A CHRONOSEQUENCE OF PODZOLS IN NORTHERN MICHIGAN

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ABSTRACT

A CHRONOSEQUENCE OF PODZOLS IN NORTHERN MICHIGAN

by Donald Paul Franzmeier

The retreat of the last glacier and a series of fluctuations of the level of the glacial Great Lakes during crustal uplift has resulted in surfaces of different ages in the northern tip of the southern peninsula of Michigan. The surfaces are named according to the glacial stage or lake stage that resulted in their deposition. Four such surfaces have been recognized and dated by geologists. They are Algoma, 2250; Nipissing, 3000; Algonquin, 8000; and Valders, 10,000 years old. A chronosequence of soils--a sequence in which four of the groups of soil-forming factors, parent material, climate, organisms, and relief are the same and only the fifth factor, time, differs--has been formed on these surfaces of different ages. The chronosequence selected for study consists of a series of Podzols developed from sand-textured parent materials. The soil series, with their horizon sequences in parentheses, are: Eastport (A1, A2, B(ir), B3, C) on the Algoma, Rubicon (A1, A2, Bir, B3, C) on the Nipissing, Kalkaska (A1, A2, Bhm, Bhir, B3, C) on the Algonquin, and two Blue Lake soils (A1, A2, Bh, Bhir, B3, A'2, Bt, C) on the Valders age surfaces.

Physical, chemical, and mineralogical properties of the five soils are presented as functions of depth and kind of horizon. Net changes in the volume and weight of the sola are calculated assuming that quartz is virtually constant in the original material and is resistant to weathering. Similarly calculated net changes of several constituents

in soil formation are presented as functions of time. Micromorphological observations are used to synthesize the results of chemical, physical, and mineralogical analyses, to give a picture of the oldest soil's genesis.

Early in the formation of these Podzols carbonates and basic cations are leached from the solum. Acid groups originating from the tissues of the flora and fauna of the ecosystem percolate through the soil causing the surface mineral soil to become acid, resulting in a pH gradient between the A and B horizons. This pH gradient makes it possible for some phosphates to be mobilized in the A horizons and immobilized in the B horizons of the soils. The migration of extractable phosphorus marks the beginning of a stage of soil formation in which the differentiation of inorganic substances into horizons of maxima and minima contents are conspicuous according to chemical analyses and observation of thin sections. The next stage in the formation of these Podzols is the differentiation of humus into horizons, conspicuous in field observations, laboratory analyses, and microscopic observations. During this stage inorganic substances are also segregated. While these two stages are occurring, the continuous processes of chemical and physical weathering of soil minerals and mineral synthesis have had their effect on soil properties. Silt-size minerals are formed from the disintegration of sand grains. Clay is continually being formed, and chlorite and illite weather to montmorillonite, possibly through a vermiculite stage.

After the clay content of the profile reaches a threshold point and after the Podzol sequum is well developed, a Gray Wooded sequum, consisting of an eluvial A'2 and a textural B horizon, develops below the Podzol sequum.

The end members of the chronosequence contain more silt, clay, organic carbon, total nitrogen, total exchangeable bases, and extractable phosphorus, iron and aluminum, and have a greater cation exchange

capacity, capillary pore space, and available water capacity than do the materials from which they were formed. Slopes of the time functions of some constituents change sign during the time interval studied, e.g., extractable phosphorus, aluminum, and iron, and the difference in pH between the podzol A2 and B horizons. Constituents such as carbonates, fine sand, diopside and "chlorite" show a continual decrease with time of soil formation.

The classification of these soils according to the recently proposed comprehensive system is: Eastport and Rubicon, Spodic Orthopsamments; Kalkaska, Entic Typorthod; Blue Lakes, Alfic Typorthod and Ultic Typorthod. It is suggested that the definition of the spodic horizon be changed to include Podzols such as Eastport and Rubicon in the Spodosol order.

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By

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TABLE OF CONTENTS

continued

TABLE OF CONTENTS - Continued

CHAPTER Page

LIST OF TABLES

continued

LIST OF FIGURES

LIST OF FIGURES - Continued

FIGURE Page

LIST OF PLATES

I. INTRODUCTION

According to Jenny (1941, 1946), a soil system is defined when its properties, s_1, s_2, s_3, . . . s_n, are stated. Since these properties are functionally interrelated, if a sufficient number are fixed, all others are fixed. The properties capable of defining the system are the independent variables or soil-forming factors. Five are recognized: climate, (cl'), organisms (o'), topography (r'), parent material (p), and time (t). The first three variables are properties of the soil coupled with those of the environment and can therefore be replaced by their environmental counterparts, cl, o, and r. The fundamental relationship between a soil property and the soil-forming factors is then expressed as:

$$s = f\ (cl,\ o,\ r,\ p,\ t \ldots)$$

To ascertain the role played by any one soil-forming factor it is necessary that the remaining factors remain constant. For instance, in a chronosequence of soils, time is the only variable factor and the relation of time to a soil property is:

$$s = f\ (t)_{cl,\ o,\ r,\ p}$$

A chronosequence of soils cannot be created artificially in the laboratory. They occur naturally only under certain sets of geologic conditions. One such set of conditions is present in northern Michigan (Spurr and Zumberge, 1956). Here the retreat of the last glacier and associated fluctuations of the levels of the glacial Great Lakes combined with crustal up-warping has resulted in a sequence of surfaces ranging in age from about 10,000 years before present to those being formed today.

In this study the relation of time to a number of the more important soil properties defining a soil system will be examined. Emphasis will be placed on properties of pedons (Soil Survey Staff, 1960) such as the distribution of clay in the profile or net changes in the solum(method of Marshall and Haseman, 1942) rather than on properties of a single soil horizon such as its percent clay.

II. LITERATURE REVIEW

Podzols and Podzolization

Dokuchaiev is commonly given credit for first applying the name Podzol to a certain group of soils (Muir, 1961). The term as originally used referred to "the infertile layer of soil, gravel, sand or heavy clay, which underlay the ashes resulting from burning the forest cuttings." Use of the term Podzol, in its early stages, was confined to the bleached horizon or A2 as it is now commonly designated in the United States.

German workers had recognized and described horizons of soils later to be known as Podzols at an earlier date, however. Sprengel called the bleached horizon "Bleisand" around 1837 and Senft in 1862 described a German Podzol as having an "Ortstein" layer beneath the bleached layer (Muir, 1961). Later in Germany, the Bleisand was taken as equivalent to the Russian Podzol except that the German concept was limited to the sandier soils in which an Ortstein layer was formed. The German concept of Podzols (Bleisand plus Orstein) was carried to the United States by Marbut. In this country typical Podzols occur on only the coarser textured parent materials according to Byers et al. (1938, p. 972).

In Canada the process of podzolization is generally thought of as the process leading to the development of a Podzol (Stobbe and Wright, 1959). When a formal definition of the process has been given, it has usually been in terms of the end product or it has enumerated the specific processes involved. In either case, the definition of podzolization depends on the definer's concept of the end product. Most definitions include or imply the mobilization of iron and usually aluminum in the surface horizons by an organic material, the downward translocation of the products formed, and their immobilization in a lower horizon resulting in a horizon of accumulation of humus, iron, and/or aluminum.

Use of the term podzolization more generally in referring to the formation of both Podzol soils and podzolic soils (Gray-Brown and Red-Yellow) has led to discrepencies among different people in the definition and use of the term. Recent views in North America seem to be that translocation of silicate clay minerals is not an essential process in the formation of Podzols (Soil Survey Staff, 1960; Stobbe and Wright, 1959). However, in the older, more general concept associated with podzolic soils in the United States, clay translocation is a part of the process (Byers et al., 1938). To distinguish between the two kinds of processes here, podzolization will refer to the processes leading to the development of a Podzol, and "podzolization" to the processes leading to podzolic soils. This later view is evidently held by Gerasimov (1960) of Russia who in 1960 included movement of clay in a definition of "podzolization" and by DeConnick of France (1960) who in the same year wrote that clay migration was the first step of "podzolization."

Bisequal soils associated with the Podzols in northern Michigan (Gardner and Whiteside, 1952) present special problems. These bisequal profiles consist of a Brown Podzolic or Podzol sequum overlying a Gray-Brown Podzolic or Gray Wooded sequum. Such soils which have developed from moderately fine to coarse textured materials have been studied by several investigators in New York and Michigan (Frei and Cline, 1949; Cline, 1959; Gardner and Whiteside, 1952; Cann and Whiteside, 1955). The general consensus of these studies is that the formation of the Gray-Brown Podzolic or Gray Wooded sequum involves clay migration down the profile. Either after this has occurred or while it is occurring, a Podzol or Brown Podzolic B horizon, characterized by an accumulation of sesquioxides and/or organic matter, develops in the upper part of the profile. Some European workers have evidently observed similar bisequal soils. Duchaufour (1956, p. 199) wrote that in an Atlantic climate lessivage prepares conditions for podzolization. In boreal climate, however, or on very permeable and very acid parent material of the Atlantic domain, podzolization could take place immediately under the action of coniferous forests or heather. Mackney (1961), too, thought that clay movement preceded podzolization in soils developed on medium textured parent materials in England. From this it appears that some European workers are distinguishing between the process which leads to the development of the sol lessivé (probably Gray-Brown Podzolic or Gray Wooded) sequum and the process which leads to the development of the Podzol sequum.

Although modern views in America and elsewhere do not include clay migration in the concept of the processes leading to a Podzol, significant amounts of increase in the clay content of the Podzol B horizon relative to the C horizon have been recently observed (Pawluk, 1960; Brown and Jackson, 1958; Gerasimov, 1960; Wurman, 1959). However, little importance was attributed to these clay increases by these investigators.

Duchaufour (1956) and Fridland (1959) differentiated the podzolization process from related processes according to the reactions undergone by clay minerals. Podzolization involves the destruction of clay minerals in the upper part of the profile and removal of the products of this destruction, while lessivage (Duchaufour) and illimerization (Fridland), involve simply the elutriation or mechanical movement of clay particles without their destruction. The difference between podzolization and elutriation (lessivage, illimerization) can be detected by the total chemical composition of the clay fractions of a profile and by micromorphological observations (Fridland, 1959). For instance, illuvial horizons of Podzols lack the oriented clay films found in illuvial horizons formed by the elutriation of clay in Gray-Brown Podzolic and Red-Yellow Podzolic soils. Furthermore, the SiO_2/R_2O_3 ratio of the clay fraction of the B horizon is different from that of the clay fraction of the A or C horizons in a Podzol but this ratio is quite uniform throughout the profile of a Gley-Pseudopodzol (probably Gray-Brown Podzolic) (Gerasimov, 1960).

In this study, in order to include the young as well as the more mature soils, the term Podzol will refer to any soil with an observable grayish A2 horizon underlain by a B horizon of which the color has a smaller value, but greater chroma than the parent material, but which lacks plastic properties or a greasy feel when moist.

Mechanisms of Translocations

As seen above, the chief mobile substances which could be involved in the process of podzolization are sesquioxides (Fe and Al), organic matter, and silicate clays. Various mechanisms have been proposed for the translocation of these substances alone, in pairs or in a combination of all three. The mechanisms of translocation will be reviewed according to all the various possible combinations of the mobile elements.

Sesquioxides

If iron and aluminum were to move without being involved in a combination with organic matter or clays, they would have to do so in the ionic or colloidal forms. Movement of iron and aluminum as the trivalent ion is unlikely because both species are highly insoluble at pH's commonly found in the surface horizons of Podzols. Under some conditions, however, iron can be reduced to the ferrous form which is much more soluble than the ferric form. McKenzie and Erickson (1954) placed an organic layer over a sand layer in a glass cylinder and leached the column with distilled water. At the conclusion of leaching the sand was divided into layers and ferrous and total iron were determined for each layer. It was found that the sand immediately below the organic layer contained a greater percentage of ferrous iron than did lower layers. From this they concluded that a possible mechanism of iron translocation in Podzols was reduction in the A horizon, translocation of the ferrous iron, and oxidation and precipitation of ferric iron in the B horizon. In a subsequent paper (McKenzie et al., 1960) they found that conditions were more oxidizing in the Kalkaska Bir than they were in the A1, A2, or Bhir horizons. From this they concluded that iron may be mobilized from the A and Bhir horizons and immobilized in the Bir horizon. Deb (1949), however, wrote that in the normal Podzol in which water logging is absent, iron is readily oxidized to the ferric state.

It should be pointed out, however, that although some mechanism of movement seems unlikely because of laboratory standards of solubility, a substance is probably never completely insoluble and the great amounts of water or solution which pass through the soil in thousands of years may transport small amounts of the "insoluble forms" in solution.

Smith (1934) passed a suspension of a positively-charged iron-oxide sol through a column of sand, washed the column with water, passed a suspension of a negatively-charged Na-clay suspension through the column, and again washed it with water. He found that when positively-charged and negatively-charged colloids were alternately passed through the column in this way, the skeletal sand grains retained the charge of the last suspension to pass through. If, however, both colloids were present in the column at the same time, they precipitated out and formed a pan which retarded the percolation of water through the column. He postulated that in humid areas positive and negative colloids moving downward in a soil profile independently could flocculate each other and be filtered out causing the formation of a pan or that positively-charged colloids might be caught and held on the walls of negatively-charged sand grains.

Concerning movement of iron as a colloidal sol, Deb (1949) wrote that "the movement of iron as a positive iron-oxide sol in association with alumina and humus has been suggested by Mattson and Koulter-Andersson. This cannot be established unless it is shown that the A horizons of podzol soils are positively charged. The authors gave no data on this point, and no one else seems to have found a podzol soil with a positive charge."

Since aluminum oxide or hydroxide is also positively charged in an acid environment (Mattson, 1930), the same argument should hold for it.

Organic matter

Relatively mineral-free, finely divided organic matter could possibly be translocated from the A2 to the B horizon. Kubiena (1953, pp. 259-262) observed that remains of droppings of small soil animals could be carried down the profile by percolating waters and could be deposited between the sand grains of the B horizons of humus and humus-iron Podzols. Mackney (1961) suggested that the previously deposited Bs horizon could act as a sieve to collect humus at the Ae-Bs (A2-Bir) interface to form the Bh horizon of a humus-iron Podzol. Stobbe and Wright (1959) reported observations of large masses of dark colored organic matter descending after rains from the Ao horizon, through the A2 horizon which has lost most of its sesquioxides, to the B horizon where the organic matter is filtered out.

Silicate clays

Mechanisms of clay accumulation can be illustrated by two postulations for an increase of chlorite in the B horizons of Podzols developed on sand in northern Alberta (Pawluk, 1960). First, partial dissolution of feldspars in the A horizons may result in the formation of skeletal alumino-silicates which could be moved to the B horizon where they could be synthesized to a chlorite mineral by the addition of a layer of gibbsite or alumina to their basal surfaces. Secondly, chlorite may be synthesized from amorphous materials which had accumulated in the B horizon following their removal from the A horizon.

Sesquioxides--organic matter

The approach to studying the reactions of sesquioxides, particularly iron, with organic matter has shifted over the years. Early workers studied the effect of the peaty surface layer of Podzols on iron. Later, it was realized that peat was ineffective in causing mobilization of iron, and that from the very fact of its persistence, peat represents a relatively inert fraction of the original plant material. It is thus probable that the organic material which does not remain in the peat exerts a greater influence in mobilizing iron and aluminum (Bloomfield, 1953). This realization shifted the emphasis to the study of leachates of freshly fallen leaves and, even further, to the solutions dripping from the living forest canopy during a rain (Schnitzer and DeLong, 1954).

Two kinds of associations of sesquioxides and organic matter have been proposed, electrostatic bonding and complex formation. First, movement could occur as a humus-protected iron oxide sol. Schnitzer and DeLong (1955) electrodialyzed leaf leachates enriched with iron and found that most of the iron migrated to the cathode. They concluded that the iron at the cathode was in the ferric hydroxide form and that at the anode was ferric hydroxide protected by negatively charged organic matter. Deb (1949) found that the amount of humus necessary for the full peptization of a sol containing 100 ppm of iron oxide was less than one-third the amount of iron oxide.

Martin and Reeve (1957, 1960) could find no evidence of the formation of coordination compounds in the organic matter of a Podzol B horizon. They suggested that electrostatic bonding could be the type of bond joining sesquioxides and organic matter and that the simultaneous presence of aluminum, iron, and humus in the B horizon could be accounted for solely by the flocculating properties of aluminum ions.

