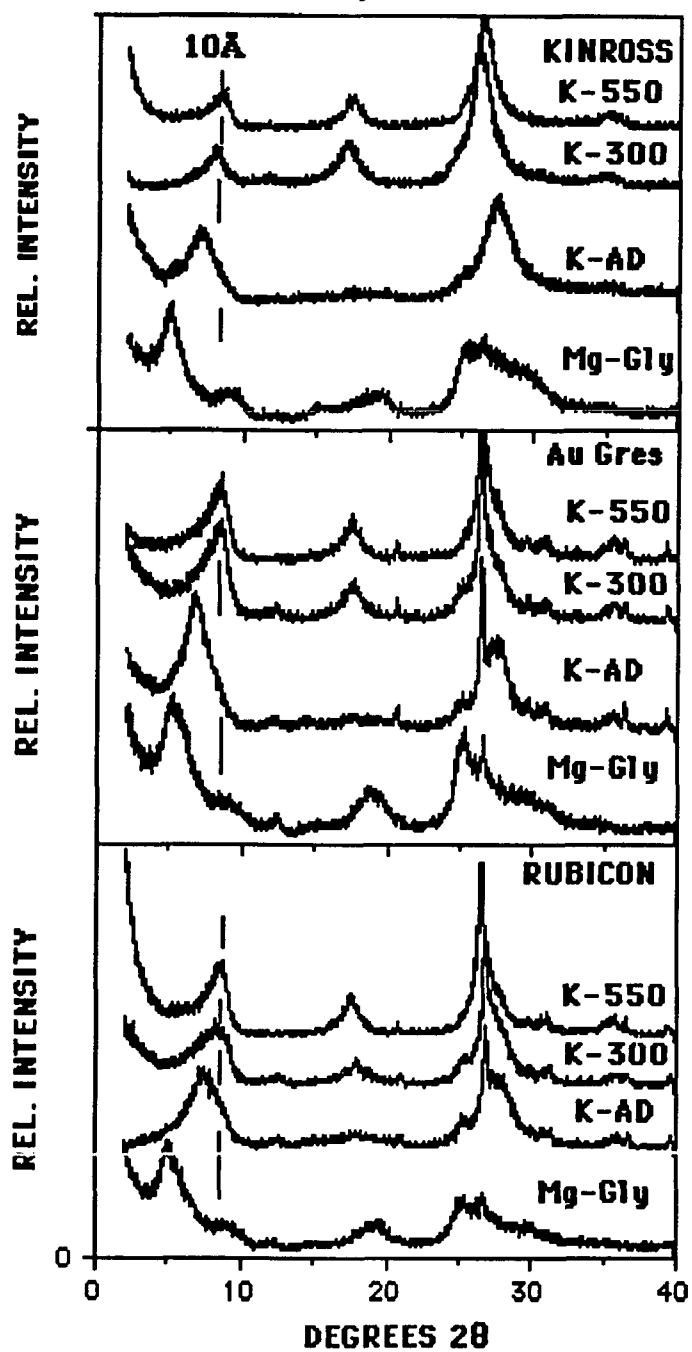


Fig. 2.12. X-ray diffractograms of fine clay fraction ($<0.2\mu\text{m}$) of the E horizons in Cheboygan hydrosequence.

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CHAPTER 3

CHARACTERIZATION OF SMECTITE IN A SPodosOL AND A MOLLISOL

ABSTRACT

Mineralogical studies have revealed smectites in the acidic E horizons of Spodosols and in basic Btg horizons of Mollisols. This study was conducted to characterize the smectite in fine-clays from the two environments in terms of layer charge using the Greene-Kelly test, re-expansion property, alkylammonium method (AAM), and elemental analysis. In both cases, the smectite was dioctahedral of the beidellitic type.

Structural formulas calculated from the chemical data had 0.47 and 0.51 molc/half unit cell formula for the Spodosol and Mollisol clays, respectively. The mean layer charge determined by AAM was 0.41 and 0.43 molc/half unit cell formula for the E and Btg horizons, respectively. This is lower than the value determined by the structural formula. The paraffin type configuration indicates the presence of unweathered mica cores in these samples. Both samples, when K-saturated, heated at 300°C, and glycerated, re-expanded to 14Å suggesting a layer charge value between 0.39 and 0.43 and part of the clay that remained at 10Å indicates a charge higher than 0.43.

The high octahedral iron in the Btg horizon clay is similar to a tetrahedrally-charged mica. In both samples soil mica weathers to beidellite with vermiculite being an intermediate product.

INTRODUCTION

Many soil mineralogists believe that smectite is unstable in acidic environments and restrict its formation mainly to basic environments (Douglas, 1982). However, others (Brown and Jackson, 1958; Gjems, 1960; Franzmeier et al., 1963; McKeague, 1965; Ross and Mortland, 1966; Brydon et al., 1968; Malcolm et al., 1969; Coen and Arnold, 1972; Kapoor, 1972; Nash, 1979; Douglas and Treala, 1979; Douglas, 1982) among others, have reported the weathering of mica and chlorite through vermiculite, to smectite in eluvial or albic horizons of Spodosols. Ross and Mortland (1966) reported beidellite to be the smectite variety in the Spodosol E horizon of their study. Beidellite was also found to be the smectite variety in Mollisols in Iowa (Laird et al., 1988) and Minnesota (Badraoui et al., 1987).

Mineralogical studies in sandy and fine-loamy hydrosequences in Michigan have revealed smectite in the acidic E horizon of Spodosols and in the basic Btg horizon of Mollisols. Weathering of mica to smectite through vermiculite as an intermediate stage is thought to be the dominant mechanism of smectite formation in Michigan soils. The purpose of this study is to characterize these smectites in terms of layer charge using the Greene-Kelly test, re-expansion properties, alkylammonium exchange, and elemental analysis.

MATERIAL AND METHODS

The E and Btg horizons from pedons of the Rousseau (sandy, mixed, frigid, Entic Haplorthods) and Brookston (fine-loamy, mixed, mesic, Typic Argiaquolls) soil series, respectively, were selected for detailed clay mineralogy studies. Soil samples were taken from each horizon and the <2-mm fraction was ultrasonically dispersed and separated into sand, silt, and clay fractions after removal of cementing agents (organic matter removed by the H₂O₂ oxidation method; carbonates removed using sodium acetate adjusted to pH 4.5; and sesquioxides were extracted with a solution of citrate-bicarbonate-dithionite (CBD) using Jackson's (1979) procedure. The total clay fractions (<2µm) were further separated into fine (<0.2µm) and coarse (2-0.2µm) fractions. The fine clay fraction was again pretreated to remove cementing agents according to Jackson (1979). Sodium hypochlorite was also used to destroy any residual organic matter in selected samples (Anderson, 1961). The fine clay fraction was saturated with 1M NaCl followed by dialysis to remove excess salts. The clays were then ultrasonically dispersed, frozen, and freeze-dried. The CEC was measured by displacing Ca from Ca-saturated clays with 0.5N MgCl₂. The Ca concentrations were determined by flame emission photometry. Surface areas of the fine clays were determined using the ethylene glycol monoethyl ether (EGME) adsorption method (Carter et al., 1986).

Fine clay fractions of the soil clays were saturated with Mg or K by washing 5 times with 1M MgCl₂ or 1M KCl, respectively, followed by sequential washes with deionized H₂O. Oriented clay films were obtained by allowing suspensions containing 25 mg of fine clay to air dry on 27-by 46-mm glass slides. Magnesium-saturated specimens were analyzed after air drying and glycerol solvation. K-saturated specimens were x-rayed after air drying, heating to 300 °C for 2h, and heating to 550 °C for 2h.

Lithium charge reduction and glycerol solvation were used to determine charge location in the smectites. Reference clay samples were included for comparison. Separate Li-saturated samples were X-rayed (1) after glycerol solvation at room temperature and (2) after heating at 300 °C overnight followed by glycerol solvation. This method was used to distinguish montmorillonite from beidellite (Greene-Kelly, 1953).

Potassium-saturation, heat treatment, and glycerol solvation were used to estimate total layer charge of the soil smectites. Reference clay samples were included for comparison. Clays were K-saturated and heated at 300 °C overnight followed by glycerol solvation. These samples were checked for expansion by XRD to determine the total net layer charge of the smectite. Charge estimation is based on the relationship between re-

expansion properties and total layer charge (Schultz, 1969; Ross and Kodma, 1984; Malla and Douglas, 1987).