In recent years much attention has been given the second proposed association between iron and organic matter, a metal-organic complex or chelate. Stobbe and Wright (1959) reviewed some of this work. They concluded that "the prevailing concepts of the genesis of Podzols are that the percolating products of organic matter, particularly the organic acids and other complexing substances, bring about the solution of sesquioxides, the reduction of iron and the formation of soluble metal-organic complexes, some of which may be chelates. The complexes move to the lower horizon and are precipitated under oxidizing conditions probably by the destruction of the ligands by microorganisms and/or by sorptions."

Since the review article was written, Canadian workers have been active in elucidating the chemical nature of the organic materials responsible for mobilizing sesquioxides. Schnitzer and Wright (1957) and Wright and Schnitzer (1959a and b) worked with the Armadale soil, an imperfectly drained Podzol developed from sandy loam on Prince Edward island. They decided that the fulvic acid fraction of soil organic matter was the most active fraction in podzolization because 85% of the organic matter of the Bh horizon was fulvic acid compared with 30% fulvic acid in the Ao horizon. The organic matter of the Bh consisted largely of an aromatic "nucleus" to which functional groups were attached. The major functional groups were found to be carboxyls, hydroxyls, and carbonyls, all of which are known to react with iron and aluminum. In contrast, the organic matter of the Ao horizon contained more aliphatic and/or alicyclic "nucleus" structures (Schnitzer, 1959; Schnitzer and Wright, 1960; Wright and Schnitzer, 1959a, 1959b, 1960, 1961).

Coffin and DeLong (1960) were able to isolate and quantitatively determine some of the actual components of the organic matter of the B horizon of a sandy Podzol. They found that four phenolic acids, m-hydroxy-, p-hydroxy-, 2,4-dihydroxy-, and 3,5-dihydroxy-benzoic acids made up about 12% of the total organic matter of the soil material. Three of these four acids were also identified in leachates resulting from natural rainfall after it had passed through a canopy of hemlock and then through the Ao and A2 horizons of a Podzol. This indicates that these acids can originate in the canopy or surface horizons.

Evidence from several laboratories suggests that the mechanism whereby soluble metal-organic complexes are immobilized is further saturation of the organic molecule with iron and aluminum or possibly small quantities of Ca^{++} or Mg^{++} (Wright and Schnitzer, 1961), causing the complex to precipitate. Bloomfield (1955) found that ferric oxide-coated sand grains in a column adsorbed iron and aluminum from leaf leachate solutions enriched in these elements when they were passed through the column. He postulated that initial dissolution of ferric oxide took place in the surface layers of the column while in lower layers adsorption occurred, resulting in a net adsorption of iron and aluminum. DeLong and Schnitzer (1955) added successive increments of ferric hydroxide to a given volume of poplar extract and found that the amount of iron in solution attained a maximum and then fell off sharply with further addition of ferric hydroxide. Using oxalic acid, instead of leaf leachates, and soil materials Kawaguchi and Matsuo (1960) obtained similar results. They treated the A2 and B2 horizons of a forest soil with 0.1N oxalic acid containing 34γ/ml of Fe_2O_3 and found that the A2 released iron and the B2 absorbed iron from the solution. They maintained that the ratio of the amount of the mobilizing material to the amount of iron oxide to be mobilized regulates the amount of mobilization of iron in soils. From the evidence obtained, these workers proposed a hypothetical developmental sequence of iron mobilization in Podzol formation.

Another mechanism of immobilizing metal-organic complexes is by biological decomposition of the organic ligand. Deb (1949) and Stobbe and Wright (1959) reviewed several references pertaining to this mechanism and concluded that it was a possibility. Aristovskaya (1958) extracted a fulvic acid-sesquioxide gel from a humus-illuvial Podzol and added aliquots of this gel and of soil suspension cultures to the surface of an agar plate. A thin film of bacteria grew on the agar and amoeba attacked these bacteria and the fulvic-sesquioxide gel. Cells of amoeba (and also flagellates, actinomyces and some bacteria) ingested the gel and metabolized the organic part of it, leaving concretions of ferric hydroxide which may surround individual cells or colonies of cells. The amoeba decomposed the gel only when bacteria were present as a supplementary food source.

Sesquioxide-silicate clays

Amorphous coatings of sesquioxides are known to occur on clay minerals surfaces (Jackson and Mehra, 1960; Aguilera and Jackson, 1953). Wurman et al. (1959) proposed movement of an iron-silicate clay association as a possible mechanism in the genesis of subsoil bands in sandy Michigan soils.

Organic matter--silicate clays

Bloomfield (1954) suggested that physical translocation of clay could result from the action of rain water charged with organic matter leached from the Ao horizon. He found that aqueous leachates of a variety of broadleaved species caused the deflocculation of kaolin suspensions. Polyphenolic compounds were chiefly responsible for this dispersion (Bloomfield, 1957). Evans and Russell (1959) found that clays rapidly adsorbed humic and fulvic acids from suspension. More fulvic acid was adsorbed by acid clays than by Ca-clays, but the converse was true in the case of humic acid. Acid systems of kaolinite and bentonite both adsorbed more fulvic acid than humic acid. Adsorptions were in the order of magnitude of 3 to 9 g C/100 g clay.

Silicate clays-sesquioxides--organic matter

Translocations may also occur as a combination of these three groups. Brydon and Sowden (1959) separated out the colloidal fraction of a Podzol using a series of dispersion methods. They found that each fraction separated contained silicate clays, "free" aluminum and iron, and organic matter. They postulated that iron and aluminum stabilized the clay-organic association. Bloomfield (1954) thought that the effectiveness of Kauri as a Podzol former may be due to its ability to deflocculate sesquioxide-coated clays. Wurman et al. (1959) postulated the existence of a clay-sesquioxide-organic matter association on the basis of changes in the x-ray diffraction and differential thermal measurements after the organic matter and "free oxides" were removed from the clays of Podzols.

Other mechanisms of mobilization and immobilization

Movement of iron as a silica-protected iron oxide sol has been suggested but this theory was criticized by Deb (1949). Mattson's theory of isoelectric weathering was also highly regarded for some time but it has since been criticized because of its requirement of a significant pH gradient in the profile, a condition not always found in Podzols (Stobbe and Wright, 1959).

Other suggested mechanisms for immobilization of sesquioxides and/or organic matter include precipitation as basic salts, loss of effectiveness of chelating agents, and drying in the illuvial horizon (Deb, 1949; Stobbe and Wright, 1959).

Mineralogy of Silt and Sand Fractions

Pettijohn (1941) reviewed the frequency of appearance of heavy minerals in arenaceous deposits of the different geologic ages and found that the mineral suites became less complex with increasing age of the deposits. That is, easily weatherable minerals disappear, leaving only the more resistant species. He proposed an "order of persistence" of 25 heavy minerals from these observations. In general, this sequence was in harmony with others proposed by Thoulet, Goldich, and Smithson, each one based on somewhat different data. Pettijohn's relative order from most to least persistent is: anatase, muscovite, rutile, zircon, monazite, garnet, biotite, apatite, ilmenite, magnetite, staurolite, kyanite, epidote, hornblende, andalusite, topaz, sphene, zoisite, augite, sillimanite, hypersthene, diopside, actinolite, and olivine. He considered quartz to be more resistant than garnet. The relative stability of minerals was observed to follow approximately the reverse order of Bowen's reaction series (Goldich, 1938), that is, the first minerals to crystallize from a magma are the first minerals to weather.

The resistance of primary minerals to podzolization processes has also been studied. Jeffries and White (1939) observed an abundance of zircon and anatase and lesser amounts of nine other heavy mineral

species in a Podzol. Cady (1940) noted a marked decrease in the hornblende and hypersthene content of the 0.04 to 0.1 mm fraction of the A2 horizon of a Podzol relative to the C horizon. There was also an apparent increase of magnetite and garnet in the A2 because of the decrease of the more readily weathered minerals. The content of heavy minerals in the A2 horizon was only about 67% of that of the C horizon. Chandler (1941) grouped heavy minerals according to resistance to podzolization as follows:

Resistant	Moderately resistant	Easily weathered
Zircon	Epidote	Hypersthene
Magnetite	Orthoclase	Hornblende
Quartz	Diopside	Plagioclase
Garnet		Olivine

This grouping was based on heavy mineral counts of the sand fractions of Podzol and Brown Podzolic soils. Observations substantiating the above grouping were also made by Richard and Chandler (1943).

Matelski and Turk (1947) studied the heavy minerals of several Podzols of northern Michigan. They worked with the heavy (s.g.>2.94) mineral portion of the fine sand, very fine sand and coarse silt fractions (0.25 to 0.02 mm) and determined the frequency of mineral grains in each of several cross-sectional area categories within these diameter limits. Their data illustrated the difficulties which could arise from using a narrow particle size limit in studying the weathering of mineral grains in a soil. For instance, in the case of garnet, the modal size of particles in the B horizon was less than that in the A horizon, and in the A less than that in the C horizon ($B < A < C$). Thus in considering any one narrow size class, garnet contents would give a distorted view of the garnet content of the whole soil sample. These authors also observed a smaller content of heavy minerals in the B horizons than in the A horizons of all seven profiles studied, and a smaller content in the B horizons than in the C horizons of all but one profile. The small particle size of garnet in the B horizon and the small quantities of heavy minerals in the B led the authors to conclude that the B horizon suffered a greater decomposition of heavy minerals than did the A or C horizons. They also concluded that of the minerals they studied the least resistant to podzol weathering was dark green hornblende, followed by gray-green hornblende, the opaque minerals, and the garnets.

Brown and Jackson (1958) attributed the higher garnet/pyroxene and garnet/hornblende ratios in the A2 horizons relative to the rest of the rest of the profiles of two Hiawatha soils to chemical weathering of pyroxenes and hornblende. Garnet was considered to be a resistant species since the zircon/garnet ratio was approximately the same throughout the profile.

In a study of the mineralogy of the 0.5 to 0.016 mm fraction of a heath Podzol in the Netherlands, Van der Marel (1949) showed that amphibole weathers most readily, followed in diminishing degree by muscovite, epidote, saussurite, feldspar, staurolite, the opaques, rutile, tourmaline, and quartz. Weathering of these minerals took place primarily in the "lead sand" (A2) and black sand (Bh) horizons, but it was more severe in the "lead sand." He noted that K-feldspars were weathered only in the A2 horizon while Ca- and Na-feldspar were scarcely weathered at all but were concentrated in the $< 16\ \mu$ separate along with quartz. Only quartz and clay minerals could withstand weathering processes in small ($< 2\ \mu$) particles.

Pawluk (1960) found the following weathering rates in the 0.1 to 0.5 mm fraction of some Alberta Podzols:

light minerals--feldspar > quartz;
intermediate minerals--chlorite > biotite > muscovite; and
heavy minerals--hematite > hornblende > garnet $\geq$ magnetite.

By horizons, the weathering rates reported were, Ae > Bir > C.

In recent studies of Michigan soils, Yassoglou and Whiteside (1960) showed a slight decrease in feldspars in the A2 horizon of bisequal soils. Hornblende, olivine, and epidote weathering took place in all horizons above the Bt, with the intensity of weathering increasing with proximity to the soil surface. Magnetite, zircon, garnet, and tourmaline were considered to be resistant. These conclusions were based on studies of the fine sand fractions of the soils. Wurman et al. (1959), using x-ray diffraction, found no distinct pattern in the feldspar content of sandy Podzol and bisequal soils. Cann and Whiteside (1955) found that orthoclase feldspars were more resistant than plagioclase feldspars in the Marlette soil.

Summarizing, most of the weathering series observed in Podzols and in the podzol sequum of bisequal soils follow the general order proposed by Pettijohn (1941) and Goldich (1938). (Exceptions are diopside in Chandler's series and plagioclase and muscovite in Van der Marel's series.)

Observations of weathering intensity within a soil profile were usually A2 > B > C. However, Matelski and Turk (1947) interpreted the order to be B > A2 > C, while Cady (1960) proposed the order A2 > B = C.

Marshall (1940) proposed a method for measuring net gains or losses which occurred in individual soils during their formation and in soil horizons during profile development. The method is based on the content, in each horizon, of an "index mineral" that is resistant to weathering, not formed in pedogenesis, and is immobile. Marshall recommended using zircon, tourmaline, garnet, rutile or anatase as index minerals. Barshad (1955) added to this list quartz, albite, microcline, or a combination of several resistant minerals. In order to apply Marshall's method, it is first ascertained that the solum has developed from material like that which is now assumed to be its parent material. Marshall (1940) proposed two criteria for depositional uniformity:

(a.) throughout the profile the relative proportions of the highly resistant minerals should be the same, (b.) throughout the profile the particle size distribution of a given resistant mineral should remain the same.

Resistance of a mineral to weathering is a relative matter; given a sufficiently long time under weathering conditions, even the most resistant minerals will undergo some weathering. Raeside (1959) pointed out that quartz, garnet and zircon are subject to physical breakdown through strain caused by crystal disorientation or crystalline inclusions. These minerals, especially iron-rich garnets, may also be susceptible to dissolution. He listed five conditions under which quartz, zircon, or garnet should <u>not</u> be used as index minerals:

1.) in soils on old land surfaces,
2.) in soils that have existed for long periods of time under high rainfall conditions,
3.) where the minerals contain large or abundant inclusions,
4.) where the minerals show extensive strain or incipient fissuring,
5.) where garnets are high in iron.

Mineralogy of Clay Fraction

Jackson and co-workers (1948) proposed a weathering sequence of clay-size minerals in soils. Although the sequence was developed from generalized changes covering a variety of weathering and soil forming processes, it appears that it fairly well describes clay mineral weathering in Podzols. The series represents weathering from the more complex to the simpler minerals, analogous to series representing weathering of sand grains. For example, as weathering stages progress through 7, 8, 9, 10 and 11 the stages are represented by illite, hydrous mica intermediates, montmorillonite, kaolinite, and gibbsite, respectively. Rolfe and Jeffries (1952) proposed a criterion for weathering of clay minerals which was essentially the amount of illite (mica) transformed to hydrous micas, (stage 7 to stage 8 in Jackson's scheme). Jackson later (1959) elaborated on the steps of the transition from micas to montmorillonite.

Podzols developed on sandy parent material sometimes show a greater percentage of montmorillonite in their A2 horizons than in deeper horizons. This trend has been demonstrated in the Hiawatha, Iron River, Ahmeek and Omega soils of northern Wisconsin (Brown and Jackson, 1958), in the Montcalm fine sand of northern Michigan (Wurman et al., 1959), and in Podzols from Fennoscandia (Gjems, 1960). This increase of montmorillonite was said to be due to removal of the interlayer from chlorite (Brown and Jackson, 1958; Wurman, 1959). Yassoglou and Whiteside (1960) indicated that montmorillonite and vermiculite are the products of weathering of illite, chlorite and interstratified systems in somewhat finer-textured Michigan soils.

Pawluk (1960), on the other hand, found that the A and C horizons of some Podzols from northern Alberta contained illite, montmorillonite, interstratified illite-montmorillonite, and kaolinite, while the B horizons were primarily chlorite-like with lesser amounts of kaolinite. He explained these results by a synthesis of chlorite in the B horizon.

Tedrow (1954) and Brown and Jackson (1958) found more quartz in the clay fractions of surface horizons of Podzols than in the clay fractions of lower horizons. This quartz was largely in the 2-1 μ or 2-0.2 μ fractions.

In the recently proposed soil classification system in the United States (Soil Survey Staff, 1960) one criterion for the spodic (Podzol B) horizon is that the SiO_2/R_2O_3 ratio of the clay fraction of this horizon is less than this ratio of the clay fractions of both the albic (A2) horizon and the parent material. To illustrate this point, data from Podzols from Washington and Georgia were presented (Soil Survey Staff, 1960, p. 52). Some other recent data on SiO_2/R_2O_3 ratios is presented in Table 1.

Table 1. Silica-sesquioxide ratios of the clay fractions of some sandy Podzols.

Location	Soil and Horizon		Fraction		Molar $\frac{SiO_2}{R_2O_3}$
			Size	Percent	
Wisconsin[1]	Hiawatha l.s.	A2	2-0.2μ	0.4	6.3
		B2	2-0.2μ	0.9	4.9
		C2	2-0.2μ	0.02	3.5
Alberta[2]	Profile 1	Ae	<2μ	tr.	4.8
		Bir	<2μ	4.0	4.9
		C	<2μ	1.0	4.2
	Profile 2	Ae	<2μ	0.4	4.2
		Bir	<2μ	7.1	4.1
		C	<2μ	3.0	3.8
England[3]	Podzol-intergrade	Ae/Bh	<2μ	n.d.	3.4
		Bs	<2μ	5.5	2.1
		C	<2μ	3.8	2.3
Russia[4]	Humic-illuvial Podzol	8-14cm (A2)	<1μ	2.6	2.8
		20-26 (Bh)	<1μ	8.6	1.5
		38-44 (Bir)	<1μ	7.7	2.0
		65-70 (C?)	<1μ	5.3	1.7
New England[5]	Brassua	A	<2μ	-	3.0
		B	<2μ	-	0.7
		C	<2μ	-	1.5

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[1] Brown and Jackson (1958)
[2] Pawluk (1960)
[3] Mackney (1961)
[4] Fridland (1959)
[5] Tavernier and Smith (1957)

This table shows that the B horizon of several Podzols in North America and part of the B horizon of a Russian Podzol could not be called spodic horizons. The Bs of the British Podzol, the Bh of the Russian Podzol, and the B of the Brassua soil would fulfill the above requirements of the definition of the spodic horizon, however.

Chronosequences of Soils

Jenny (1941) reviewed some of the early work, especially that from Europe, concerning time as a soil forming factor. Since then Chandler (1942), and later Crocker and Dickson (1957), have studied soil development on a series of recessional moraines deposited by the Mendenhall glacier in Alaska. Vegetation invaded the moraines quite rapidly after the retreat of the glacier. Within two years mosses, lichens, and fireweeds were growing. In three years red alder came in, and in 15 years Sitka spruce seedlings were present. Around 100 to 120 years after the ice had retreated from a moraine the Sitka spruce forest was established. Aspen or hemlock were reported to be in association with spruce later in the succession. Soil properties which had changed during the first century or two were largely those affected by the incorporation of organic matter into the surface of the mineral soil, such as carbon content, nitrogen content, color, reaction, and bulk density. The reaction of the surface horizons gradually became more acid as carbonates were leached and the bulk density of the surface horizon decreased with increasing age of the surface. Nitrogen was found to accumulate rapidly during the first 50 to 60 years--possibly due to nitrogen fixation by the nodules of alder. The two reports did not agree on the type of soil being formed. Chandler described his oldest soil (± 1,000 years, corrected to 3,000 to 4,000 years by Crocker and Dickson), as having a well humified surface accumulation of organic matter 8 inches thick, an A2 horizon which was ash gray in color and

ranged from 2 to 4 inches thick, and a B horizon 6 to 8 inches thick which was "dark coffee brown and showed a tremendous accumulation of humas and iron." Crocker and Dickson, however, wrote that ". . . there is little evidence indeed that anything approaching a typical podzol is the sub-terminal, or terminal, result of soil formation on glacial moraines in this region," but their study did not describe soils older than about 200 years.

A study was made by Crocker and Major (1955) at Glacier Bay, Alaska, under conditions similar to those near the Mendenhall glacier. The vegetational sequence and soil changes reported for the two areas were in general agreement. The chronosequence at Glacier Bay covered a span of 0 to about 200 years. It was found that under alder vegetation nitrogen accumulates rapidly, at the rate of 55 pounds per acre per year, over a period of 50 years.

Gjems (1960) studied the clay minerals in a chronosequence of Podzols near the Bay of Bothnia in Fennoscandia where the rate of uplift of the shore is 1 m/100 years. Even in the youngest of the profiles studied, 300 years, the clay fraction of the A2 horizon showed strong evidence of the presence of montmorillonite, while this mineral could not be found in the C horizon.

Olson (1958) studied the ecology of the sand dunes of southern Lake Michigan and related the vegetational succession to early soil development. Pioneer grasses, with or without cottonwoods or dune-building shrubs, eventually led to various types of black-oak communities, often with an intervening stage of jack or white pine. His data again illustrated the effects of organic matter accumulation in the soil. However, he wrote about the likelihood of fire in these areas, and recent fires would greatly alter the present properties of the surface soil closely related to the kind and amount of organic matter.

Another chronosequence reported was on a succession of river terraces in the Northwest Territories (Wright, et al., 1959). The sequence consisted of an Alluvial soil on the lowest and youngest terrace, a Brown Wooded soil on the middle terrace, and a Grey Wooded soil on the highest and oldest terrace. The parent material of all soils was fine textured alluvium. The pattern of development found here was (1.) accumulation of organic matter in the upper part of the calcareous parent material, (2.) decomposition of carbonates, with calcium removal occurring about twice as fast as magnesium removal, followed by a depletion of organic matter, (3.) greater loss of silica than of sesquioxides in the earlier stages of development, probably during the depletion of carbonates, (4.) continued loss of bases, particularly calcium, accompanied by a decrease in pH, and (5.) marked eluviation of clay and sesquioxides and their accumulation in the B horizon.

Hensel and White (1960) studied the clay mineralogy of the surface horizons and parent materials of primarily Gray-Brown Podzolic soild in a transect across moraines of Tazewell and Cary age. They estimated that the rate of weathering of K_2O from the 2-0.2 μ fraction of the 0-6 inch layer of soils was about 0.10% per 1000 years.

III. RELATION OF SOILS TO ENVIRONMENT

Geologic History

Valders glaciation

The last glacial substage of the Wisconsin age to reach the northern tip of Lower Michigan has been correlated with the Valders substage of eastern Wisconsin (Melhorn, 1954). Valders ice was thought to have been thin and to have lost most of its energy by the time it covered that part of the state so that it reached but did not over-ride the Port Huron moraine. Because the ice was so thin it caused little scour of the bedrock over which it passed, but instead, reworked the drift deposited by previous glaciations. Melhorn thought that Valders ice covered the entire Emmet moraine (Emmet County, north of Little Traverse Bay) which attains an elevation of around 1330 feet at Emmet Heights, but the highest elevation at which he found evidence of Valders drift on the Lake Michigan slope of the older Port Huron moraine in the Little Traverse Bay area was 860 feet (near Petoskey). The highest elevation at which he identified red (Valders) till or red till over blue-gray (Port Huron) till in the lower peninsula was nearly 1300 feet (judging from the elevations, according to USGS topographic maps, of the locations he gave for the points where he made the observations). This occurred on the Lake Huron slope of the Port Huron moraine, however, near Johannesburg.

Because of the characteristic weakness of the Valders ice and the lack of evidence that it attained elevations greater than 860 feet on the Lake Michigan slope of the Port Huron moraine, it is possible that it did not cover all of the Emmet moraine and that the higher elevations of that moraine are actually of Port Huron age. The two soils on the Emmet moraine selected for study herein occurred at elevations of about 850-900 feet. Even though the Valders glacier was not very active, it is very likely that it would have reworked at least the surface of the previously deposited glacial drift at this altitude, leaving a fresh surface on which soil forming agents could begin to work when the ice melted.

Calumet, Toleston, and Kirkfield Lake stages

As the Valders ice melted and its margin retreated northward, the Lake Michigan and Lake Huron basins may have been connected by a channel which flowed through what is now Cheboygan, Emmet, Antrim, Grand Traverse, and Leelanau Counties (Hough, 1958, pp. 178-181). The final Glenwood stage of Lake Chicago occupied the Michigan basin at this time and had its outlet at Chicago.

The increased volume of water supplied to this lake as Valders ice melted was sufficient to cause downcutting of the outlet to establish a new level, the Calumet stage, of Glacial Lake Chicago at 620 feet above sea level.

Further cutting of the Chicago outlet down to bedrock was responsible for creating the Toleston-Early Algonquin stage at 605 feet.

As the Valders ice retreated farther northward, a lower outlet was opened which drained the Huron and Michigan basins eastward through the Trent Valley in Ontario and lowered the level of the glacial lakes by 40 to 50 feet. This Kirkfield stage of Hough (1958) may have been the same as the "pre-Algonquin" lake that Spurr and Zumberge (1956) identified in Emmet and Cheboygan Counties.

Main Algonquin stage

Subsequently, the Kirkfield outlet was again closed--either by uplift or by re-advance of the glacial ice close to the Kirkfield outlet--

and the level of the glacial lakes rose again to 605 feet above sea level resulting in the main Algonquin stage of the Michigan and Huron basins. During this stage most of what is now Emmet and Cheboygan counties was under water. This level was maintained by the levels of both the Chicago and Port Huron outlets. Lake Algonquin lasted from around 9000 to 8000 years before present.

Low water stages

As the glacial ice retreated still farther northward, a series of new outlets lower than the southern outlets were opened. Each new outlet caused a successively lower stage of the lakes in the Huron and Michigan basins until the North Bay outlet was uncovered. This channel, which led from Georgian Bay, northeast to North Bay, Ontario, and on to the St. Lawrence valley, controlled the level of the Stanley stage of the Huron basin at around 180 feet and drained the Chippewa stage of the Michigan basin which was about 230 feet above sea level.

Melting of the ice removed a great load from the earth's surface and resulted in uplift of the earth's crust. The greatest amount of uplift occurred where the ice had been thickest and it tapered off where the glacier was thinner. Around Cheboygan the surface exposed when the Algonquin stage ended had risen 110 feet by the end of the low water stage (Spurr and Zumberge, 1956, fig. 4) after which lake levels again reached the same elevation as they were during the Algonquin stage. Uplift continues today in this area.

Nipissing stage

Uplift closed the North Bay outlet around 4000 years before present creating the Nipissing stage in the Huron and Michigan basins. The lake level was controlled by the Port Huron and Chicago outlets, the same ones that had controlled the level of Lake Algonquin, and thus the level of the Nipissing stage was also 605 feet above sea level.

Algoma stage

The Nipissing stage was ended by downcutting of the Port Huron outlet around 3000 years ago producing a new lake level of 595 above sea level. This Algoma level was stabilized only briefly and further downcutting of the Port Huron outlet gradually lowered Lakes Michigan and Huron to their present level of 580 feet, leaving a series of young beaches.

Geomorphology--Soils Relations

General relations

The parts of the Emmet moraine high enough to remain above the highest Algonquin stage of the glacial Great Lakes were called Riggsville, Levering, and Brutus Islands by Spurr and Zumberge (1956). The soils on Riggsville Island in Cheboygan County (Foster *et al.*, 1939) were mapped primarily as Emmet sandy loam with small areas of Emmet loamy sand (now probably Leelanau or Montcalm loamy sand), and Onaway loam. Brutus and Levering Islands account for a large share of the land area of Emmet County. The only soil map available in this county is a land type map (Galloway, 1940). This map shows the soils of Levering Island to be primarily Emmet sandy loam with smaller amounts of Emmet loamy sand. Soils of Brutus Island are somewhat coarser in texture, mostly Emmet loamy sand with some Emmet sandy loam.

On Brutus Island there are some areas of sand textured "washed drift" (Flint, 1957, p. 109) materials and it was in these areas that suitable sites were found for this study.

Most of the area which had been below Algonquin but above Nipissing waters in Emmet and Cheboygan Counties is now occupied by organic or poorly drained sandy soils. Some of it, however, bears well drained soils which have been mapped largely as Kalkaska (medial Podzol) or Rubicon sands (minimal Podzol), with smaller areas of Grayling sand (Brown Podzolic) south of Burt, Mullet, and Black Lakes. The reasons for these different degrees of podzolization on similar parent materials of the same age have not been worked out.

The parent materials which had been under Nipissing, but above Algoma waters in Cheboygan and Emmet counties are largely gravels and sands in the form of beach ridges with interspersed wet areas. The well drained sandy soils were mapped Eastport, Rubicon, Kalkaska, or Wallace sands or gravelly sands. Wallace soils were mapped on former sand dunes which are prevalent on Nipissing beaches because this stage was characterized by a dry climate. On several dunes where Wallace sand was mapped the soil observed did not conform to the current description of Wallace, but would now be Rubicon or Kalkaska. Kalkaska soils were mapped in a small area on the Nipissing beach at the east side of Cheboygan County, but those were not investigated in this study.

The Algoma beaches comprise but a thin strip of land along the Great Lakes in Cheboygan and Emmet Counties except for a more extensive area in the Wilderness State Park area north of Sturgeon Bay. The soil on the beach ridges is Eastport; poorly drained sands and organic soils occupy the low areas between the ridges. In most places along the lakes, the Algoma beach has been disturbed in the building of summer homes, motels, etc.

Selection of sites

The object of this study was to follow soil development in a chronosequence of soils; therefore, the following items were considered in selecting sample sites:

(1.) The sites should be as uniform as possible in the four remaining soil formation factors, i.e., parent material, topography, climate, and vegetation.

(2.) The soils selected should have the maximum podzol development occurring on that age surface, disregarding anomalous situations such as sand dunes, gravelly areas, relatively high water tables, etc.

(3.) The sites should occur near each other to achieve greater similarity in the two active factors, climate and organisms.

These objectives were well met in a sequence of soils on Algoma, Nipissing, and Algonquin beaches near Cordwood Point about 8 miles east of Cheboygan on Lake Huron. Here the three beaches lie parallel to each other with a distinct cliff between the Algonquin and Nipissing beaches and with a less distinct transition between the Nipissing and Algoma beaches. The three sites are located along a transect about one-half mile long perpendicular to the lake shore. The soils found on the former beaches were Eastport sand, Rubicon sand, and Kalkaska sand on the Algoma, Nipissing, and Algonquin beaches, respectively.

The sites selected on Valders age materials were located about 5 miles west of Pellston on the Emmet moraine. This was as close to Cordwood Point as sites which met the previously stated objectives could be found. It was intended to sample one soil having textural bands and one without them; however, after the pits were dug it was found that bands occurred in both soils. In this morainic material it was difficult to find a sandy area of appreciable size that did not have textural bands or pockets present at some depth.

Formation Factors of Soils Studied

Time

The relation of the soils studied to geologic deposits and surface ages is summarized in Table 2. Four values of the independent variable, time, were indicated by the geologic history of the area.

Table 2. Relation of soils studied to geologic deposits and surface ages.

Geologic Deposit	Surface Age (years B.P.)	Soil Studied Type	Soil Studied Elevation* (ft.)
Algoma beach	2,250	Eastport sand	590
Nipissing beach	3,000	Rubicon sand	615
Algonquin beach	8,000	Kalkaska sand	640
Valders drift	10,000	Blue Lake sand (I and II)	850-900

*The elevation of shorelines at Cordwood Point are: Algoma, 605 ft; Nipissing, 630 ft; Algonquin, 760 ft. The Algonquin shoreline at Pellston is 730 ft. above sea level.

Parent material

The textures of the parent materials of all five soils were sand or coarse sand according to the USDA classification system (Soil Survey Staff, 1951). If we assume that the beach sands originated from the moraine behind the beaches, each successive lake stage should have caused further water working of the original glacial material resulting in successively better sorted sands. This appears to be the actual case as shown in Figure 1. The frequency curves of sand size distribution become progressively narrower and higher in moving from the Valders washed drift to the Algoma beach sands.