Layer charge estimation was also based on XRD measurement of the (001) interplanar spacings of alkylammonium-clay complexes (Lagaly and Weiss, 1969; Ruehlicke and Kohler, 1981). Alkylammonium chloride salts with even-numbered alkyl chain lengths of 6 - 18 C atoms were used. The Na- saturated and freeze-dried fine clay samples (25 mg) were treated with the various alkylamine hydrochlorides as described by Senkayi et al. (1985). All X-ray diffraction analyses were conducted with a Phillips XRD using $\text{CuK}\alpha$ radiation at 35 kV and 20 mA, a theta compensating slit, and a diffracted beam graphite monochromator. All samples were step-scanned using 0.05° 2θ step intervals and a count time of 5 seconds per step.

Total chemical analyses of the fine clay fractions were performed using fused glass disks prepared by melting a mixture of 1.000 g of an homogenized, freeze-dried clay powder at 950°C with 9.000 g of lithium tetraborate flux and 0.16 g of ammonium nitrate in Pt-Au alloy crucibles (Hagan, 1982; Bower, 1985; and Bower and Vaentine, 1986). Analyses were performed with a Rigaku S-Max automated XRF system in the Geology department of Michigan State University. Abundances of major element oxides were calculated by the fundamental parameters matrix correction method (Criss, 1980). A U.S.G.S. reference standard (W-2) was analyzed to provide a check on the accuracy and precision of the analyses.

RESULTS AND DISCUSSION

The X-ray diffraction patterns of the fine clay samples from the E and Btg horizons of the Spodosol and the Mollisol, respectively, are presented in Fig. 3.1. The dominant clay mineral in both fine clay fractions is smectite as shown by a strong $17.8\text{\AA}$ peak (Fig. 3.1). Based on XRD, the presence of a small amount of mica in the E horizon sample is indicated by a low-angle shoulder on the second-order smectite $9.0\text{\AA}$ peak and by the presence of peaks at $5\text{\AA}$ and $3.34\text{\AA}$. A small amount of mica is also evident in the fine clay fraction of the Btg horizon from a broad peak at $9\text{-}10\text{\AA}$ and by peaks at $5\text{\AA}$ and $3.34\text{\AA}$. A small amount of kaolinite is indicated in both clays by a $7.2\text{\AA}$ peak which persists after 300°C treatment, but disappears after 550°C treatment. Some random interstratification of smectite and mica in the Mollisol clay (Btg) is indicated by the diffuse nature of the (001) XRD reflections and the absence of a rational series of higher-order (001) reflections (Reynolds, 1980; Laird et al., 1988). The K_2O content of the fine clay fraction of the E and Bt samples (Table 3.1) indicates that approximately 18% and 26% of

these samples are mica, respectively, based on the K_2O content of muscovite which is 10% (Reynolds, 1980) and the assumption that all of the K_2O content in these samples is derived from mica.

The (060) powder diffraction patterns of both clays show a b-dimension spacing of $1.50\text{\AA}$, which is characteristic of dioctahedral 2:1 layer silicate clays. The fine clays were also Li^+ -saturated and heated to test for the Hofmann-Klemen (1950) effect. Lithium-saturated and air-dry samples show $12.5\text{\AA}$ peaks that are indicative of smectite (water monolayer). Clay samples Li-saturated and heated to $300\text{ }^\circ\text{C}$ show a diffraction peak of $10\text{\AA}$. However, both clays (E and Btg) re-expanded to $17.8\text{\AA}$ when glycerated (Fig. 3.2). This test indicates that more of the charge is located in the tetrahedral sites than in the octahedral sites and the smectite phase has a charge distribution like beidellite (Greene-Kelly, 1955). Differentiation of vermiculite and high-charge smectite from low-charge smectite in soils based on K-saturated clays and solvating them with a glycerol-ethanol solution was employed by Barshad (1960). Schultz (1969) found a proportional relationship between the re-expansion and total net layer charge of smectite that had been K-saturated, heated to $300\text{ }^\circ\text{C}$, and solvated with ethylene glycol. Recently, Malla and Douglas (1987), using Schultz's (1969) principle of re-expansion, have classified minerals into four layer-charge groups based on re-expansion.

Based on the re-expansion behavior of the K-saturated fine clays of the E and Btg horizons, the expanded clay in these samples is smectite. Potassium-saturated clays that have been heated at $300\text{ }^\circ\text{C}$ show a diffraction peak at $10.1\text{\AA}$. However, after glyceration, these samples re-expanded to only $14.3\text{\AA}$. (Fig. 3.3) According to Schultz (1969), the re-expansion of some of the K-saturated, heated (300°C) samples by glycerol to only $14\text{\AA}$ suggests the presence of beidellite as did the Greene-Kelly test. Some of the clay remains at $10.1\text{\AA}$ after glycerol solvation indicating a higher layer-charge component is also present. In contrast, low-charge smectite re-expands to $17\text{\AA}$ (Schultz, 1969). According to the layer charge groupings of Malla and Douglas (1987) the samples in this study have a layer charge between 0.46 and 0.57 per half unit cell. . The presence of relatively high- and low-charge smectite indicates the heterogeneous distribution of charge in these soil clays.

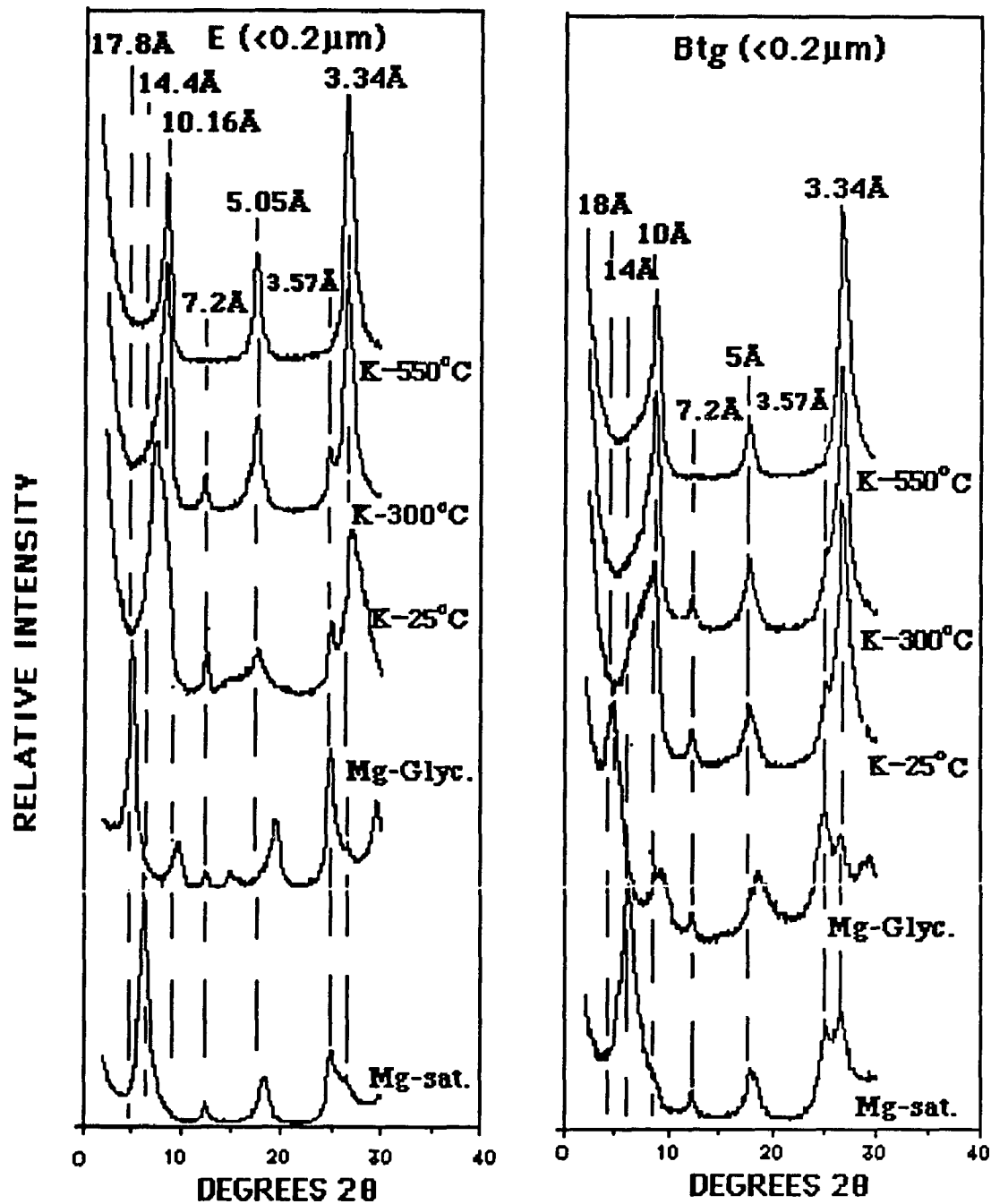


Fig.3.1. X-ray diffractograms of the fine clay (<0.2μm) fractions of the Spodosol E and Mollisol Btg horizons (treatments specified at right).