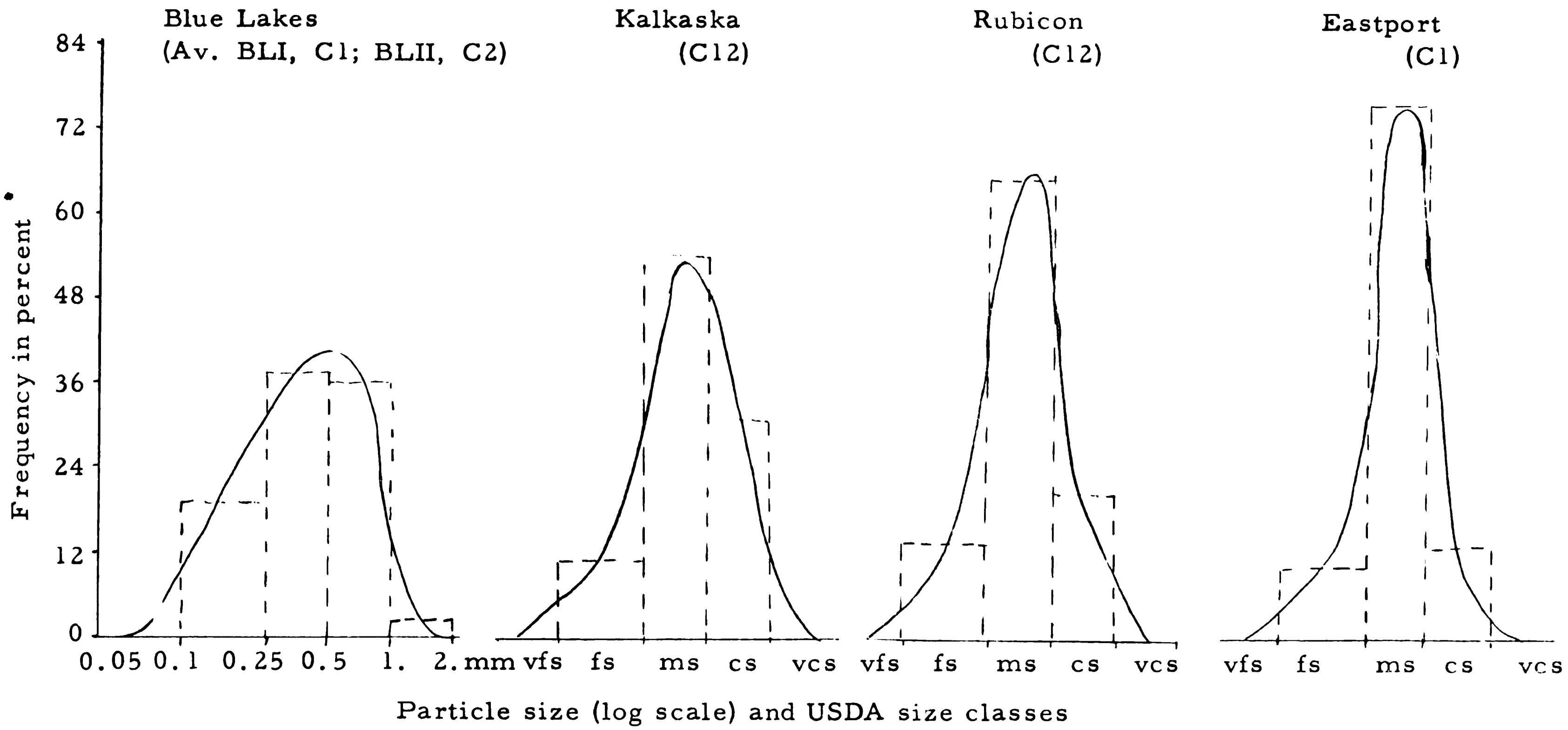

Figure 1. Frequency distributions of particle size classes of the parent materials of soils developed on surfaces of different ages.

Topography

The topography factor was held uniform by selecting all sites for sampling at the tops of beach ridges or morainic knolls. The slopes in the general areas of the pits were around 6 to 9%.

Climate

Pollen analysis has been used to determine the vegetational history of an area and from this, climatic changes can be inferred. Zumberge and Potzger (1956) studied two bogs in southwestern Michigan. They were able to relate horizons in the bog to recent Pleistocene history by stratigraphy, and also to date these horizons by radiocarbon methods. From this information they could relate the vegetational history and inferred climatic changes to geologic stages. The relations they found are given in Table 3.

Table 3. Climatic change inferred from forest history in southwestern Michigan (Zumberge and Potzger, 1956).

Years before present	Forest cover	Climate
3500-4000	Expanding oak-hemlock broad leaved forest	Warmest and driest since retreat of ice
5000	Decline of pine period and ascendency of oak and chestnut	Continued warming
6000	Pine maximum, near elimination of spruce and fir	Warming climate
8000	Decline of spruce and fir, increase of pine	Moderating climate
11,000	Spruce - fir	Cool to cold, moist

Although the bog they studied was about 230 miles from the sites studied here, the climate may not have been greatly different, especially during immediate post-glacial times, because both the sites studied here and those in southwestern Michigan were near the margin of Valders ice. A warming trend continued as the margin of Valders glaciation retreated northward climaxing with the xerothermic conditions of Lake Nipissing time during which many sand dunes were initiated on beaches unprotected from westerly winds.

More recently than 3500 to 4000 years before present the climatic optimum (for plant growth) continued to develop as shown by an increase of oak, hickory, and pine. In most recent times climatic deterioration (cooling?) occurred during which change pine has increased in abundance according to Zumberge and Potzger (1955).

Climatic records kept at Cheboygan and Pellston by the Weather Bureau (1957) show the normal temperature and precipitation for these two stations (Table 4). Additional data has been gathered during summer months at Douglas Lake (University of Michigan Biological Station) and was summarized by Gates (1937).

Pellston received somewhat more precipitation and was around 1° to 2° F colder on the average than Cheboygan during the last decade, Table 4. The difference in precipitation can be attributed largely to differences in amounts of snowfall. Mean annual snowfall at Cheboygan was 70 inches while at Pellston it was 98 inches.

Vegetation

Jenny (1941, pp. 201-293; 1946) considered the vegetation factor to be uniform for different areas if each received seeds or spores of the same group of species. The particular species which subsequently grew need not be the same in the different areas. Thus, the assumption that the vegetation factor is constant for the three youngest sites should

Table 4. Precipitation in inches and temperature in degrees F for Cheboygan and Pellston, Michigan (Weather Bureau, 1957).

Station and Measurement	Month												
	J	F	M	A	M	J	J	A	S	O	N	D	Ann.
Cheboygan													
Mean precipitation (1891-1930)	1.6	1.2	1.5	1.8	3.0	2.7	2.8	3.0	2.9	2.8	2.4	1.7	27.5
(1931-1952)	2.0	1.2	1.5	2.0	2.6	2.6	2.1	2.6	3.7	2.6	2.5	1.8	27.3
Mean temperature (1891-1930)	18	16	26	40	51	62	67	65	59	48	35	24	42.7
(1931-1952)	21	20	28	40	52	62	68	67	59	48	36	25	43.9
Pellston													
Mean precipitation (1942-1952)	2.3	1.6	2.5	2.4	2.9	3.3	2.7	2.2	3.8	2.3	3.4	2.2	31.6
Mean temperature (1942-1952)	18	17	26	40	51	61	66	64	56	47	34	23	41.9

be safe because of their proximity. What is needed is some comparison of vegetation on former beaches with that on the nearby moraines to learn if it is sufficiently similar.

Wilson and Potzger (1942) reported on a comparison of the vegetational history around Douglas Lake, between Pellston and Cheboygan on the Algonquin plain, and around Middle Fish Lake in sandy drift of the Port Huron moraine (Sec. 34, T29N, R2E, Montmorency Co.). They made the comparison by identifying and counting pollen grains from trees preserved in the various layers of lake sediments and peat deposits. Their findings showed that at both locations the vegetative sequence was spruce, to spruce-pine, to pine, to pine-hemlock-broad leaved species (birch, beech and oak). The final stages of the sequence, following the decline of pine, were different at the two locations. At Middle Fish Lake pine again regained much of its former importance (60-80% of total pollen grains) and the broad leaved species declined in importance (to 20-35%), but at Douglas Lake pine remained more suppressed (30-60%) while the broad leaved species became more prevalent (35-60%). The workers realized that the low representation of Acer (maple) pollen in the deposits probably did not reflect the true importance of this genus in the forest cover. This would result in under-estimating the prevalence of maple and over-estimating the prevalence of pine and other species of the forests. Despite this discrepency, pine was still considered to be of greater importance in the moraine than on the former beach deposits because the early reports of vegetational cover confirm this relationship.

The ecological relations of the northern tip of the peninsula during recent times has been described by Gates (1926) based on observations made in the vicinity of the University of Michigan Biological Station from 1911-1925:

> Following the withdrawal of the ice, the different parts of the area became vegetated until, at the time of lumbering in the 1870's, three conspicuous types of vegetation were present. The poorer or sandy uplands were covered with pine forest

> (*Pinus strobus* and *P. resinosa*), grading rather sharply into beech-maple forest on the better soils of the uplands. The lowlands were cedar bogs (*Thuja occidentalis*). Depressions which filled with water became lakes, and aquatic vegetation was developed in and bordering them. The region was one of extensive forest.
>
> With the lumbermen came the removal of the forests, first from the pineland and later, even up to the present time, the beech-maple forest (*Fagus grandifolia* - *Acer saccharum*). Areas that were lumbered were nearly always burned and usually burned repeatedly. The cedar bogs were largely cut and more or less burned, but, as bog conditions are much less favorable for extensive fires, such areas are not so badly damaged. The immediate result of the clearing and burning was the installation of a new vegetation cycle over wide areas. Fireweeds (especially *Epilobium angustifolium*) came first and later shrubs and trees. Areas that have been repeatedly burned are now largely covered with aspens (*Populus spp.*). This type of vegetation is favored by the occasional fires at the expense of the pines, beech, or maples.

Gates also wrote that the vegetational succession on sandy soils in the northern tip of the peninsula was dune association, to heath association, to jack pine association, and, if sufficient humification of the sandy soils takes place, to beech-maple association. Wilson and Potzger (1942) agreed that northern hardwoods is the climatically favored type and that pine maintains itself because of edaphic conditions.

The vegetation of the sites when the soils were sampled is given in the soil profile descriptions. Broad-leaved species were dominant on all sites. On the Eastport site red oak and red maple were the dominant species and on Rubicon quaking aspen, birch, red oak, and red maple predominated. The stocking on these two sites was relatively thin. Sugar maple appeared on the Kalkaska site but it was outnumbered by paper birch and red maple. The sugar maple-beech association was predominant on both Blue Lake sites. At site I there were a few yellow birch, elm, and basswood, while on site II big tooth aspen was common. This vegetational sequence supports the theory that sugar maple and

especially beech do not enter the succession until soil changes such as addition of organic matter to the surface and development of B horizons has proceeded to a sufficient extent. Fire was a factor at all sites since the A1 horizons all contained charcoal. (In some cases it was large enough to observe macroscopically, but in all cases finely divided charcoal not oxidizable with H_2O_2 was present.) Judging from the kind of reproduction, pine would have been a more important species on the two youngest sites had it not been for fires.

Summarizing, the vegetational factor, except where it acts as a dependent variable in Jenny's functional representation of a soil system, is assumed to be constant for the five sites because of the similarity of genera in the vegetational history of sites representative of those studied here.

IV. SOIL PROFILE DESCRIPTIONS

Procedure Used in Describing and Sampling Soils

A soil pit, about 2 to 3 feet by 4 to 6 feet at the top, was dug deep enough to describe and sample the major horizons from the wall of the pit. A field description of each soil profile was written according to standard conventions (Soil Survey Staff, 1951) except that the Inter-Society Color Council-National Bureau of Standards (ISCC-NBS, Kelley and Judd, 1955) color names were used. Depths of horizons were "averaged out" considering the entire area of the pit walls. Soil horizons are also designated according to a proposed genetic system (Whiteside, 1959, 1960) as shown in parentheses. Munsell color notations are for moist soil conditions. Laboratory results for texture and reaction are incorporated into the narrative descriptions. Species of vegetation and stumps are listed in order of decreasing abundance.

Six core samples (3 x 3 in.) were taken from each major horizon with a Uhland sampler. Care was taken to avoid taking samples so near each other that compaction would result. In addition, a bulk sample of around 10 pounds was obtained by taking numerous subsamples from the walls of the pit, mixing them, and taking a subsample of the mixture. This bulk sample was used for all analyses except water retention, bulk density, and thin sections for which the core samples were used. The very deep horizons were sampled with a bucket auger.

Four of the soils are represented photographically in Plate 1.

Eastport sand

Rubicon sand

Kalkaska sand

Blue Lake sand I

Plate 1. Color photographs of profiles of Eastport sand, Rubicon sand, Kalkaska sand, and Blue Lake sand I. Photographs of the first three profiles represent one wall of the pit used for describing and sampling the soils; the cut in the photograph of the Blue Lake I is a few hundred feet from the site studied. Photo-flash light supplemented natural light in the photos of the Eastport and Kalkaska profiles. The natural surface of the Kalkaska soil is covered with a thin layer of debris from the pit. The spade is about 42 inches high.

Eastport Sand

Vegetation:

Dominant: Red oak (Quercus borealis), red maple (Acer rubrum).

Intermediate: Red maple, red oak, white pine (Pinus strobus), striped maple (Acer pennsylvanicum), white spruce (Picea glauca), black cherry (Prunus serotina).

Reproduction: White pine, red maple, red oak.

Ground cover: Bracken (Pteridium aquilinum), wintergreen (Gaultheria), blueberry (Vaccinium), hazel brush, juniper (Juniperus).

*Stumps: Red pine, red oak, balsam fir.

Physiography and relief:

The soil described occurs on top of an Algoma beach ridge, about 6 feet above the swales between adjacent ridges. The beach ridges trend west southwest-east northeast and are about 80-100 feet apart.

Drainage: well drained.

Ground water: deeper than 90 inches.

Moisture: moist

Stoniness: none

Elevation: 590 feet.

Location:

NE$\frac{1}{4}$ of NE$\frac{1}{4}$ of SE$\frac{1}{4}$ of Sec. 20, T38N, RIE, Benton Township, Cheboygan County, Michigan.

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*Species of former vegetation now represented by stumps as identified by Steve Messenger.

Horizon	Depth (inches)	Description
Aoo (Od)	-	Intermittent; undecomposed leaves and twigs.
Ao (Of)	$1\frac{1}{2}$ - 0	Fibrous mat.
A1 + A2 (Vh + Em)	0-5	Sand; brownish gray (10YR 4/1) and yellowish gray to light grayish yellowish brown (10YR 7/2) mixed in a blotchy pattern; very weak, fine, granular structure; very friable; very strongly acid (pH 4.5); clear, wavy boundary. 4 to 8 inches thick.
B(ir) (Ii)	5-19	Sand; light yellowish brown to dark orange yellow (10YR 6/6) with some spots of strong yellowish brown (10YR 5/6); single grain structure; loose; strongly acid (pH 5.5); diffuse, wavy boundary. 8 to 16 inches thick.
B3 (Iw)	19-38	Sand; light yellowish brown (10YR 6/4); single grain structure; loose; medium acid (pH 5.6); diffuse, wavy boundary. 15 to 22 inches thick.
C1 (Wm)	38-90	Sand; light yellowish brown (10YR 7/4); single grain structure; loose; medium acid (pH 6.0).
D (Uu)	90 +	Gravelly coarse sand; light yellowish brown (10YR 7/4); single grain structure; loose; calcareous.

Additional Notes:

(1.) Horizons are not distinct.

(2.) There is little variation of the soils in an area of about 80 acres on Algoma beaches near the profile described and sampled.

(3.) An Eastport soil described on an Algoma beach in northern Emmet county is very similar to the soil described above as indicated below:

Eastport sand (NW$\frac{1}{4}$ of NW$\frac{1}{4}$ of SW$\frac{1}{4}$ of Sec. 29, T39N, R4W, Emmet county, Michigan):

Horizon	Depth	Texture	Color	pH
A1	0-4	Sand	10YR 6/3	6.5
A2	4-12	Sand	10YR 7/2	5.5
B(ir)	12-20	Sand	10YR 6/6	6.0
B3	20-28	Sand	10YR 6/4	
C	28 +	Sand	10YR 7/4	8.0+

(All horizons have single grain structure and loose consistence)

Rubicon Sand

Vegetation:

Dominant: Quaking aspen (Populus tremuloides), paper birch (Betula papyrifera), red oak, red maple.

Intermediate: Red maple, balsam fir (Abies balsamea).

Reproduction: White pine, red pine (Pinus resinosa), balsam fir, red oak, jack pine (Pinus banksiana).

Stumps: Red pine, paper birch.

Ground cover: Bracken.

Physiography and relief:

The soil described occurs on top of a Nipissing beach ridge, about 6 feet above the adjacent swales. The ridge is about 130 feet wide and trends southeast-northwest.

Drainage: well drained.

Ground water: deeper than 102 inches.

Moisture: moist.

Stoniness: none.

Elevation: 615 feet.

Location:

NE$\frac{1}{4}$ of SE$\frac{1}{4}$ of SE$\frac{1}{4}$ of Sec. 20, T38N, RIE, Benton Township, Cheboygan County, Michigan.

Horizon	Depth (inches)	Description
Aoo (Od)	-	Intermittent; partially decayed leaves and twigs
A1 (Vh)	0-2	Sand; brownish gray (10YR 3/1); very weak, very fine, granular structure; loose to very friable; very strongly acid (pH 4.7); clear, wavy boundary. 1 to 4 inches thick.
A2 (Em)	2-11	Sand; light yellowish grayish brown (10YR 6/2), light yellowish brown (10YR 6/4) in lower part; single grain structure; loose; very strongly acid (pH 4.8); gradual, wavy boundary. 6 to 13 inches thick.
Bir (Ii)	11-22	Sand; light brown to strong yellowish brown (7.5YR 5/6) and light brown to dark orange yellow (7.5YR 6/6) with spots of strong brown (5YR 4/6); weak, medium, subangular blocky structure; very friable to friable; strongly acid (pH 5.1); diffuse, irregular boundary. 2 to 30 inches thick with some tongues extending deeper than 66 inches.
B3 (Iw)	22-42	Sand; light yellowish brown to dark orange yellow (10YR 6/6); very weak, medium, subangular blocky structure; very friable; medium acid (pH 5.8); diffuse, wavy boundary. 7 to 36 inches thick.
C11 (Wm1)	42-86	Sand; light yellowish brown (10YR 6/4); single grain structure; loose; slightly acid (pH 6.2-6.4).
C12 (Wm2)	86-102	Sand; light yellowish brown (10YR 6/4); single grain structure; loose; slightly acid (pH 6.2-6.4).
D (Uu)	102+	Very gravelly.

Additional Notes:

(1.) B horizons are interspersed with each other.

(2.) Range in characteristics (representing 2 additional profiles from an area of about 80 acres in the vicinity of the profile described and sampled):

Horizon	Thickness	Texture	Color	pH
A1	2-3	Sand	10YR 4/1	5.0
A21	5-6	Sand	10YR 6/2-6/3	5.5
A22	4	Sand	10YR 6/4	5.5
Bir	8-12	Sand	10YR 5/8 7.5YR 5/8	5.8
B3	8-10	Sand	10YR 6/8	6.0
C	32-40 in. from surface; (mottled below 30-36 inches)	Sand	10YR 7/6-6/6	6.0

Kalkaska Sand

Vegetation:

Dominant: Paper birch, red maple, sugar maple (Acer saccharum).

Intermediate: Balsam fir, sugar maple, red maple.

Reproduction and seedlings: Sugar maple, striped maple, balsam fir, red maple, red oak.

Stumps: Balsam fir or eastern hemlock, white cedar, sugar maple, black cherry.

Physiography and relief:

Soil described occurs on a 2-3% slope on top of a knoll about 70 feet in diameter. The knoll is part of an Algonquin beach ridge.

Drainage: well drained.

Ground water: deeper than 113 inches.

Moisture: moist.

Stoniness: none

Elevation: 640 feet

Location:

NW¼ of NW¼ of NW¼ of Sec. 28, T38N, RIE, Benton Township, Cheboygan County, Michigan.

Horizon	Depth (inches)	Description
Aoo (Od)	1½ - 1	Partly decomposed leaves and twigs. 1/2 to 2 inches thick.
Ao (Of)	1-0	Fibrous root mat. 1/2 to 2 inches thick.
A1 (Vh)	0-1	Coarse sand; dark grayish yellowish brown (10YR 2/1); weak, fine, granular structure; very friable; very strongly acid (pH 4.7); abrupt, wavy boundary. 1/2 to 2 inches thick.
A2 (Em)	1-9	Coarse sand; yellowish gray to light grayish yellowish brown (10YR 7/2); single grain structure; loose to very friable; very strongly acid (pH 4.8); abrupt, wavy boundary. 5 to 12 inches thick.
Bhir (Ihi)	9-23	Coarse sand; strong brown (7.5-5YR 4/6); weak, coarse, subangular blocky structure; very friable to firm; medium acid (pH 5.7); gradual, irregular boundary. 5 to 42 inches thick. The material described below as the Bhm horizon is discontinuous and occurs in tongues and irregular chunks throughout the Bhir horizon. Some tongues of the Bhm extend deeper than 72 inches. The vertical dimensions of the chunks are usually greater than their horizontal dimensions. The Bhm material occupies about 20% of the volume assigned to the Bhir horizon.

Horizon	Depth (inches)	Description
		Bhm (Ih): Sand; dark grayish reddish brown (2.5YR 2/2) and dark reddish brown (2.5YR 2/4) in a network pattern; massive structure; weakly to strongly cemented; medium acid (pH 6.0).
B3 (IW)	23-38	Sand; light brown to dark orange yellow (7.5YR 6/6); weak, coarse, subangular blocky structure; very friable to firm; slightly acid (pH 6.2). 4 to 19 inches thick.
C11 (Wu1)	38-66	Coarse sand; light brown (7.5YR 6/4); single grain structure; loose, slightly acid (pH 6.4).
C12 (Wu2)	66-113+	Sand; light brown (7.5YR 6/4); single grain structure; loose; slightly acid (pH 6.4).

Additional Notes:

(1.) In any one horizontal plane of about one foot square from 18 to 42 inches deep, all three B horizons are evident.

(2.) Range in characteristics (representing 7 additional profiles from an area of about 640 acres in the vicinity of the profile described and sampled):

A1: 0-3 inches thick, average 2 inches; sand; 10YR 2/1; pH 4.5-5.3, average 5.0.

A2: 3-10 inches thick, average 6 inches; sand; 10YR 6/2, some 10YR 5/2; pH 5.0-5.8, average 5.4.

Bhir: (occurred in 3/7 of profiles) 2-3 inches thick; sand; 7.5YR 3/4, 5YR 3/2; pH 5.0.

Bir: 6-10 inches thick, average 7½ inches; sand; 7.5YR 4/4, 4/6, 10YR 4/4; pH 5.0-5.8, average 5.4.

B3: 10-28 inches thick, average 17 inches; sand; 10YR 5/8, some 10YR 5/6; pH 5.5-6.3, average 5.8.

C: 26-60 inches from surface, average 40 inches; sand; 10YR 6/4, 6/6, 7/4, 5/6; pH 5.8-8.3 (one site was calcareous), average 6.3.

Blue Lake Sand I

Vegetation:

Dominant: Sugar maple and beech (*Fagus grandifolia*) are most common; also yellow birch (*Betula lutea*), basswood (*Tilia americana*), and elm (*Ulmus*).

Intermediate: Sugar maple, beech.

Reproduction: Sugar maple, beech.

Stumps: Sugar maple, yellow birch, beech, eastern hemlock.

Physiography and relief:

Moraine. Site described occurs on a small ridge top which breaks to about a 20% slope to the southwest, west, and northwest; 7% to the east; and 4% to the southeast.

Drainage: well drained.

Ground water: deep.

Moisture: moist.

Stoniness: few stones.

Elevation: 850-900 feet.

Location:

NW¼ of NE¼ of Sec. 2, T5W, R36N, Pleasantview Township, Emmet County, Michigan. (865 feet south of Robinson road, 780 feet east of corner of Pleasantview and Robinson roads).

Horizon	Depth (inches)	Description
Aoo (Od)	1-0	Partially decomposed leaves and twigs. 1/2 to 1 1/2 inches thick.
A1 (Vh)	0-1	Loamy sand; dark grayish yellowish brown (10YR 2/1); weak, fine, granular structure; very friable; extremely acid (pH 4.4); abrupt, wavy boundary. 0-2 inches thick.

Horizon	Depth (inches)	Description
A2 (Em1)	1-9	Sand; light grayish brown (7.5YR 6/2); very weak, fine, granular structure; loose; extremely acid (pH 4.5); abrupt, irregular boundary (markedly tongued). 2 to 20 inches thick.
Bh (Ih)	9-15	Coarse sand; dark grayish brown (5YR 2/2) to grayish brown (5YR 3/2); very weak, coarse, subangular blocky to massive structure; friable to weakly cemented; very strongly acid (pH 5.0); clear, irregular boundary, (tongued); 1 to 8 inches thick with some tongues as deep as 34 inches.
Bhir (Ihi)	15-28	Coarse sand; moderate brown (5YR 3/3, 3/4, and 4/4); very weak, coarse, subangular blocky to massive structure; firm to moderately cemented; strongly acid (pH 5.4); clear, irregular boundary. 7 to 21 inches thick.
B3 (IE)	28-41	Sand; moderate brown (7.5YR 4/4) to light brown (7.5YR 5/4); very weak, coarse, subangular blocky structure; friable to very friable; medium acid (pH 5.6); clear, irregular boundary. 6 to 33 inches thick.
A'21 (Em2)	41-48	Sand; moderate yellowish brown (10YR 5/4)to light yellowish brown (10YR 6/4); very weak, very coarse subangular blocky structure; weakly coherent to very friable; medium acid (pH 5.6); abrupt; wavy boundary. Plus 6 to 8 thin bands; sand; light brown (7.5YR 5/4-6/4); fragile. 1/8 to 1/4 inch thick.
Bt1 (It1)	48-49	Sand; light grayish brown to light brown (5YR 5/3 to 7.5YR 5/3); weak, medium to coarse, subangular blocky structure; friable to firm, slightly hard when dry; strongly acid (pH 5.4); abrupt, wavy boundary.
A'22 (Em3)	49-51	(see A'21)

Horizon	Depth (inches)	Description
Bt2 (It2)	51-53	(see Bt1)
A'23 (Em4)	53-71	Coarse sand; moderate yellowish brown (10YR 5/4) to light yellowish brown (10YR 6/4); very weak, very coarse, subangular blocky structure; weakly coherent to very friable; medium acid (pH 5.9); abrupt, wavy boundary.
Bt3 (It3)	71-80	Coarse sand; light grayish brown to light brown (5YR 5/3 to 7.5YR 5/3); weak, medium to coarse, subangular blocky structure; friable to firm, slightly hard when dry; strongly acid (pH 5.4); abrupt, wavy boundary. 4 to 16 inches thick.
C1 (Wm)	80-106	Coarse sand; light grayish yellowish brown to light yellowish brown (10YR 6/3); single grain structure; loose; neutral (pH 7.2).
C2 (Pu)	106+	Similar to C1, except calcareous.

Additional notes:

(1.) Roots were more plentiful in the upper part of the Bt3 horizon than in the adjacent horizons.

(2.) In some places in the pit there were 6 light brown (7.5YR 5/4) Bt horizons between 41 and 71 inches.

(3.) Associated soil series in the general vicinity are Kalkaska and Leelanau. Since the Podzol sequum development is largely medial and the textures are more frequently sand than loamy sand, the latter would be a minor component.

Blue Lake Sand II

Vegetation:

Dominant: Sugar maple, big tooth aspen (*Populus grandidentata*), beech.

Reproduction and seedlings: Sugar maple, beech.

Ground cover: a few bracken.

Physiography and relief:

Moraine. Soil described occurs on a slope of about 7%. Relief is nearly level to the north and a 10-15% down-slope to the south.

Drainage: well drained.

Ground water: deep.

Moisture: moist.

Stoniness: A few stones in profile. A large (12x8x4 inches) dolomite boulder was 15 inches below the surface. No samples were taken from this segment of the pit.

Elevation: About 850 feet.

Location:

NW¼ of Sec. 11, T36N, R5W, Pleasantview Township, Emmet County, Michigan (300 feet south of Tower Road, 1/4 mile east of Pleasantview Road).

Horizon	Depth (inches)	Description
Ao (Of)	--	Intermittent; fibrous organic mat.
A1 (Vh)	0-1½	Loamy sand; dark grayish yellowish brown (10YR 2/1) to brownish gray (10YR 3/1); weak, fine, granular structure; very friable; very strongly acid (pH 4.6); abrupt, wavy boundary. 1/2 to 2 inches thick.
A2 (Em)	1½-6	Sand; light grayish brown (7.5YR 5/2); very weak, fine to medium, crumb structure; very friable to loose; very strongly acid (pH 5.0); abrupt, wavy boundary. 3-13 inches thick.

Horizon	Depth (inches)	Description
Bh (Ih)	6-10	Loamy sand; dark grayish brown (5YR 2/2) to grayish brown (5YR 3/2); weak to moderate, fine to medium, subangular blocky structure; very friable to firm (some weakly cemented chunks); very strongly acid (pH 5.0); abrupt, irregular boundary. 2-10 inches thick.
Bhir (Ihi)	10-17	Sand; moderate brown (5YR 3/3-4/4); weak, fine to medium, subangular blocky structure; very friable to firm; strongly acid (pH 5.1); clear, irregular boundary. 3 to 12 inches thick.
B3 (IE)	17-25	Sand; moderate brown (7.5YR 4/4) to light brown (7.5YR 5/4); very weak, medium to coarse, subangular blocky structure; very friable; strongly acid (pH 5.2); gradual, wavy boundary. 5 to 17 inches thick.
A'2 + Bt (Em+It)	25-45	A'2: Sand; light brown (7.5YR 6/4) to light yellowish brown (10YR 6/4); single grain structure; loose; strongly acid (pH 5.2). Bt: 4 to 6 bands 1/8 to 1/2 inch thick; slightly finer in texture than A'2; light brown (7.5YR 5/4); firm; abrupt, smooth to wavy boundary.
Bt (II, It)	45-52	Gravelly coarse sand; moderate brown (5YR 4/4); very weak, medium to coarse, subangular blocky structure; friable; very strongly acid (pH 4.9). 3 to 7 inches thick.
C11 (Wm1)	52-72	Sand, light brown (7.5YR 5/4); single grain structure; loose; very strongly acid(pH 5.0).
C12 (Wm2)	72-92	Coarse sand; light brown (7.5Y 5/4); single grain structure; loose; strongly acid (pH 5.3).
C13 (Wm3)	92-105+	Sand; light brown (7.5YR 5/4); single grain structure; loose; medium acid (pH 5.7).

Additional notes:

(1.) Range of depth to C11 horizon is 23 to 42 inches. A couple of tongues of B in gravelly streaks extend deeper.

(2.) The podzol B horizon seems to overlap the thin bands in the A'2 - Bt horizon.

(3.) Leelanau is the most commonly associated soil series in this vicinity. The texture of the morainic material is largely loamy sand.

Podzol B-Horizon Designation

The degree of development of the podzol B horizon, used in classifying Podzols, is reflected in its horizon designation. It is commonly judged by soil color and designated by Bh, Bhir, or Bir. These designations represent podzol B horizons having an apparent enrichment in humus, humus and iron, and iron, respectively. The following relationship between soil color and horizon designations was noted in the soils previously described and may serve as a guide in assigning horizon names.

Table 5. Relation of the colors of the podzol B horizons and the subscripts of their designations.

Hue	Value				
	2	3	4	5	6
2.5YR	h	x			
5 YR	h	h hir	hir		
7.5YR		hir	hir ir	ir	ir
10 YR			ir	ir	(ir)

The subscripts h, hir, and ir are placed in the diagram according to the Munsell designation of the color of the B horizon they represent. The x represents a likely inclusion in the scheme but this color was not observed in the soils described. Chromas were, in general, 2 for the "h" group; 3, 4, and 6 for the "hir" group; and 4, 6, or 8 for the "ir" group. The rings enclose the combinations of hue and value proposed to be grouped together in the three categories.

V. LABORATORY PROCEDURES

Physical Analyses

Sample preparation

Each bulk soil sample was thoroughly air dried, weighed and passed through a 2 mm sieve. The particles remaining on the sieve were weighed and reported as percentage of the bulk sample. The soil material passing through the sieve (fine earth) was thoroughly mixed and a subsample was taken for laboratory analyses.

Particle size analysis

A 50.0 g sample was placed in a tall-form 600 ml beaker, digested with 30% technical grade H_2O_2 to destroy organic matter, and the resulting suspension was adjusted to about 0.1 N in HCl to dissolve carbonates and other acid soluble materials such as iron coatings on soil particles. After occasional mixing and standing overnight, most of the supernatant solution was poured off and discarded. The flocculated suspension was filtered through a hard (Whatman No. 50) filter paper in a Buchner funnel. It was washed about 5 times with 0.1 N HCl and then several times with distilled H_2O to remove Cl^-. The sample was then transferred from the filter to a glass shaker bottle with distilled H_2O. The suspension was titrated to the phenolphthalein end point (pH 9) with 0.1 N NaOH, and then it was shaken in a reciprocating shaker for 24 hours. Occasional checks were made of the pH of the suspension and NaOH was added if necessary during the shaking. The suspension was passed through a 300 mesh sieve to separate the sands from the silt and clay. The suspension of silt and clay was diluted to 1000 ml. A subsample of the suspension was taken with a 25 ml pipet while it was being stirred to obtain the total content of silt plus clay. After coming to constant temperature, the cylinder was shaken end-over-end to disperse the sediment evenly throughout and a subsample was taken with the pipet at a depth calculated according to Stokes law for particles 2 μ in diameter assuming a particle density of 2.65. The suspensions removed with the pipet were oven-dried at 105° C and weighed. The sands were oven-dried, shaken in a nest of sieves 2½ inches in diameter on a mechanical shaker for 10 minutes, and then the separates were weighed. Duplicate mechanical analyses were made and the results were reported on an air dry basis. (The differences between air dry and oven dry weights of the entire sandy soil samples were negligible.) Clay for mineralogical analysis was separated from the silt of some samples by 5 or more decantations with a siphon. The sand fractions were also saved for mineralogical analyses.