Figure 3.4 shows X-ray diffraction patterns of the E and Btg horizon clays that were treated with selected alkylammonium hydrochlorides. In both clays, the XRD patterns indicate the presence of kaolinite (7.2Å), mica (10Å) and smectite (13.4Å-21Å). Vermiculite should expand to 18Å or more with C6 alkylammonium treatment; no vermiculite is evident in either sample. The Spodosol clay (E) shows a low angle peak (28Å-30Å) with 16- and 18-carbon alkylammonium ions indicative of vermiculite. Similarly, the Mollisol (Btg) clay has peaks at 23.1Å-25.4Å with C12-C14 and 28-30Å with C16-C18. The Btg sample C12 and C14 diffraction patterns contain two peaks representing low- and high-charge phases. According to Laird et al. (1987, 1988), Senkayi et al. (1985), and Badraoui et al. (1987), the low angle diffraction peaks were associated with K^+ depletion and expansion of soil mica by alkylammonium cations. The absence of vermiculite, the K content, and the presence of a weak 10Å peak in these clays suggest that they contain some un-weathered mica. Smectite in these clays may be a product of mica weathering.

In Figure 3.5, the d(001) values for Spodosol E and Mollisol Btg fine clays are plotted against the chain lengths of the alkylammonium cations (n_c). The smectite in both clays had basal spacings indicative of a monolayer at C6, a bilayer at C10-C14 and a paraffin complex configuration at C16-C18 (Lagaly and Weiss, 1969 and Laird et al., 1988). Mean layer charge was calculated using the method of Lagaly and Weiss (1976) using d-values of the alkylammonium-clay complexes in the monolayer (13.4-13.8Å) to bilayer (17.5-17.7Å) transition range. Because of the heterogeneous charge distribution in most soil clays, the procedure of Stul and Mortier (1974) was employed to calculate the mean layer charge. The mean layer charge was 0.41 and 0.43 molc per half unit cell for the Spodosol (E) and the Mollisol (Btg) fine clays, respectively.

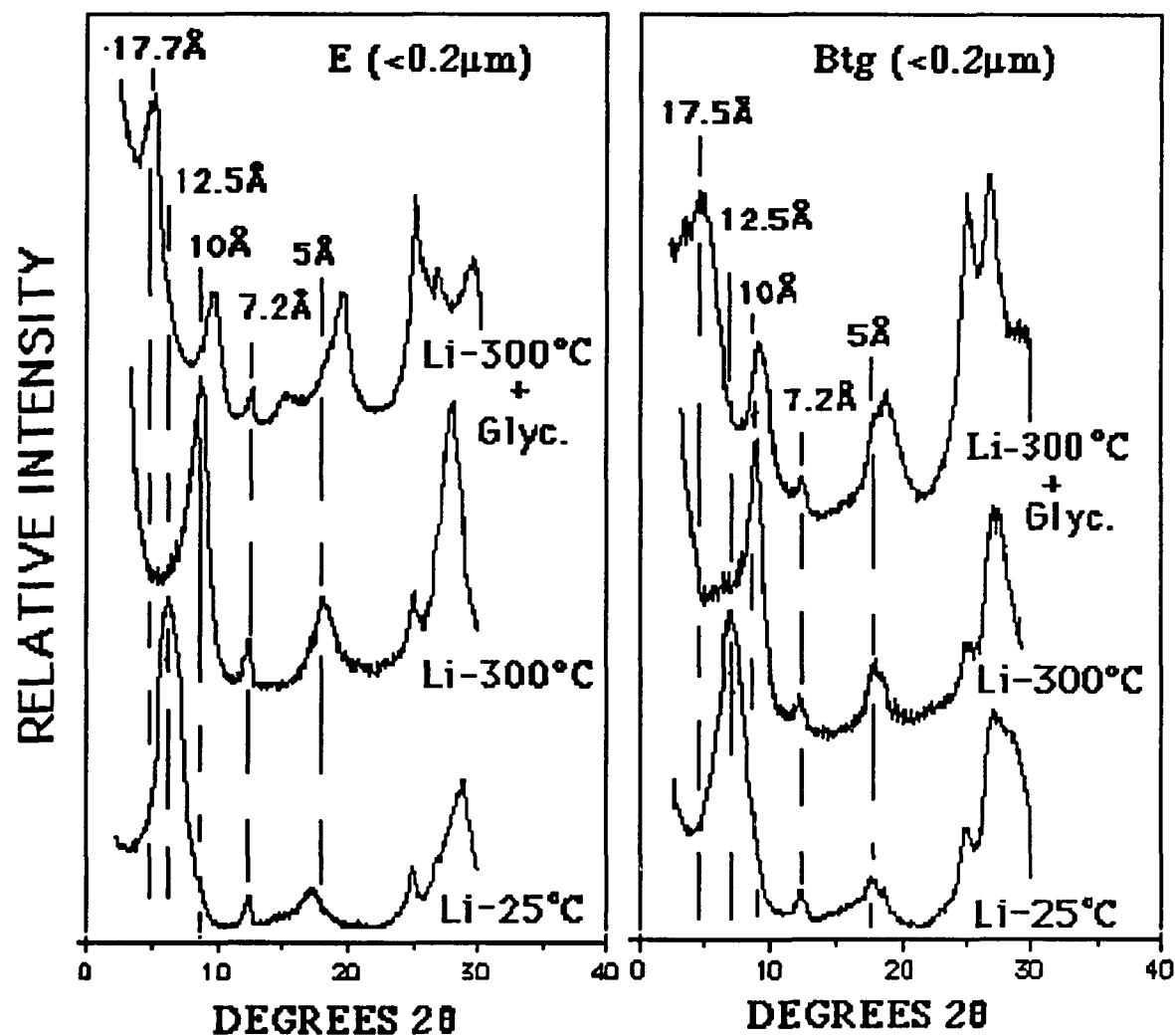


Fig. 3.2. XRD patterns of fine clays from the E and Btg horizons of Spodosol and Mollisol, respectively (treatments are specified at right).

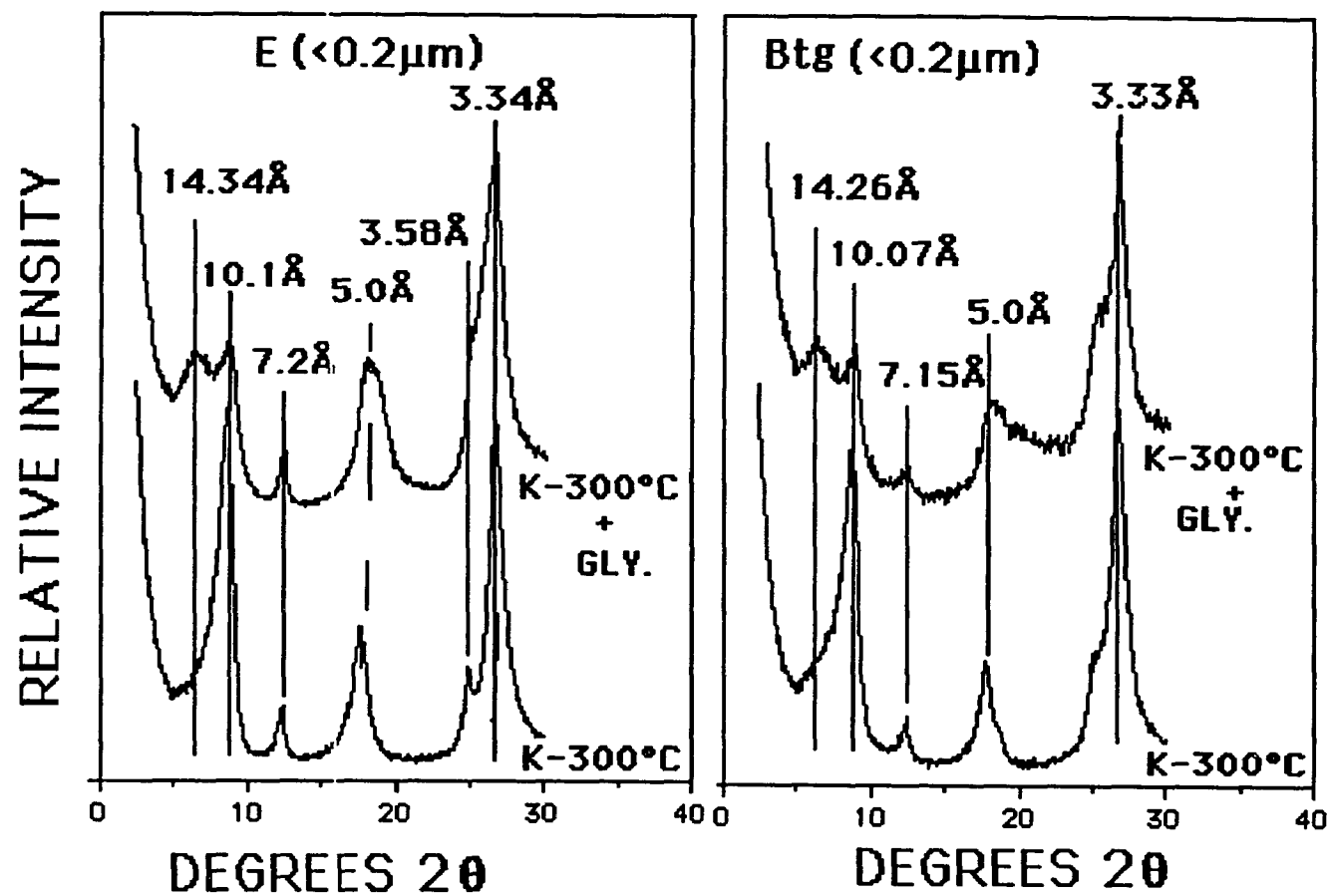


Fig 3.3. XRD of the fine clay from E and Btg horizons of the Spodosol and Mollisol, respectively. Re-expansion properties of the fine clays (treatments specified at , right.).

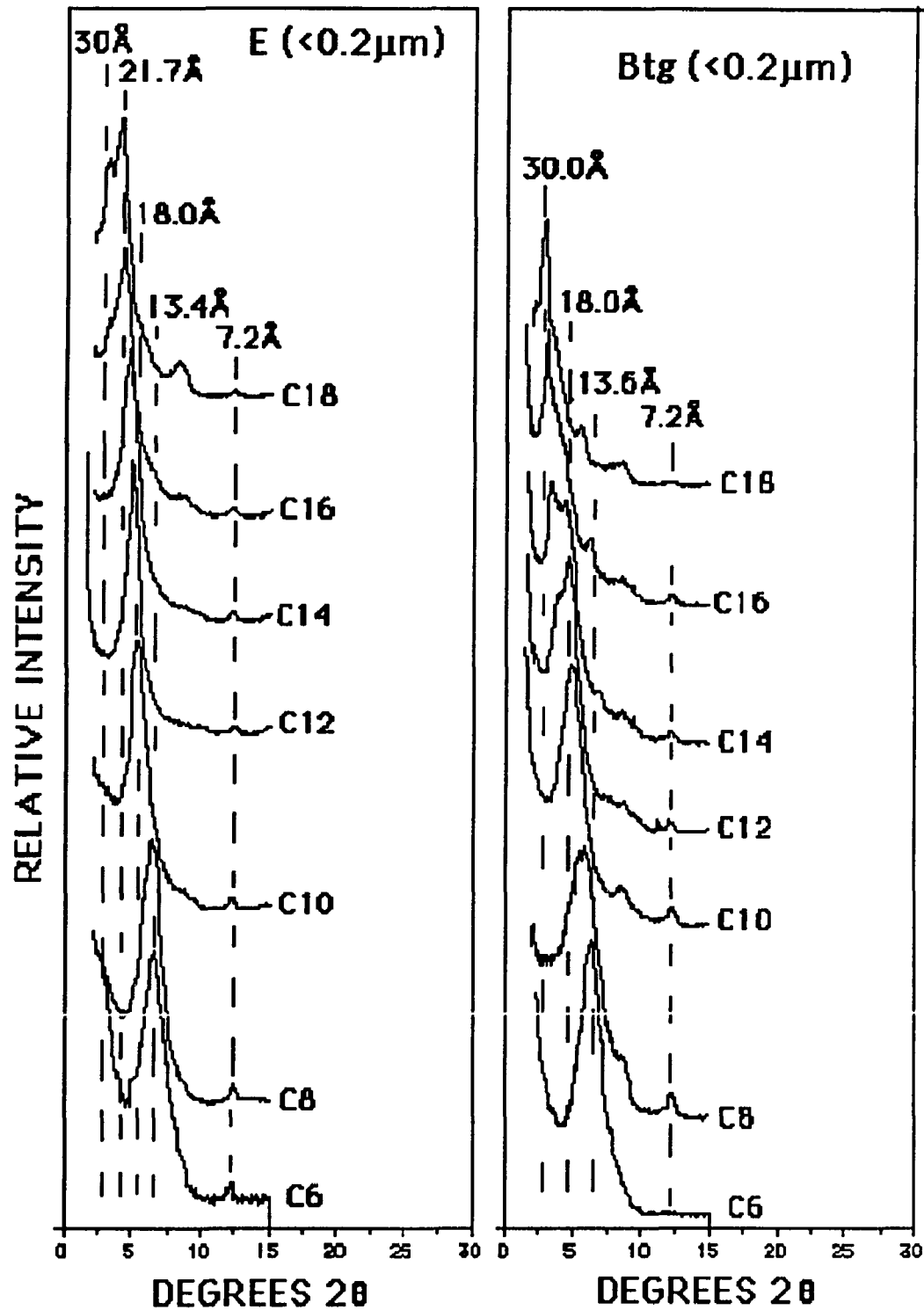


Fig. 3.4. X-ray patterns of the (<0.2μm) soil clays from the E and Btg horizons of the Spodosol and Mollisol pedons, respectively, and treated with various alkylammonium hydrochlorides (carbon chain length specified at right).

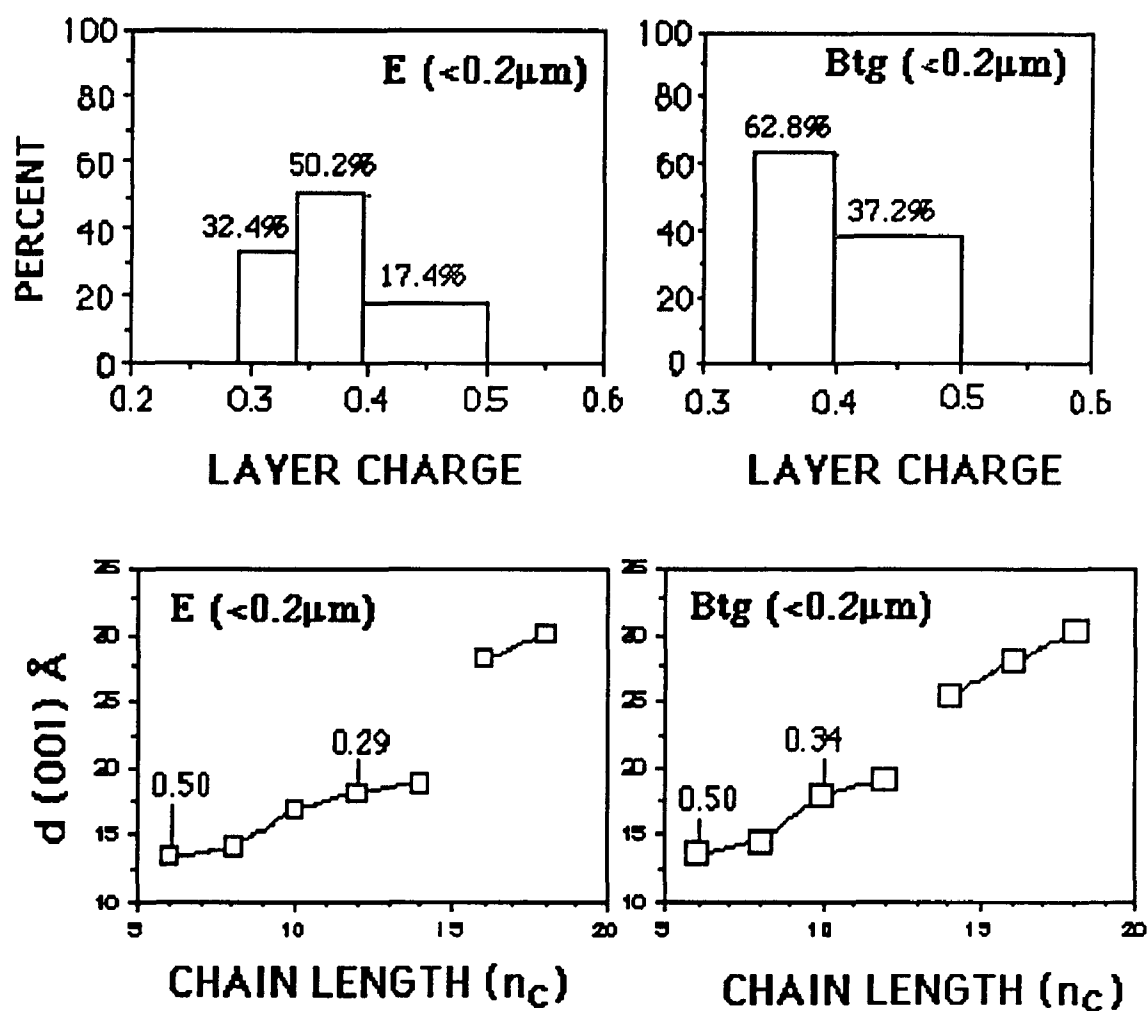
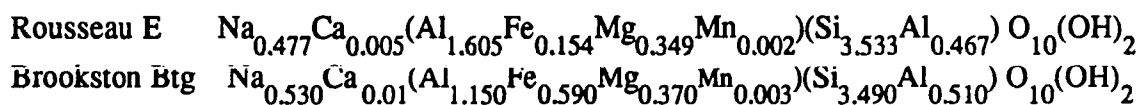


Fig. 3.5. Basal plane spacings of alkylammonium complexes with the E and Btg fine clay Spodosol and Mollisol, respectively, and the corresponding layer charge distribution.