Water retention

Water retention by undisturbed soil cores was measured at saturation; at 10, 20, 30, 40 and 60 cm of water tension by the blotter paper-tension table method of Leamer and Shaw (1941); and at 1/3 and 1 atmosphere tension by the ceramic plate-pressure cooker method of Richards and Fireman (1943) and Richards (1948). Water retention at 5 and 15 atmospheres was measured on disturbed soil samples using Richard's pressure membrane apparatus (1941, 1947). Stolzy (1954) has described some of the details and adaptations in the MSU laboratory of the methods referred to above.

Determinations of water held at 0 to 1 atmosphere tension were made on 6 replicate core samples and that held at 5 and 15 atmospheres on duplicate samples. Percent water retained at each tension was expressed on an oven-dry basis.

Bulk density

Bulk density was calculated by dividing the oven dry weight of the core sample used for the water retention determinations by the volume of the core. Six replications were used.

Chemical Analyses

Total carbon

Total carbon content was determined by the dry combustion method in a stream of oxygen using the sequence of gas purifying devices and collection tube suggested by Kolthoff and Sandell (1952, p. 675). Soil samples were ground in an agate mortar and pestle to pass through a 0.25 mm sieve and thoroughly mixed. From 2 to 5 g of the ground sample was weighed exactly and placed in an alundum boat. About 0.25 g of MnO_2 was mixed with the sample to provide an additional source of O_2 (Winters and Smith, 1929), before it was placed in the silica tube of the combustion furnace at 940° C for 35 to 40 minutes. Determinations were made in duplicate.

Carbonate-carbon

The carbonate content of soil samples having a pH of 6.4 or higher was estimated according to the method of Jackson (1958, pp. 77-78) for the neutralization equivalence of limestone. Determinations were made on duplicate 5.00 g samples ground to pass a 0.25 mm sieve. The results were calculated as percent of C as $CO_3^=$ in the air dried sample.

Organic matter

The organic carbon content was calculated by subtracting the $CO_3^=$ carbon from the total C. Organic matter contents were estimated by multiplying the organic carbon content by 1.724 (Jackson, 1958, p. 206).

Total nitrogen

Total nitrogen was determined by the Kjeldahl method as described by Jackson (1958, pp. 183-190), except that Se was omitted from the digestion salt mixture. Duplicate determinations were made.

Reaction

Soil pH was measured on a soil-water mixture at the "water saturation percentage" with a Beckman zeromatic glass electrode pH meter. Duplicate determinations were made.

Extractable iron and aluminum

The amount of iron and aluminum removed from the entire soil was measured by the sodium dithionite-citrate-bicarbonate method of Jackson and Mehra (1960). The purpose of the dithionite was to reduce ferric iron to ferrous iron, citrate was to act as a complexing or chelating agent, and bicarbonate was to serve as a buffer. The values obtained by this method were not called "free oxides" because much of the iron and some of the aluminum extracted by this method probably occurred in the soil in forms other than oxides, such as a complex with organic compounds, which would be brought into solution by the citrate ion.

The published procedure was followed except for the following modifications or adaptations: 10.0 g of air dry soil were placed in a 125 ml. Erlenmeyer flask, 40 ml. of 0.3 N Na-citrate and 5 ml of 1 M $NaHCO_3$ were added, and the flasks were placed in a water bath held at 80^oC until the temperature of the contents was $75-80^oC$. Then 1 g $Na_2S_2O_4$ was added, the flasks were shaken for one minute on a gyrating shaker at full speed, and placed again in the bath for 15 minutes. The suspension was filtered through Whatman No. 42 filter paper in a

Buchner funnel. The sample was washed twice by decantation and again while in the funnel with the Na-citrate solution. The soil particles on the funnel appeared very free from coatings. The filtrate and washings were diluted to a volume of 500 ml.

Iron was determined, after H_2O_2 oxidation of citrate and organic matter in solution, by the KSCN colorimetric method (Jackson, 1956).

Consistent results were not obtained when Al was determined on the H_2O_2-oxidized solution, probably because citrate interferes with the Aluminon determination of Al and this organic ion may not have been completely destroyed. Because of this, the soil extract was digested in a ternary mixture of concentrated acids (100 ml HNO_3, 10 ml H_2SO_4, 40 ml $HClO_4$) and evaporated to dryness. The residue was taken up in HCl, the pH adjusted to 4.2 ± 0.1, and the solution brought to a known volume. An aliquot of this solution was placed in a 25 ml volumetric flask, 1.0 ml of 4% thioglycollic acid was added to prevent the Aluminon from forming a complex with Fe (Robertson, 1950; Chenery, 1948), and the color was developed essentially according to the procedure of Jackson (1958, par. 11-99). A modification used was that the solutions were kept in a boiling water bath for 10 minutes (Yuan and Fiskell, 1959) to facilitate color development before they were cooled to room temperature and brought to volume.

Available phosphorus*

Available phosphorus was extracted from about a 2.5 g sample with 20 ml of a solution 0.03 N in NH_4F and 0.025 N in HCl (Bray and Kurtz, 1945, No. 1 solution). The suspension was shaken for one minute and then filtered. Phosphorus in solution was determined colorimetrically using the ammonium molybdate-hydrochloric acid solution of Dickman

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*Analyses by Soil Testing Laboratory, Michigan State University. Soil samples were measured volumetrically, approximating the weight of sample given in the procedure.

and Bray (1940) and the 1-amino, 2-naphthol, 4-sulphonic acid reducing agent developed by Fiske and Subbarrow (1925).

Exchangeable bases*

Exchangeable bases were extracted by adding 20 ml of neutral 1 N NH_4Ac to about a 2.5 g soil sample, shaking the suspension for one minute, and filtering. Calcium, magnesium and potassium were determined using a flame photometer.

Exchangeable hydrogen*

Exchangeable hydrogen was estimated by the Shoemaker, McLean, and Pratt (1961) buffer method.

Cation exchange capacity

Cation exchange capacity was estimated by summing the four exchangeable cations; hydrogen, calcium, magnesium, and potassium.

Mineralogical Analyses

Quartz determination

The quartz content of the total sand fraction was determined with the X-ray diffraction spectrometer using fluorite as an internal standard. Klug and Alexander (1954, pp. 410-438) discussed the importance of using an internal standard in quantitative work and presented the theoretical relationship between X-ray pattern intensities and the absorptive properties of the sample. They recommended using fluorite as the internal standard for quartz determinations because it provides a strong

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*Analyses by Soil Testing Laboratory, Michigan State University. Soil samples were measured volumetrically, approximating the weight of sample given in the procedure.

diffraction line near the strong diffraction line of quartz and because it does not overlap lines of quartz or other common constituents of the sample.

Precision and reproducibility of measurements using the Geiger-counter method of detecting X-radiation depends on a number of factors (Klug and Alexander, p. 422): (1.) crystallite size of the powder, (2.) mixing of the standard with the sample, (3.) mounting of the specimen, (4.) correction for dead-time losses, (5.) type of technique--manual scanning or automatic recording, and (6.) instrumental stability and reproducibility.

Particle size is quite critical. Powders passed through a 50 micron sieve should give fairly precise results if they are rotated around an axis normal to their surfaces and several replications are made (Klug and Alexander, p. 295). More reproducible results are obtained however with a finer particle size group--e.g., < 5 micron fraction.

Dead time losses were thought to be negligible. When dead time losses become significant, the response deviates from linearity. Under the conditions used, the maximum number of counts per second was around 200. According to the manual supplied with the instrument used, the response of the Geiger tube is linear up to about 800-1000 cps.

All five sand fractions from the second replication of particle size analysis of each soil sample were poured into a vial and tumbled to mix. A subsample was secured by continually dividing the sample in half, using a glass funnel with a razor blade beneath the spout to divide the sand into equal portions, until a sample weighing about 1.1 to 1.2 g was obtained. This subsample was ground in an agate mortar and pestle until it passed through a 0.1 mm sieve. It was divided in half by pouring on over-lapping sheets of paper and each sample handled as follows.

The 0.55-0.60 g sample was placed in the stainless steel capsule of a Wig-L-Bug (Crescent Dental Manufacturing Company) amalgamator, the pestle introduced, and the sample ground four minutes. An exactly equal weight of fluorite (Matheson, calcium fluoride reagent, powder) was added by balancing it against the ground sand sample on opposite pans of an analytical balance and the two components were mixed for one minute, in a larger plastic vial containing a plastic ball, with the Wig-L-Bug. The mixed sample was poured into a shallow mount, pressed down with a glass slide, and leveled with a razor blade. The mount was placed in the spinner mechanism which rotated the sample around an axis normal to its surface and scanned back and forth between 25.5° and 29° 2θ by setting the scanning limit arms of the wide-range goniometer. Two to three tracings of the diffraction pattern were made of both the quartz peak (3.35 Å) and the fluorite peak (3.16 Å) with the chart recorder. After subtracting the background the ratio of the average height of the quartz peaks to the average height of the fluorite peaks (H_Q/H_F) was calculated.

Quartz for a standard curve was prepared by grinding pure quartz (Fisher, silica, obtained from D. E. Van Farowe, chief chemist, Division of Occupational Health, Michigan Department of Health) in an agate mortar to pass through a 0.1 mm sieve, digesting the crystals in concentrated HCl, washing them with water, and drying. Subsamples of 0.55 g were ground in the Wig-L-Bug and standards of 0, 20, 40, 60, 80, and 100% quartz were made up using calcium carbonate as a filler. These were balanced with an equal weight of fluorite and treated the same as the sand fraction of each soil sample.

In a grinding experiment, grinding times of 2, 4, 8, and 16 minutes gave nearly the same values for H_Q/H_F. Grinding 2 minutes was sufficient to cause 95% or more of the quartz to pass through a 50 micron sieve. Even with longer grinding times, not all of the sample became finer than 50 microns and the coarse crystals may have been the cause of some variability between duplicate readings of the same sample. A grinding time of 4 minutes was chosen.

Quartz contents of the silt and clay samples were determined in the same way except that these samples were not ground.

The average standard deviation from the mean of duplicate determinations, $\bar{s}^*$, for the unknown sand samples was ± 2.7% which compares well with the commonly expected precision of ± 2 to ± 4%. (Klug and Alexander, 1954, p. 424).

Conditions used on the Norelco X-ray unit with wide range goniometer and Brown recorder were: CuKα radiation; 35 kv; 20 ma; 1° divergence and scatter slits; 0.003" receiving slit (+ Ni filter); time constant, 4 seconds; scanning rate, 1° 2θ per minute; scale factor, 8 (occasionally 4); multiplier, 0.8. Chart peaks were usually between 20 and 50 with S.F. = 8.

Identification of clay minerals

An oriented clay mineral sample was prepared essentially according to the method published by Kinter and Diamond (1956). The clay was deposited on a porous ceramic plate by drawing the water from a Na-clay suspension (from particle size analysis) through the plate, using a vacuum pump, leaving a thin layer of clay on the surface of the plate. The sample thus deposited was leached with a solution 0.1 $\underline{N}$ in $MgCl_2$ and containing 3% glycerol by volume, washed with a 10% glycerol solution, air dried, and then dried over $CaCl_2$ in a dessicator. An X-ray diffraction pattern was obtained from this Mg-saturated glycerol-solvated sample.

After X-raying, the plate was again placed in the sample holder, vacuum was applied, and the clay film was leached with several increments of 0.1 $\underline{N}$ KCl and washed with water. This preparation was dried

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* $\bar{s} = \dfrac{\Sigma \sqrt{2\left(\dfrac{X_1 - X_2}{2}\right)^2}}{M}$ where X_1 and X_2 are results of duplicate determinations and M is the number of samples analyzed.

first at room temperature and then at 110° C. The interplanar distance of some of the 2:1 clay minerals had now become smaller and the plate was again X-rayed.

Finally, the plate was heated at 550°C for several hours to destroy the lattice structure of minerals of the kaolinite family and the plate was X-rayed for the third time.

The three X-ray tracings were used for the qualitative identification of the clay minerals present according to Table 6 (see Grim, 1953, Chapter 5).

Table 6. Approximate first order basal spacings of clay minerals according to previous treatment.

Mineral	Treatment Mg^{++}, glycerol	 K^{+}, 110°C	 K^{+}, 550°C
	Å	Å	Å
Kaolinite	7	7	(decomposes)
Halloysite	10	7	(decomposes)
Montmorillonite	18	10	10
Illite	10	10	10
Vermiculite	14	10	10
Chlorite	14	14	14

Instrumental conditions used were: CuKα radiation; 35 kv; 20 ma; 1° divergence and scatter slits; 0.006" receiving slit (Ni filter); time constant, 4 seconds; scanning rate, 1° 2θ per minute; scale factor, 8, 16, or 32; multiplier, 0.8.

Differential dissolution analysis

According to Hashimoto and Jackson (1960), boiling a clay sample in 0.5 N NaOH for 2½ minutes will dissolve allophane but not other clay minerals. After dehydroxylation at 500°C, kaolinite and halloysite become amorphous and are also dissolved by boiling in NaOH. Differential dissolution analyses were carried out just as described by Hashimoto and Jackson (1960) and Si and Al were determined colorimetrically (Jackson, 1958) using the modification of the Aluminon method for determining Al listed under "Extractable iron and aluminum."

For the dissolution analyses clay fractions were separated from the bulk soil sample according to the procedures of Jackson (1956, p. 111) with minor modifications because of the small amount of clay in the soil samples used. The soil sample was digested in reagent grade H_2O_2 to remove organic matter, and the resulting paste was diluted with water and the pH adjusted to 3.5 to 4.0. The supernatant solution was poured off and discarded and the solids were passed through a 0.177 mm sieve to get rid of most of the sand. The < 0.177 mm fraction was cleaned with a sodium citrate-dithionite-bicarbonate solution, centrifuged, and the solids boiled in a 2% Na_2CO_3 solution for dispersion. The solids remaining after centrifugation were passed through a 50 μ sieve, and the < 50 μ fraction diluted to 1000 ml for determination of clay content and separation of clay from silt by siphoning. The clay was flocculated with a minimum of HCl, dried under infra-red lamps and crushed in an agate mortar. This powder sample was also used for the total analyses.

Total chemical analysis of clays

The powder sample described in the previous section after being dried in the oven at 110° C was used for total analysis by the semi-micro system of Jackson (1958, Chapter 11). Total Si was determined after fusion with Na_2CO_3. K, Mg, Fe, and Al were determined using the residue following HF decomposition of the silicate minerals. K and Mg were determined using solution "B" (Jackson, 1958, Fig. 11-1) following the HNO_3 treatment and evaporation to dryness. Al and Fe were determined using the precipitate following the NH_4OH separation of solution "A.." Al was determined by the Aluminon method with the modifications listed under "Extractable iron and aluminum," and Fe was determined by the KSCN method.

Micropedology

Mineralogy of fine sand fraction

The fine sand fraction from the first replication of the particle size analysis was further cleaned with a citrate-dithionite-bicarbonate solution (Jackson and Mehra, 1960) and used for identification of heavy minerals. The density separation was made in glass funnels using tetrabromoethane adjusted to a density of 2.80 with nitrobenzene.

Duplicate density separations were made, the first using 1 to 2 g and the second using an amount of the fine sand fraction which would yield around 800-1000 (ca.15 mg) heavy mineral grains so that they all could be mounted on two slides and counted. The heavy mineral grains from this separation were split by halving with small sheets of paper and mounted in a synthetic resin (Araclor, Monsanto, R.I. = 1.66).