Table 3.1. Elemental analysis of the Ca⁺⁺-saturated fine clay fraction (<0.2µm) from the E horizon of a Spodosol and the Btg horizon of a Mollisol.

Oxide	Based on 950°C weight, %	
	E (Spodosol)	Bt g (Mollisol)
SiO ₂	55.43	53.02
Al ₂ O ₃	26.51	21.54
Fe ₂ O ₃	3.62	9.45
K ₂ O	1.85	2.63
MgO	3.57	3.52
CaO	0.06	0.10
MnO	0.03	0.03
Na ₂ O	3.01	2.79
TiO ₂	1.62	0.50
P ₂ O ₅	0.05	0.06
pH(H ₂ O)	4.4	7.1
CEC	102 meq/100g	90 meq/100g
Surface area	567.12 m ² /g	497.30 m ² /g

The layer charge density of these fine clays was also determined from the structural formulas. Using the elemental analyses (Table 3.1), the following structural formulas were calculated:



Assuming the mica in these samples is similar to Hower and Mowatt's (1966) Silver Hill illite, the mica content was subtracted based on the K₂O content. According to the structural formula, these soil smectites have a layer charge of 0.47 and 0.51 molc per half unit cell formula for the E and Btg samples, respectively. These layer charge values are higher than the mean layer charge values determined by the alkylammonium method which is typical according to Laird et al. (1987, 1989). The chemical analyses indicate that the smectite in the Btg horizon of the Mollisol is an iron rich beidellite. From the XRD patterns of the Btg sample (Figure 3.1), the presence of randomly interstratified smectite and clay mica is evident. The presence of a small amount of mica in the fine clay fractions suggests the presence of unweathered mica, and that the smectite present might have been the

weathering product of mica. The layer charge values (0.41 and 0.43) determined by the alkylammonium method fall below the range (0.46 - 0.57) classified by Malla and Douglas (1987) based on re-expansion properties. However, the layer charge values determined from the structural formula fall within the range estimated by the re-expansion properties. The layer charge value 0.47 determined from the structural formula of the Spodosol fine clay is similar to the value of 0.49 obtained by Ross and Mortland (1966).

The structural formulas, the re-expansion properties, the Greene-Kelly test, and the b-dimension value indicate that both smectites are beidellitic dioctahedral phyllosilicates. Smectite formation in the Spodosols is attributed to high leaching environment, low pH and high organic matter in the surface horizon. Below pH 4.5, Al is complexed by organic matter and hence the Al is not available in large amounts for the formation of polymers (Douglas, 1982). The high octahedral iron content in the fine clay of the Brookston Btg sample is similar to a tetrahedrally-charged illite. The oxidation of structural iron might have been one of the primary mechanism of layer charge reduction during weathering. A dioctahedral mica will always transform to a high-charge smectite, and the occurrence of a high-charge smectite is associated with dioctahedral mica (Egashira and Tsuda, 1983). The alteration of mica has probably occurred without a significant change in the tetrahedral sheet substitution (Badraoui et al., 1987). Vermiculite is the intermediate product in the transformation process, as shown in the total clay mineralogy and the weathering of mica to smectite might have occurred prior to deposition. Ross and Mortland (1966) concluded that soil mica in a Spodosol weathered to beidellite. However, weathering of chlorite, present in the total clay, may also have been a source for some of the smectites found in these samples. Robert (1973) pointed out that smectites derived from mica will inherit characteristics of mica such as K fixation, and suggested the need to differentiate them from smectites found in geological deposits or formed by crystallization in the soil environment. Soils dominated by beidellite will fix K more readily than montmorillonitic soils (Ross and Mortland, 1966; Badraoui et al., 1987). As a result, identification of the right clay mineral is important to understand the dynamics of K in respect to the clay mineral present.

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LIST OF REFERENCES

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SUMMARY CONCLUSION

The sand, silt, and clay mineralogy of the two fine-loamy hydrosequences of south-central Michigan suggest the glacial till parent material is relatively uniform. Depth and duration of water tables were similar for soils with the same natural drainage class. Having similar parent material, vegetation, climate, and time, topography has produced some noticeable differences in distribution of minerals among and within profiles. Weathering of muscovite/sericite to smectite (beidellite) through interstratified vermiculite-smectite seems to be the dominant trend in the poorly drained Brookston pedon whereas direct transformation to vermiculite is the prevalent weathering mechanism in the other drainage classes. Except for the smectite in the Brookston pedon, the fine-loamy soils in this study do not show significant differences in sand, silt, and clay mineralogies with respect to natural drainage.

The Spodosol hydrosequences in Michigan are very low in weatherable minerals. The sand mineralogy is dominated by quartz followed by small amounts of feldspar and sericite. The silt fraction is devoid of weatherable minerals including sericite. It is dominantly composed of quartz and small amounts of feldspar. Differences in drainage does not indicate a particular distribution of sand and silt minerals.

The clay mineral distribution indicates the parent material is composed of chlorite, mica, kaolinite and small amounts of vermiculite. Smectite (dioctahedral beidellite) is the dominant layer silicate found in the E horizons of all pedons. The intensity of smectite peak and the presence and absence of vermiculite in the E horizons, suggest increasing weathering intensities from poorly drained to well drained soils in these hydrosequences. Based on the clay mineral distribution of the total clay fraction the following weathering sequence is observed: Sericite/muscovite → vermiculite → smectite, with or without mixed-layer formation.

The structural formula, the re-expansion property, the Greene-Kelly test, and (060) XRD pattern indicate the smectite in the fine clay fractions of the Spodosol E and Mollisol Btg horizons are both dioctahedral phyllosilicates of beidellitic phase which is dominated by tetrahedral charge. The high octahedral iron content in the fine clay of the Btg horizon is similar to a tetrahedrally charged illite, and it seems the oxidation of structural iron might have been one of the primary mechanisms of layer charge reduction during weathering. Weathering of mica to smectite might have occurred prior to deposition. According to the

structural formula, these soil smectites have a layer charge of 0.47 and 0.51 molc per half unit cell formula for the E and Btg samples, respectively. These layer charge values are higher than the mean layer charge values determined by the alkylammonium method.

APPENDIX A

PEDON DESCRIPTIONS

Soil code : M1

Sampled as: Glossoboric Hapludalf, fine-loamy, mixed, mesic.

Classification: Essex Township, Clinton county, NE 1/4 NW 1/4 NW 1/4 NW 1/4 NE 1/4 sec. 15 about 23 m south of Island Road, T. 8 N., R. 3 W.

Geomorphic position: Summit position on moraine system, gently sloping.

Drainage: Moderately well drained.

Vegetation: Acer Saccharum, Tilia americana, and Quercus rubra.

Parent material: Calcareous glacial till.

Sampled by: D. Cremeens and O. Doumbia. July 1, 1981.

Remarks: C2 sample collected with bucket auger. Thin lens (1 cm thick) of strong brown (7.5YR 4/6) loamy sand found at 85 cm depth. Less than 2% coarse fragments throughout pedon.

- A 0-12 cm. Dark grayish brown (10YR 4/2) silt loam (26% sand, 14% clay); moderate medium granular structure; friable; abrupt wavy boundary.
- E/B 12-26 cm. Yellow brown (10YR 5/6) and brownish yellow (10YR 6/6) silt loam (22% sand, 18% clay); weak medium platy structure parting to moderate medium subangular blocky; friable; clear wavy boundary.
- Bt1 26-40 cm. Dark yellow brown (10YR 4/4) silty clay loam (13% sand, 31% clay); moderate medium subangular blocky structure; firm; thin patchy dark grayish brown (10YR 4/2) clay films; gradual smooth boundary.
- Bt2 40-84 cm. Dark yellowish brown (10YR 4/4) silty clay loam (15% sand, 31% clay); moderate medium angular blocky structure; firm; few fine faint yellowish brown (10YR 5/4) mottles; thick continuous dark grayish brown (10YR 4/2) clay films; clear wavy boundary.
- BC 84-108 cm. Dark yellowish brown (10YR 4/4) silt loam (17% sand, 26% clay); strong coarse platy structure parting to moderate medium angular blocky; firm; few medium faint yellowish brown (10YR 5/4) mottles; thick continuous dark grayish brown (10YR 4/2) clay films; moderately effervescent; clear wavy boundary.
- C1 108-165 cm. Grayish brown (10YR 5/2) silt loam (16% sand, 22% clay); strong coarse platy structure parting to moderate medium subangular blocky; very firm; few medium faint yellowish brown (10YR 5/4) mottles; strongly effervescent.
- C2 165+ cm. Brown (10YR 5/3) silt loam (15% sand, 23% clay); very firm; common fine faint yellowish brown (10YR 5/4) mottles; strongly effervescent.

Soil code: C1

Sampled as: Capac, Aerio Ochraqualf, fine-loamy, mixed, mesic.

Classification: Aerio Haplaquept, coarse-loamy, mixed, mesic.

Location: Essex Township, Clinton County, MI. NW1/4NW1/4NE1/4NE1/4NW1/4
sec.15 about 30 m south of Island Road, T. 8 N., R. 3 W.

Geomorphic position: Foot slope position on moraine system, gently sloping.

Drainage: Somewhat poorly drained.

Vegetation: Acer rubrum, Acer saccharum, Quercus rubra, and Carva ovata.

Parent material: Calcareous glacial till.

Sampled by: D. Cremeens. July 2, 1981.

Remarks: A horizon could have been divided in to A1 and A2 based on size of structural units. Augered to approximately 2.5 m no C2 horizon detected. water table at 1.8 m. About 10% coarse fragments throughout pedon except BC which contained slightly more and 2C which contained approximately 5%.

- A 0-22 cm. Very dark gray (10YR 3/1, 10YR 5/2) loam (42 % sand, 19% clay); moderate medium granular structure; friable; clear wavy boundary.
- B/E 22-32 cm. Brown (10YR 5/3) and light yellowish brown (10YR 6/4) sandy loam (54 % sand, 13% clay); weak fine subangular blocky structure; friable; few fine faint mottles; clear smooth boundary.
- Bt1 32-53 cm. Brown (10YR 5/3) loam (49 % sand, 18 % clay); moderate medium angular blocky structure; firm; moderate medium distinct strong brown (7.5YR 4/4) and few medium faint grayish brown (10YR 5/2) mottles; medium continuous dark brown (7.5YR 4/2) clay films; clear wavy boundary.
- Bt2 53-97 cm. Dark grayish brown (2.5Y 4/2) loam (48 % sand, 16 % clay); moderate medium subangular blocky structure; friable; common medium distinct strong brown (7.5YR 4/4) and few medium distinct brown (10YR 5/3) mottles; medium discontinuous grayish brown (10YR 5/2) clay films; gradual smooth boundary.
- BC 97-125 cm. Dark grayish brown (2.5Y 4/2) sandy loam (57 % sand, 14 % clay); weak medium subangular blocky structure; friable; many medium prominent strong brown (7.5YR 5/6) and common fine distinct gray (N 5/0) mottles; thin discontinuous grayish brown (10YR 5/2) lining root channels; gradual smooth boundary.
- 2C 125 + cm. Olive brown (2.5Y 4/4) silt loam (28 % sand, 19 % clay); moderate coarse platy structure breaking to weak coarse angular blocky; firm; common coarse distinct gray (N 5/0) and many fine distinct dark yellowish brown (10YR 4/6) mottles; moderately effervescent.

Soil code : P1

Sampled as: Parkhill, Mollic Haplaquept, fine-loamy, mixed, mesic.

Classification: Humic Haplaquept, fine-loamy, mixed, mesic.

Location: Essex Township, Clinton County, NE1/4 NE1/4 NW1/4 NE1/4 NW1/4 sec.
15 about 38 m south of Island Road, T. 8 N., R. 3 W.

Geomorphic position: Toe slope position on moraine system, nearly level.

Drainage: Poorly drained.

Vegetation: Fraxinus americana, Quercus alba, Quercus bicolor, and Cyperus esculentus.

Parent material: Non calcareous glacial till.

Sampled by: D. Cremeens and G. Lemme. July 3, 1981.

Remarks: No carbonates detected down to 2.4 m. C horizon delineated due to structureless condition. Approximately 5-10% coarse fragments throughout pedon.

- A 0-23 cm. Very dark grayish brown (10YR 3/2, 10YR 5/1 dry) silt loam (19 % sand, 25 % clay); strong very fine subangular blocky structure; firm; clear smooth boundary.
- Bg1 23-53 cm. Dark gray (5Y 4/1) loam (36 % sand, 21% clay); moderate fine subangular blocky structure; firm; few fine distinct brown (10YR 4/3) and few fine prominent yellowish red (5YR 4/6) mottles; clear wavy boundary.
- Bg2 53-91 cm. Gray (5Y 5/1) loam (38 % sand, 21% clay); moderate medium subangular blocky structure parting to moderate fine subangular blocky; common fine prominent strong brown (7.5YR 5/6) mottles; gradual wavy boundary.
- C 91 + cm. Dark grayish brown (2.5Y 4/2) loam (39 % sand, 24 % clay); structureless, massive; firm; common medium distinct brown (10YR 5/3) and strong brown (7.5YR 5/6) mottles with gray (N 6/0) coatings along root channels.

Soil Code: M2

Sampled as: Marlette

Classification: Fine-loamy, mixed, mesic Glossoboric Hapludalf

Location: Ronald Township, Ionia County, MI. S. NE 1/4 of NW 1/4 of NW 1/4 of Sec. 3, T. 8 N., R. 6 W.

Physiographic position: Glacial till plain

Topography: 3 percent slope, NE aspect; linear across slope and convex down slope

Elevation: 253 m (4 m above soil I-FL-L)

Distance from low member of catena: 250 m W

MAST: 9.8 °C (mean air temperature 0.4 °C above normal)

Drainage: Well drained

Vegetation: Forest. White oak (Quercus alba L.), pin oak (Quercus palustris Muenchh.), and big shellbark hickory (Carya lacinosa (Michx. f.) Loud.)

Parent material: Glacial till

Sampled by: D. Cremeens, O. Doumbia, and L. Gloden; 8 July 1981.

- A 0-12 cm. Dark grayish brown (10YR 4/2) loam; moderate medium granular structure; friable; strongly acid; clear wavy boundary.
- B/E 12-32 cm. Dark brown (7.5YR 4/4) and grayish brown (10YR 5/2) loam; weak medium platy structure parting to moderate fine subangular blocky; friable; strongly acid; clear wavy boundary.
- Bt1 32-48 cm. Strong brown (7.5YR 4/6) loam; thin discontinuous dark brown (10YR 4/3) clay skins; strong fine subangular blocky structure; friable; strongly acid; clear wavy boundary.
- Bt2 48-86 cm. Brown (7.5YR 5/4) loam; thick continuous dark brown (7.5YR 4/3) clay skins; moderate medium subangular blocky; firm; neutral; clear wavy boundary.
- BC 86-127 cm. Brown (10YR 5/3) silt loam; thin discontinuous dark brown (7.5YR 3/4) clay skins; strong medium platy structure parting to moderate medium angular blocky; friable; few fine roots; moderately alkaline; clear wavy boundary.
- C 127+ cm. Dark brown (10YR 4/3) loam; few fine distinct yellowish red (5YR 5/6) mottles; strong coarse platy structure parting to moderate coarse angular blocky; friable; moderately alkaline.

Soil Code: C2

Sampled as: Capac

Classification: Fine-loamy, mixed, mesic Udollic Ochraqualf

Location: Ronald Township, Ionia County, MI. NE 1/4 of NE 1/4 of NW 1/4 of Sec. 3, T. 8 N., R. 6 W.

Physiographic position: Glacial till plain

Topography: <1 percent slope, W. aspect; linear across and down slope

Elevation: 250 m (1.5 m above soil I-FL-L)

Distance from low member of catena: 150 m E

MAST: 9.8 °C (mean air temperature 0.4 °C above normal)

Drainage: Somewhat poorly drained

Vegetation: Forest. Bitternut (Carya cordiformis (Wang.) K. Koch.), shagbark hickory (Carya ovata (Mill.) K. Koch.), white oak (Quercus alba L.), quaking aspen (Populus tremuloides Michx.).

Parent material: Glacial till.

Sampled by: D.Cremeens, and O.Doumbia, 8 July 1981; mottle organization sampled and described by S.W.Sprecher and D.L.Mokma, 12 August 1986.