Mineral grains were identified and counted by using standard optical mineralogical procedures and comparing the unknown mineral with sketches and descriptions in reference books (Krumbein and Pettijohn, 1938; Milner, 1952). The percent of garnet on duplicate slides was determined for a sample and it was found that there was little difference between the slides; hence, it was thought there would be no great differences between duplicate slides in the percentage of any species, and therefore one slide (300-700 grains) was counted for each sample.

Thin sections

Thin sections were prepared according to the method of Dalrymple (1957) using Lakeside 70C thermoplastic cement (Hugh Courtright and Company, 7652 Vincennes Avenue, Chicago 20, Illinois). An undisturbed soil sample was removed from a soil core with an aluminum frame. In taking these samples, one of the six sides of the frame was left open--for horizontal samples, the top (1 x $1\frac{1}{2}$ in.); and for vertical samples the end ($\frac{1}{4}$ x 1 in.). The frame was fastened together with copper wire and the specimen in the holder was presoaked in absolute methyl alcohol, placed in a mixture of about 5 parts alcohol to one part crushed cement, and heated gently to evaporate the alcohol. When a test sample of the cement became brittle on drying (in about 3 hours) the specimens were taken out of the cement, cooled, and the aluminum holder removed. Thin sections were made from these consolidated samples (by Cal-Brea, P.O. Box 254, Brea, California) and examined under the petrographic microscope.

VI. RESULTS AND DISCUSSION

Depth Functions of Soil Properties

Physical and chemical properties of the soil horizons are presented in Tables 15 through 19 in the Appendix. Some of this data will be presented here in graphic form by plotting soil properties versus depth in order to show differences in depth functions among pedons of the chronosequence.

Particle size distribution

Particle size distribution is shown in Figure 2. Medium sand is the predominant size fraction in all except one horizon (Blue Lake I C), yet many of the textures are classified as coarse sand according to the USDA system (Soil Survey Staff, 1951). A certain amount of stratification is evident in all five profiles. In a few horizons this stratification appears more pronounced when one considers the content of particles > 2 mm in diameter. The D horizon of Eastport, the C2 of Blue Lake I, and the Bt of Blue Lake II contain from 18-28% gravels.

Silt and clay contents

Silt and clay contents are shown graphically in Figure 3 at a scale which shows their distribution in the profiles better than does Figure 2. Although the silt content of the parent materials of all soils is low, much larger amounts are found in the uppermost horizons. The amount of silt present in the upper parts of the profiles increases with age of the soil. Although the silt could have been added to the soils as loess, it seems more likely that it weathered from the sand fraction

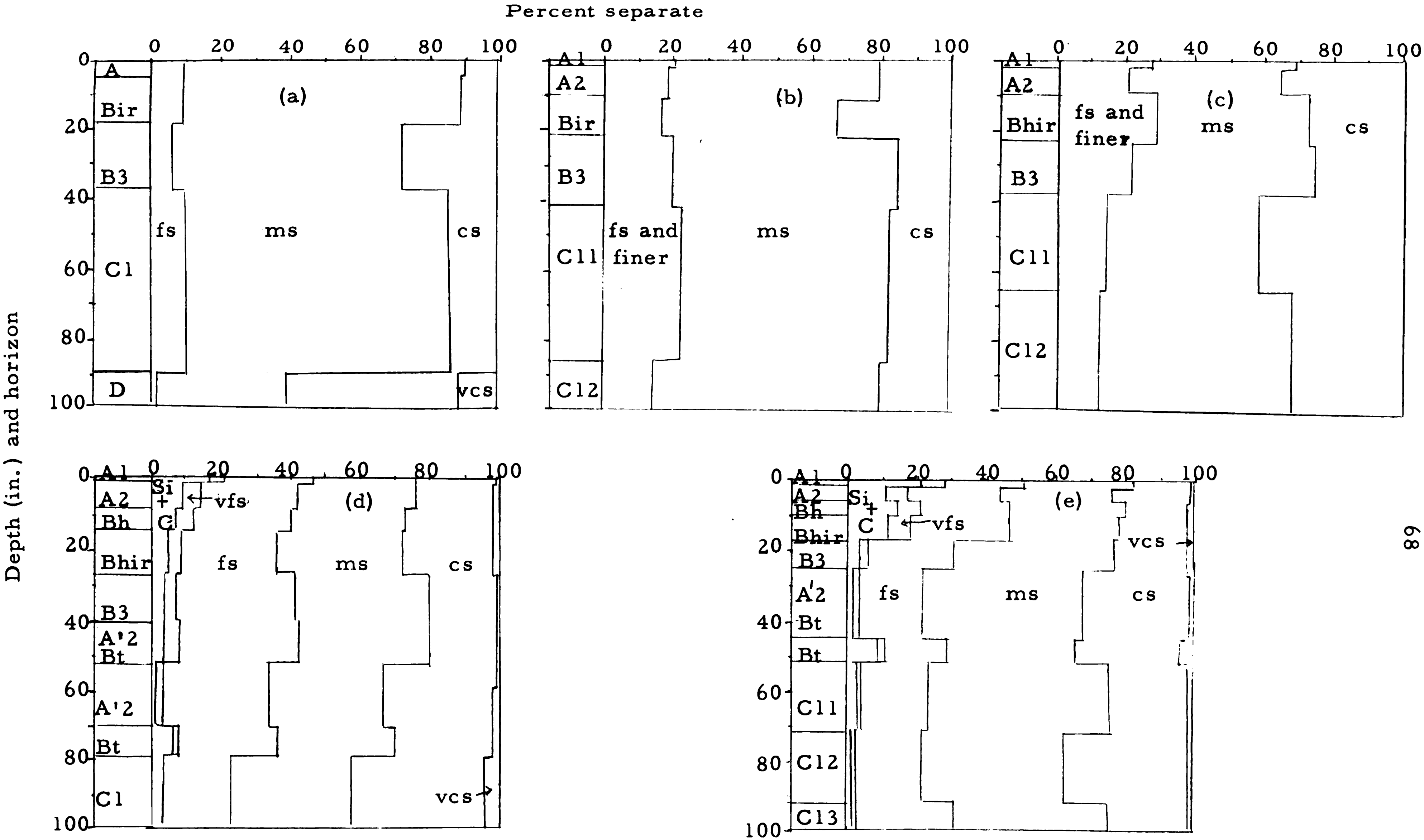


Figure 2. Particle size distribution of the organic matter-free and carbonate-free fine earth (< 2 mm) fraction as a function of depth and horizon for five soils: a, Eastport; b, Rubicon; c, Kalkaska; d, Blue Lake I; and e, Blue Lake II.

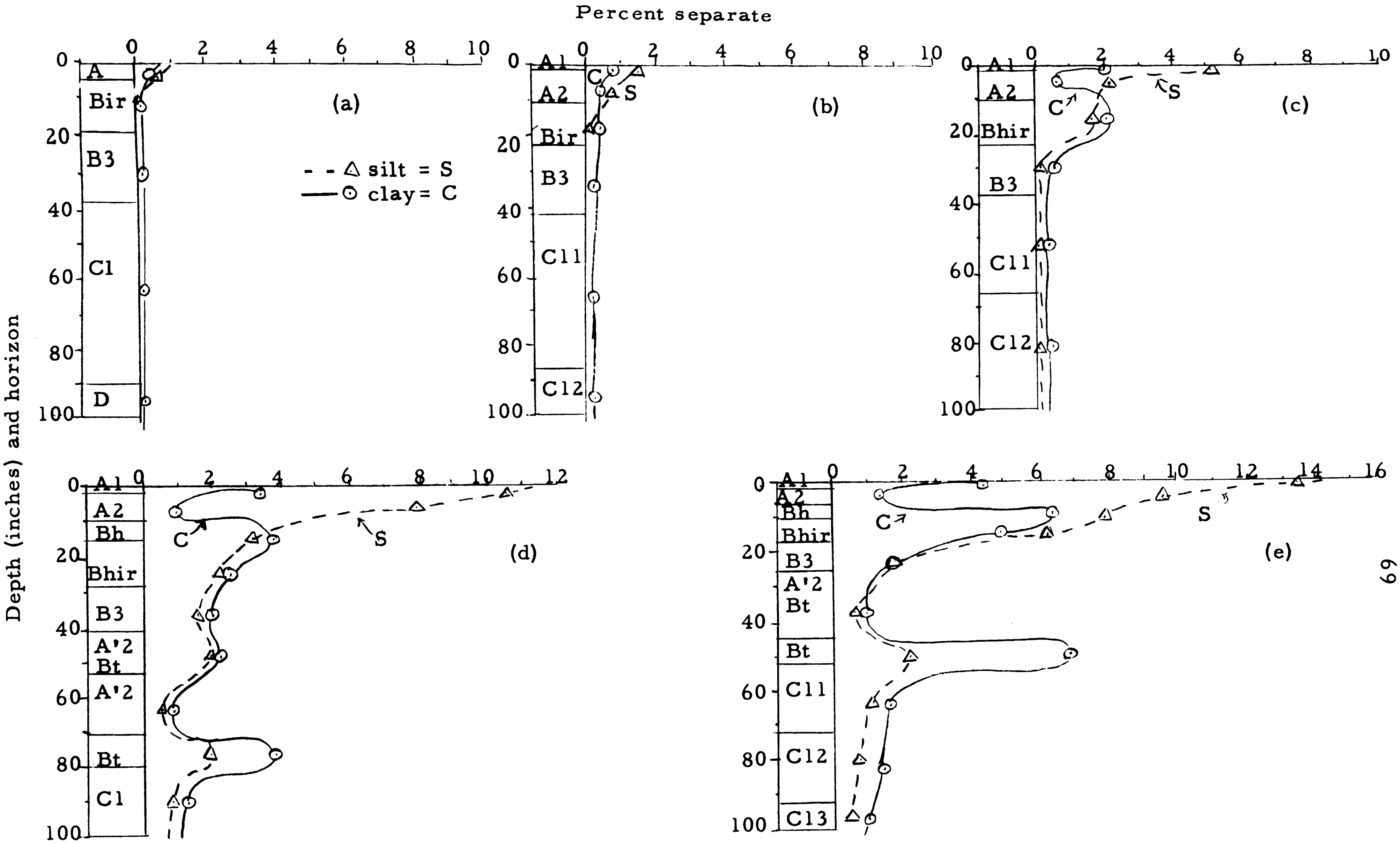


Figure 3. Silt (2-50μ) and clay (< 2μ) contents of the entire fine earth fraction as functions of depth and horizon for five soils: a, Eastport; b, Rubicon; c, Kalkaska; d, Blue Lake I; and e, Blue Lake II.

because its distribution in the profile follows the pattern of intensity of physical weathering, i.e., increasing with proximity to the soil surface. Repeated freezing and thawing could cause physical disintegration such as this. St. Arnaud (1961) demonstrated that significant amounts of sand were lost from the coarse sand fractions of the Ae and C1 horizons of a Grey Wooded soil when they were subjected to 200 cycles of freezing and thawing. The maxima of silt contents in the Bt horizons of the two Blue Lake soils may be best explained as relics of stratification of the parent materials.

The depth functions of clay contents, Figure 3, show progressively increasing minimum-maximum relationships with increasing age of the soils. In the Eastport the amount of clay in the A horizon is greater than that in the B, in the Rubicon the two are equal, and in the Kalkaska and Blue Lake soils there is more clay in the podzol B horizons than in the A2 horizons. This could be interpreted to mean that translocation of clay from the A to the podzol B horizons began at about the Rubicon (3000 year) stage of the chronosequence. The apparent increase in the amount of clay in the profile in excess of that supplied by the parent material also increases with the age of the soils. The relatively low clay content in the horizons above the textural B horizons of the Blue Lake soils suggests that, in part at least, the clay accumulation in these B horizons is due to translocation of clays from the overlaying A'2 horizons.

Porosity

Relative volumes of capillary pores, non-capillary pores, and solid particles were calculated from water retention and bulk density (BD) data as follows:

Per cent (vol.) total pore space = per cent H_2O (saturated) x BD

Per cent (vol.) capillary pore space = per cent H_2O (0.06 atm) x BD

The values found are shown graphically in Figure 4. Except for two horizons, Rubicon A2 and Blue Lake II Bh, these values were within 3 percentage points of total porosity calculated by:

$$\text{Per cent (vol.) total pore space} = \left(1 - \frac{BD}{\text{particle density}}\right) \times 100$$

where the average particle density was assumed to be 2.66, the specific gravity of quartz.

Although the non-capillary pore space of the parent materials or A'2 horizons of all soils ranged between 4 and 7%, it was greater near the surface especially in the Blue Lake soils.

All profiles showed a trend toward greater capillary and total porosity with proximity to the soil surface. This could be caused by a loss of soil materials or by a "fluffing-up" process in which material was not lost but the average distance between grains became greater with the cultivating action of roots, burrowing of soil animals, or freezing and thawing of soil water.

Reaction

Figure 5 shows that the pH is lowest in the A1 horizons and increases with depth in the profiles. Exceptions to this continuous increase are the textural B horizons of the Blue Lake soils which are more acid than the neighboring horizons. The reactions of the 0-15 inch layer follow the same general pattern in all soils regardless of age. Deeper in the profiles, from about 30 to 70 inches, the reactions are relatively uniform within a profile but do not follow a time or developmental sequence among profiles. The Blue Lakes are most acid, followed by Eastport, Rubicon, and Kalkaska, the least acid. Calcareous sands were found in the Eastport and Blue Lake I soils below 7 to 8 feet.

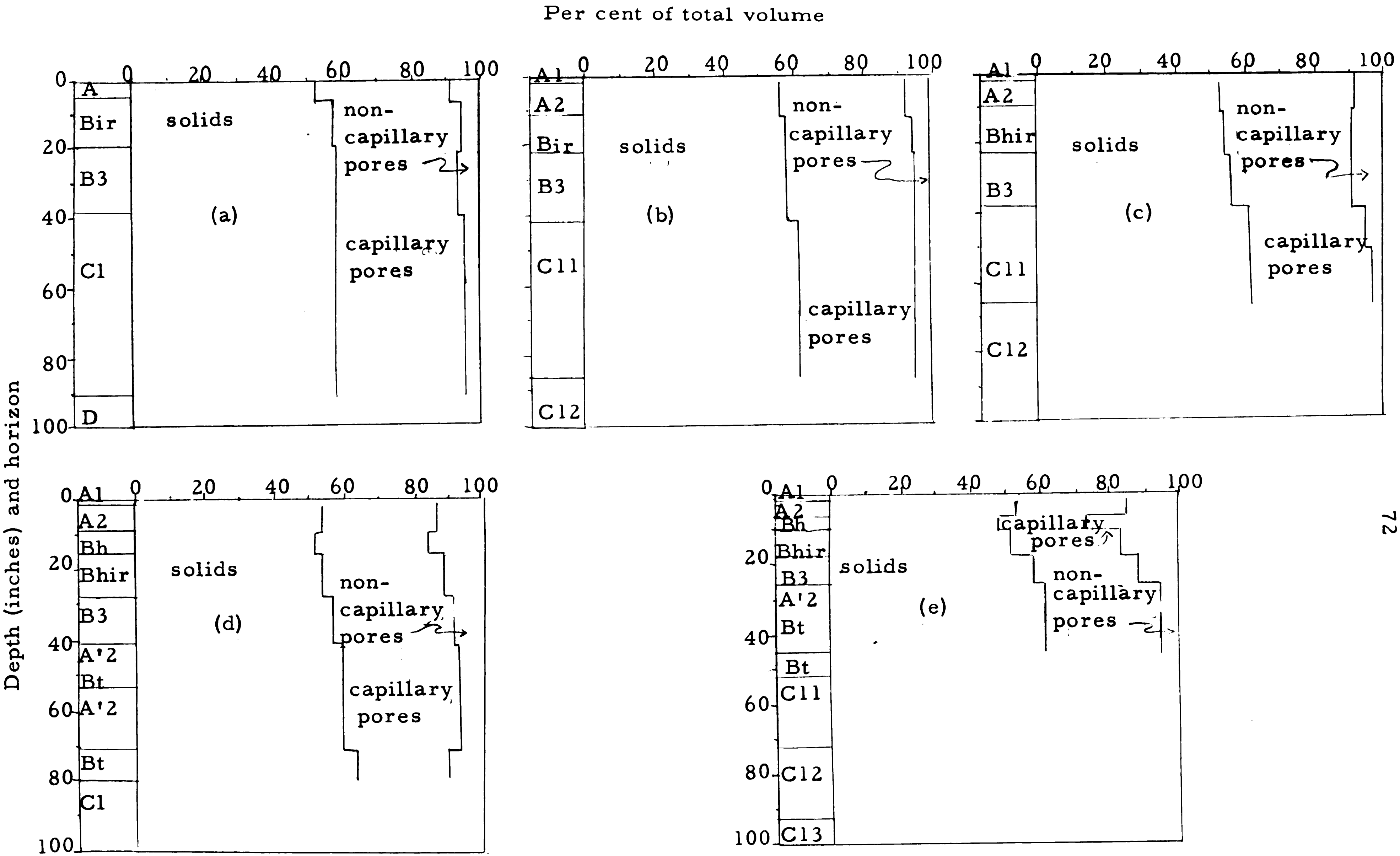


Figure 4. Capillary and non-capillary pore space as functions of depth and horizon for five soils: a, Eastport; b, Rubicon; c, Kalkaska; d, Blue Lake I; and e, Blue Lake II.