- A 0-17 cm. Very dark gray (10YR 3/1) sandy loam; moderate fine granular structure; friable; medium acid; abrupt wavy boundary.
- B/E 17-33 cm. Dark yellowish brown (10YR 4/4) loam and brown (10YR 5/3) loam; many coarse prominent yellowish brown (10YR 5/6) and common coarse faint (10YR 5/3) mottles; thin discontinuous dark grayish brown (10YR 4/2) clay skins in root channels in bottom of horizon; moderate fine subangular blocky structure; friable; acid; clear wavy boundary.
- Bt 33-58 cm. Dark yellowish brown (10YR 4/4) loam; thin discontinuous dark grayish brown (10YR 4/2) clay skins; common fine distinct grayish brown (2.5Y 5/2) and common medium distinct strong brown (7.5YR 4/6) mottles; moderate fine subangular blocky structure; firm; slightly acid; clear wavy boundary.
- Btg 58-85 cm. Grayish brown (2.5Y 5/2) loam; thick discontinuous dark grayish brown (10YR 4/2) clay skins; common medium distinct dark yellowish brown (10YR 4/4) and common fine distinct grayish brown (10YR 5/2) mottles; moderate medium subangular blocky structure; firm; neutral; clear wavy boundary.
- BC 85-160 cm. Yellowish brown (10YR 5/6) sandy loam; thin patchy reddish brown (5YR 5/4) clay skins; many fine distinct gray (10YR 6/1) mottles (some as weakly developed neoalbans) and common medium distinct reddish brown (5YR 5/4) mottles (mainly ped interiors); weak coarse angular blocky structure; friable; moderately alkaline; clear smooth boundary.
- C 160+ cm. Pale brown (10YR 6/3) loam; moderate medium faint gray (10YR 6/1) and few coarse distinct dark brown (7.5YR 4/4) mottles; friable; moderately alkaline.

Soil Code: B2

Sampled as: Brookston

Classification: Fine-loamy, mixed, mesic Typic Argiaquoll

Location: Ronald Township, Ionia County, MI NE 1/4 of NE 1/4 of NW 1/4 of Sec. 3,
T. 8 N., R. 6 W.

Physiographic position: Glacial till plain

Topography: <1 percent slope; concave across and down slope

Elevation: 248 m

MAST: 9.9 °C (mean air temperature 0.4 °C above normal)

Drainage: Poorly drained

Vegetation: Forest. Sugar maple (Acer saccharum Marsh.), slippery elm (Ulmus rubra Muhl.), basswood (Tilia americana L.).

Parent material: Glacial till

Sampled by: D. L. Cremeens, 3 Sept. 1981; mottle organization sampled and described by S.W. Sprecher and D.L. Mokma, 12 August 1986.

- A 0-25 cm. Black (10YR 2/1) and dark gray (10YR 4/1) sandy loam; moderate medium granular structure; friable; slightly acid; abrupt wavy boundary.
- BA 25-40 cm. Dark gray (10YR 4/1) sandy loam; few fine distinct dark grayish brown (10YR 4/2) mottles and common fine distinct strong brown (7.5YR 4/6) mottles organized as channel and ped ferrans; moderate fine subangular blocky structure; friable; neutral; clear smooth boundary.
- Btg 40-58 cm. Olive gray (5Y 5/2) loam; common medium distinct yellowish brown (10YR 5/4) and common fine distinct strong brown (7.5YR 5/6) mottles (weakly developed ferrans); medium discontinuous gray (N 5/0) clay skins; weak medium subangular blocky structure parting to moderate fine subangular blocky; friable; neutral; clear smooth boundary.
- Btg 58-95 cm. Gray (5Y 5/1) loam; few fine distinct dark yellowish brown (10YR 4/4) mottles; medium discontinuous gray (N 5/0) clay skins; weak coarse prismatic structure parting to moderate medium subangular blocky; friable; neutral; gradual wavy boundary.
- BC 95-170 cm. Gray (5Y 5/1) sandy loam; thin discontinuous olive gray (5Y 5/2) clay skins; many fine prominent strong brown (7.5YR 5/6) mottles; weak fine subangular blocky structure; friable; mildly alkaline; clear wavy boundary.
- C 170+ cm. Dark yellowish brown (10YR 4/4) loam; common medium distinct gray (N 5/0) mottles; massive; firm; moderately alkaline.

Soil Code: B-S-H

Sampled as: Rubicon (mesic taxadjunct)

Classification: Sandy, mixed, mesic Entic Haplorthod

Location: Inverness Township, Cheboygan County, MI. NW 1/4 of NW 1/4 of SW
1/4 of Sec. 14, T. 37 N., R. 2 W.

Physiographic position: Glacial outwash plain

Topography: 5 percent slope, NE aspect; concave across and down slope

Elevation: 209 m (2.2 m above soil B-S-L)

Distance from low member of catena: 49 m S

MAST: 8.2 °C (mean air temperature 0.1 °C below normal)

Drainage: Well drained

Vegetation: Forest. Red maple (Acer rubrum L.), Eastern hemlock (Tsuga canadensis (L.) Carr), yellow birch (Betula lutea Michx. f.), bracken fern (Pteridium aquilinum (L.) Kuhn), tree clubmoss (Lycopodium obscurum L.), Clintonia (Clintonia borealis (Ait.) Raf.), starflower (Trientalis borealis Raf.)

Parent material: Sandy glacial drift

Sampled by: S.W.Sprecher, D.L.Mokma, and S.Haile-Mariam; 20 Aug.1985.

- A 0-10 cm. Black (10YR 2/1) sand; moderate medium granular structure; very friable; many very fine and fine and few medium and coarse roots; medium acid; abrupt smooth boundary.
- E 10-34 cm. Grayish brown (10YR 5/2) sand; single grain structure; loose; few roots; strongly acid; abrupt wavy boundary.
- Bs1 34-50 cm, tongues penetrating to 84 cm. Yellowish red (5YR 5/8) sand; patches of dark reddish brown (5YR 2/2) weakly cemented ortstein; weak coarse subangular blocky structure; very friable; cracked coatings on sand grains; few fine medium and coarse roots; strongly acid; clear irregular boundary.
- Bs2 50-113 cm. Strong brown (7.5YR 4/6) sand; weak medium subangular blocky structure; very friable; cracked coatings on sand grains; few fine roots; strongly acid; gradual wavy boundary.
- C1 113-153 cm. Yellowish brown (10YR 5/6) sand; common fine distinct dark yellowish brown (10YR 3/4) mottles; moderate coarse subangular blocky structure; very friable; strongly acid; clear wavy boundary.
- C2 153-175 cm. Yellowish brown (10YR 5/8) sand; single grain structure; loose.

Soil Code: B-S-M

Sampled as: Au Gres (mesic taxadjunct)

Classification: Sandy, mixed, mesic Entic Haplaquod

Location: Inverness Township, Cheboygan County, MI. NW 1/4 of NW 1/4 of SW 1/4 of Sec. 14, T. 37 N., R. 2 W.

Physiographic position: Glacial outwash plain

Topography: 3 percent slope, SE aspect; linear across slope and convex down slope

Elevation: 208 m (0.6 m above soil B-S-L)

Distance from low member of catena: 21 m S

MAST: 8.3 °C (mean air temperature 0.1 °C below normal)

Drainage: Somewhat poorly drained

Vegetation: Forest. Red pine (Pinus resinosa Ait.), red maple (Acer rubrum L.), Eastern hemlock (Tsuga canadensis (L.) Carr), yellow birch (Betula lutea Michx. f.), bracken fern (Pteridium aquilinum (L.) Kuhn)

Parent material: Sandy glacial drift

Sampled by: S. W. Sprecher and S. Haile-Mariam; 4 July 1985.

- Oi 8-0 cm. Very dark brown (10YR 2/2) partially decomposed leaf litter; moderate coarse platy structure parting to moderate coarse granular; friable; few medium and coarse roots; very strongly acid; abrupt wavy boundary.
- E 0-31 cm. Light gray (10YR 7/1) sand; many medium distinct light brownish gray (10YR 6/2) mottles; weak coarse subangular blocky structure; very friable; few very fine and common fine roots; very strongly acid; abrupt wavy boundary.
- Bs1 31-45 cm. Strong brown (7.5YR 5/6) sand; few medium distinct dark brown (7.5YR 3/4) and few medium fine light yellowish brown (2.5Y 6/4) mottles; weak coarse subangular blocky structure in discontinuous strong brown (7.5YR 4/6) ortstein; cracked coatings on sand grains; very firm; few very fine and fine roots; very strongly acid; clear broken boundary.
- Bs2 45-66 cm. Dark reddish brown (5YR 3/4) and strong brown (7.5YR 4/6) sand; weak coarse subangular blocky structure; firm; cracked coatings on sand grains; few fine roots; very strongly acid; clear wavy boundary.
- BC 66-85 cm. Dark brown (7.5YR 4/4) sand; common coarse distinct yellowish brown (10YR 5/4) mottles; weak medium subangular blocky structure; very friable; strongly acid; clear wavy boundary.
- C 85-150 cm. Yellowish brown (10YR 5/4) sand; single grain structure; loose; strongly acid.

B-S-L

Sampled as : Kinross (mesic taxadjunct)

Classification : Sandy, mixed, mesic Entic Haplaquod.

Location : Inverness Township, Cheboygan County, MI.

NW 1/4 NW 1/4 SW 1/4 Sec. 14, T. 37 N., R. 2 W.

Physiographic position : Glacial outwash plain

Topography : 0 % slope; concave across and down slope

Elevation : 207 m

MAST : 8.8 °C (mean air temperature 0.1 °C below normal)

Drainage : Poorly drained

Vegetation : Forest. Red maple (Acer rubrum L.), Eastern Hemlock (Tsuga canadensis (L.) Carr.); paperbirch (Betula papyrifera Marsha.), bracken fern (Pteridium aquilinum (L.) Kuhn), bunchberry (Cornus canadensis L.), staghorn clubmoss (Lycopodium clavatum L.), star flower (Trientalis borealis Raf.)

Parent material : Sandy glacial drift

Sampled by : S. W. Sprecher, D. L. Mokma, and S. Haile-Mariam; 20 August 1985.

- Oa 8-0 cm. Very dark brown (10YR 2/2) organic matter; moderate medium platy structure; very strongly acid; abrupt smooth boundary.
- E 0-18 cm. Light gray (10YR 7/1) sand; single grain structure; loose; common fine and few medium roots; very strongly acid; abrupt wavy boundary.
- Bs 18-50 cm. Strong brown (7.5YR 5/6) and yellowish red (5YR 4/6) sand; common medium distinct dark brown (7.5YR 4/6) mottles; weak coarse subangular blocky structure; friable; cracked coatings on sand grains; few medium roots; strongly acid; gradual wavy boundary.
- C 50-125 cm. Brown (10YR 5/3) sand; single grain structure; loose; strongly acid.

Soil Code: P-S-H

Sampled as: Liminga

Classification: Sandy, mixed, frigid Typic Haplorthod

Location: Munuscong State Forest, Chippewa County, Michigan. NE 1/4 of NW 1/4 of NE 1/4 of Sec. 20, T. 45 N., R. 1 W.

Physiographic position: Glacial outwash plain

Topography: 15 percent slope, SE aspect; convex across and down slope

Elevation: 224 m (1.6 m above soil P-S-L)

Distance from low member of catena: 30 m E

MAST: 8.3 °C (mean air temperature 1.1 °C above normal)

Drainage: Well drained

Vegetation: Forest. Red maple (Acer rubrum L.), Eastern hemlock (Tsuga canadensis (L.) Carr.), quaking aspen (Populus tremuloides Michx.), bracken fern (Pteridium aquilinum L.), bunchberry (Cornus canadensis L.), wintergreen (Pyrola secunda L.).

Parent material: Sandy glacial drift

Sampled by: S.W.Sprecher, D.L.Mokma, and S.Haile-Mariam; 20 Aug. 1985

A 0-7 cm. Black (N 2/0) fine sand; weak medium granular structure; very friable; many fine roots; extremely acid; clear wavy boundary.

E 7-11 cm. Brown (7.5YR 5/2) fine sand; weak medium platy structure; very friable; extremely acid; clear irregular boundary.

Bhs 11-22 cm, tonguing to 97 cm. Dark reddish brown (5YR 3/2) fine sand; many coarse prominent strong brown (7.5YR 4/6) mottles; very firm; discontinuous ortstein; cracked coatings on sand grains; extremely acid; clear irregular boundary.

Bs 22-63 cm. Strong brown (7.5YR 4/6) fine sand; firm; cracked coatings on sand grains; extremely acid; diffuse irregular boundary.

C 63-192 cm. Yellowish brown (10YR 5/4) fine sand; single grain structure with broken patches of weak medium subangular blocky material in upper 10 cm; loose; strongly acid.

Soil Code: P-S-M

Sampled as: Wainola

Classification: Sandy, mixed, frigid Entic Haplaquod

Location: Munuscong State Forest, Chippewa County, Michigan. NE 1/4 of NW 1/4 of NE 1/4 of Sec. 20, T. 45 N., R. 1 W.

Physiographic position: Glacial outwash plain

Topography: 1 percent slope, N aspect; linear across slope, concave down slope

Elevation: 223 m (0.5 m above soil P-S-L)

Distance from low member of catena: 24 m W

MAST: 7.8 °C (mean air temperature 1.1 °C above normal)

Drainage: Somewhat poorly drained

Vegetation: Forest. Red maple (*Acer rubrum* L.), Eastern hemlock (*Tsuga canadensis* (L.) Carr.), black spruce (*Picea mariana* (Mill.) BSP.), bracken fern (*Pteridium aquilinum* L.), bunchberry (*Cornus canadensis* L.), tree clubmoss (*Lycopodium obscurum* L.), starflower (*Trientalis borealis* Raf), wintergreen (*Pyrola secunda* L.).

Parent material: Sandy glacial drift

Sampled by: S. W. Sprecher, D. L. Mokma, and S. Haile-Mariam; 20 Aug. 1985

- Oi 7-0 cm. Black (N 2/0) fibric organic materials mixed with fine sand; weak medium granular structure; friable; many very fine and fine roots and common medium roots; very strongly acid; abrupt wavy boundary.
- E 0-15 cm. Light gray (7.5YR 6/1) fine sand; weak medium platy structure extremely acid; abrupt wavy boundary.
- Bhs 15-43 cm. Dark brown (7.5YR 3/2) and brown (7.5YR 4/4) fine sand; common medium distinct dark brown (10YR 4/3) mottles; weak medium subangular blocky structure; pockets of weakly cemented ortstein; cracked coatings on sand grains; firm; common fine and medium roots; very strongly acid; abrupt irregular boundary.
- BC 43-77 cm. Yellowish brown (10YR 5/8) fine sand; common fine distinct very dark gray (10YR 3/1) streaks; weak coarse platy structure parting to weak medium subangular blocky; friable; few fine and medium roots; very strongly acid; gradual wavy boundary.
- C 77-118 cm. Dark yellowish brown (10YR 4/6) fine sand; few fine distinct light brownish gray (10YR 6/2) and common medium distinct strong brown (7.5YR 5/6) mottles; weak coarse platy structure; very friable; strongly acid.

Soil Code: P-S-L

Sampled as: Kinross

Classification: Sandy, mixed, frigid Aeric Haplaquod

Location: Munuscong State Forest, Chippewa County, Michigan. NE 1/4 of NW 1/4 of NE 1/4 of Sec. 20, T. 45 N., R. 1 W.

Physiographic position: Glacial outwash plain

Topography: 1/2 percent slope, N. aspect; linear across slope, concave down slope

Elevation: 222 m

MAST: 8.4 °C (mean air temperature 1.1 °C above normal)

Drainage: Poorly drained

Vegetation: Forest. Red maple (Acer rubrum L.), Eastern hemlock (Tsuga canadensis (L.) Carr.), cinnamon fern (Osmunda cinnamomea L.), bunchberry (Cornus canadensis L.), clubmosses (Lycopodium L. spp.), starflower (Trientalis borealis Raf), mosses.

Parent material: Sandy glacial drift

Sampled by: S.W.Sprecher, D.L.Mokma, and S.Haile-Mariam; 20 Aug.1985

- Oa 0-10 cm. Black (N 2/0) and very dark brown (10YR 2/2) decomposed organic matter; moderate very coarse platy structure parting to moderate fine platy; very friable; many roots; extremely acid; abrupt wavy boundary.
- E 0-8 cm. Gray (5Y 6/1) loamy fine sand; common coarse distinct light brownish gray (10YR 6/2) mottles; weak very coarse platy structure; very friable; few roots; very strongly acid; abrupt wavy boundary.
- Bhs 8-19 cm. Dark brown (7.5YR 3/2) loamy fine sand; common medium faint grayishbrown (10YR 5/2) mottles; weak medium subangular blocky structure; few fine roots; very friable; cracked coatings on sand grains; very strongly acid; clear broken boundary.
- Bg 19-34 cm. Light brownish gray (2.5Y 6/2) loamy fine sand; common medium faint grayish brown (10YR 5/2) mottles; weak medium subangular blocky structure; few fine roots; very friable; very strongly acid; clear broken boundary.
- C 34-56 cm. Dark brown (7.5YR 4/4) fine sand; common fine distinct dark gray (10YR 4/1) and strong brown (7.5YR 5/6) mottles; single grain structure; loose; strongly acid.