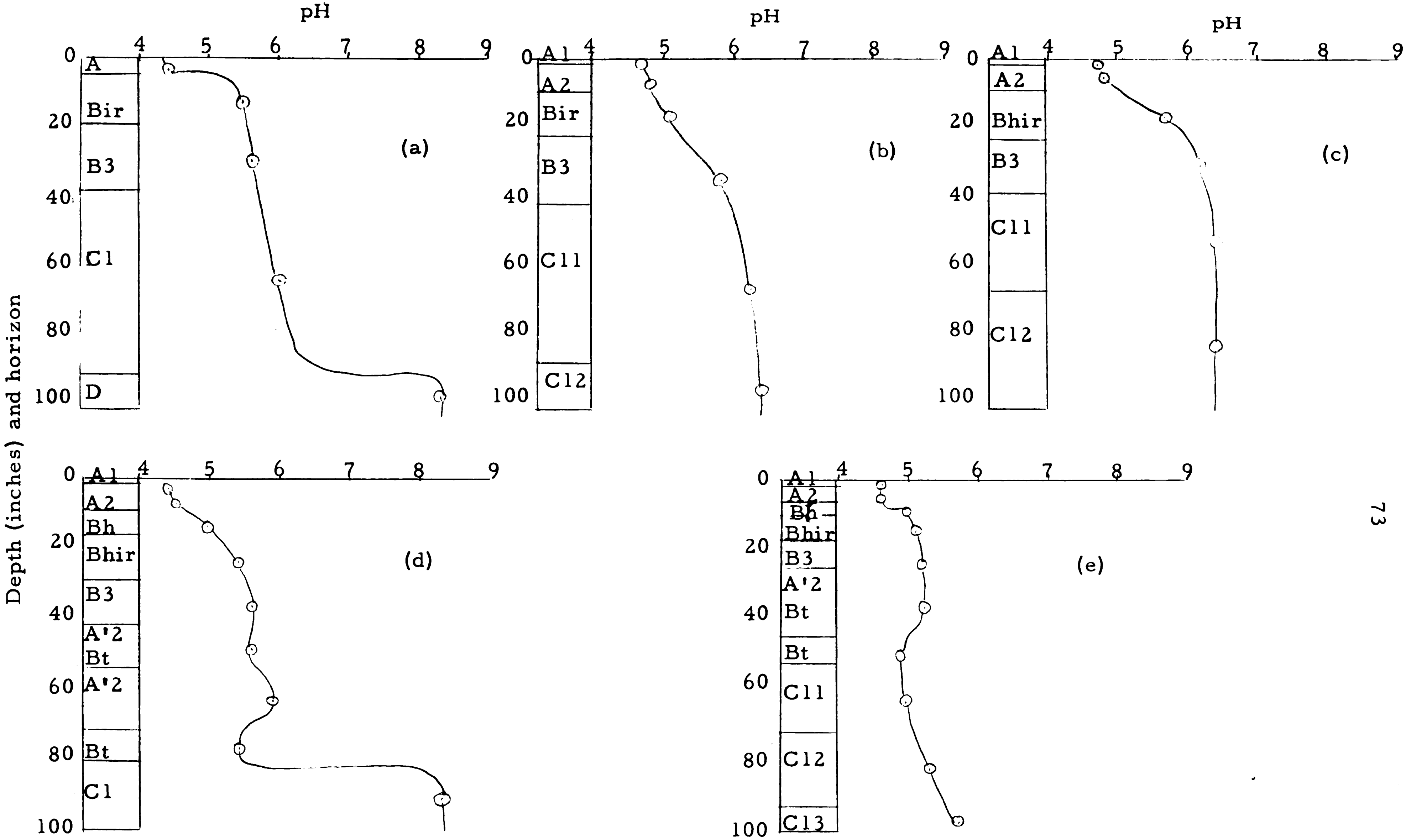


Figure 5. Reaction (pH) as a function of depth and horizon for five soils: a, Eastport; b, Rubicon; c, Kalkaska; d, Blue Lake I; and e, Blue Lake II.

Extractable sesquioxides

The extractable aluminum and iron contents in the B horizon of the youngest soil show subsurface maxima and the intensities of these maxima increase with increasing age of the soils (Figure 6). There is some evidence that the B horizons develop from the bottom upward as suggested by Aaltonen and Mattson (from Jenny, 1941), and by Kawaguchi and Matsuo (1960). However, in order to verify this, the A and B horizons of the Rubicon, Eastport, and possibly a younger soil would have to be sampled at closer intervals to ascertain the exact depth of the sesquioxide maxima. Since the Fe_2O_3 content of the B3 of Eastport is nearly as great as that of the B2, the maximum may occur near the boundary of the two horizons, 19 inches. In the Rubicon and older soils the iron maxima are clearly in the uppermost B horizon. The depths to the centers of these horizons are $16\frac{1}{2}$, 16, and 10 inches for the Rubicon, Kalkaska, and the average of the Blue Lakes, respectively. The shapes of the curves reported here show a marked similarity to the schematic graph for a chronosequence of soils shown in Jenny's book (1941, p. 41) and to the hypothetical curves of iron migration of Kawaguchi and Matsuo (1960).

Disregarding the Kalkaska Bhm horizon, which occurs scattered throughout the Bhir horizon, these conclusions can be drawn. In all except the youngest soil there is more extractable Al_2O_3 than extractable Fe_2O_3 in the B3 horizons, while there is more iron than aluminum in the upper part of the podzol B of all five soils. The organic carbon maxima coincide with the iron maxima in all soils and with the aluminum maxima in the three youngest soils, but in the Blue Lakes the aluminum maxima occur lower in the profile than the carbon-iron maxima. Thus, the general trend is for aluminum to accumulate slightly deeper in the podzol sequum than iron and to a greater extent than iron in the Bt horizons.

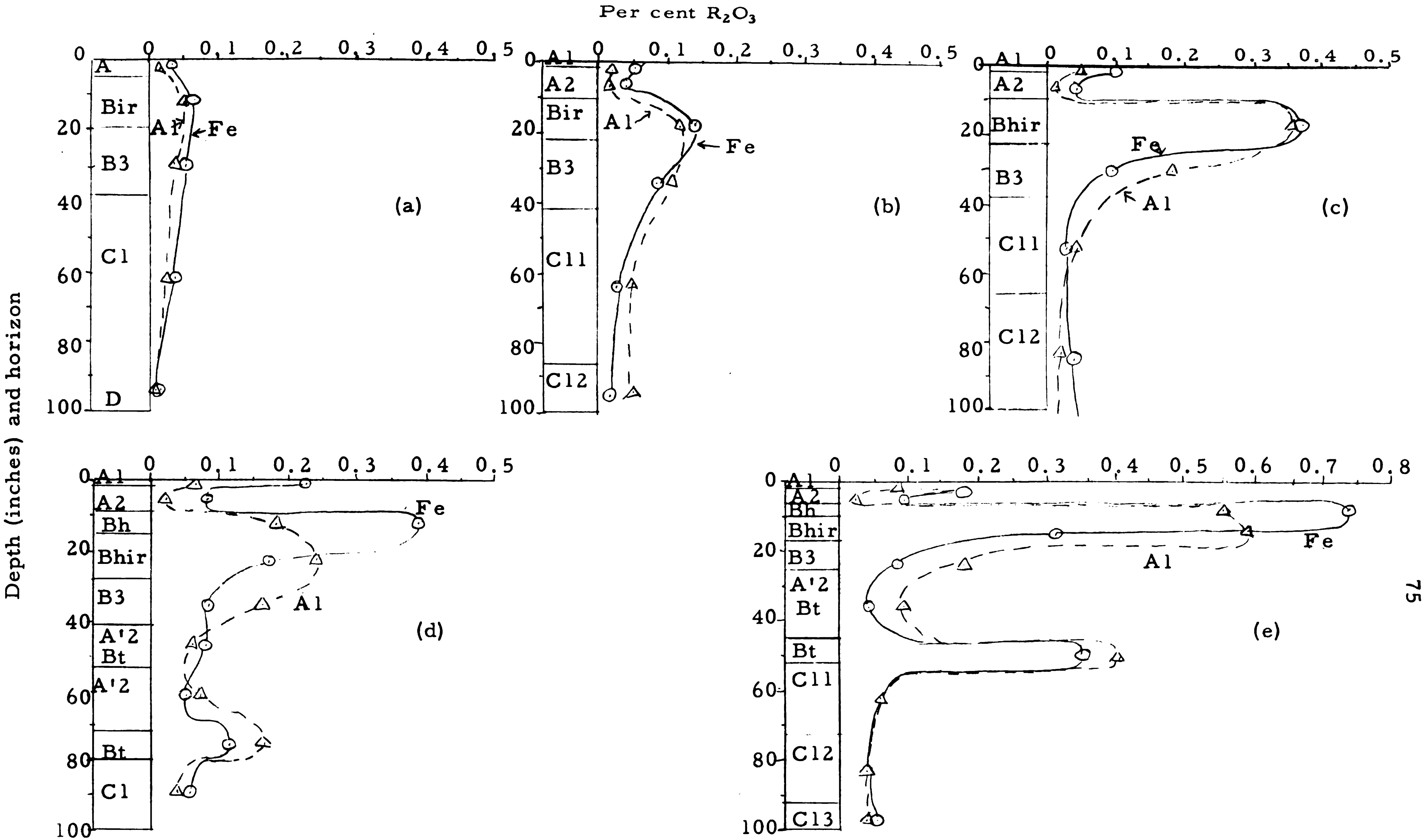


Figure 6. Extractable sesquioxide contents as functions of depth and horizon for five soils: a, Eastport; b, Rubicon; c, Kalkaska; d, Blue Lake I, and e, Blue Lake II.

The Bhm horizon of Kalkaska is anamolous, both in its position in the profile and in its chemical characteristics relative to the surrounding horizon and to similar horizons of the Blue Lake soils. The Bhm contains more extractable Al_2O_3 than is in the Kalkaska Bhir, less extractable Fe_2O_3 than is in the Bhir, and more Al_2O_3 than Fe_2O_3. In the Kalkaska the organic carbon maximum coincides with the aluminum maximum rather than the iron maximum.

Since the surpluses of sequioxides in the B horizons relative to the parent materials are greater than the deficits in the A2 horizons, net conversions of sesquioxide forms not soluble in the extracting solution to forms that are soluble have occurred in the profile.

Organic carbon and total nitrogen

Organic carbon depth functions (Figure 7) do not show subsurface maximum values for the two youngest soils, but attain pronounced maximum values in the Kalkaska and Blue Lake soils. Hence, apparent mobilization of organic matter in the A horizons and a noticeable accumulation of it in the B horizon began between 3000 years (Rubicon) and 8000 years (Kalkaska) before present. The organic matter in the profiles is composed of two components, the recently-living root material which was not removed when the samples were prepared for laboratory analyses, and the amorphous material capable of being moved down the profile. It is possible that depth functions of the latter components show weak minimum-maximum relations but that they are masked by the relatively greater amounts of the former component in the youngest soils. However, in light of Martin's (1960) observation that small amounts of aluminum can cause flocculation of humus, it is possible that previously deposited aluminum causes the immobilization of humus in the B horizon. This, then, would require that sesquioxides

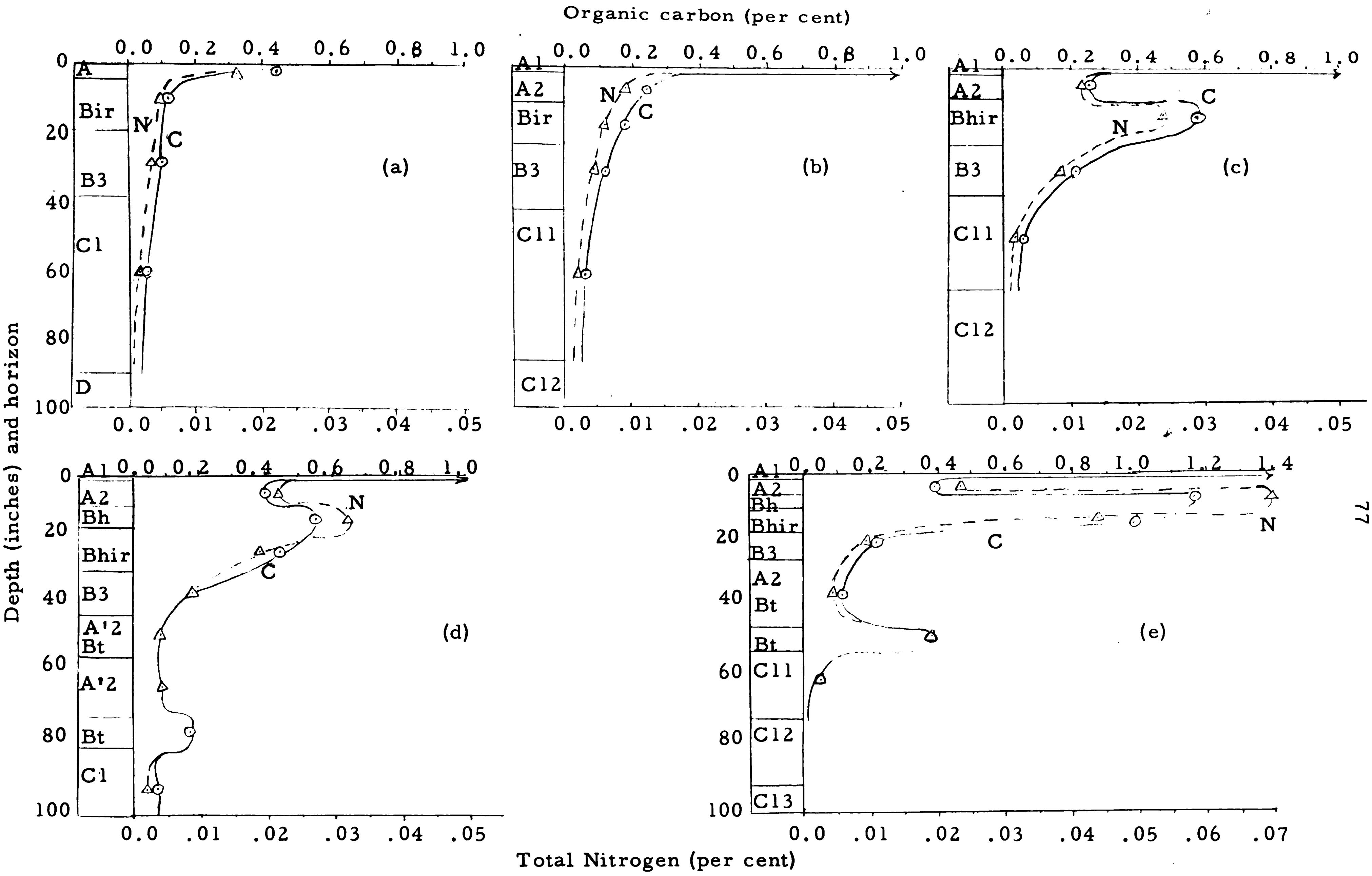


Figure 7. Organic carbon and total nitrogen contents as functions of depth and horizon for five soils: a, Eastport; b, Rubicon; c, Kalkaska; d, Blue Lake I; and e, Blue Lake II. (Both scales apply to all graphs.)

(especially aluminum) be differentiated into horizons of minimum and maximum before organic matter can accumulate in the podzol B horizon.

The Blue Lake soils both show two subsurface maxima in organic components corresponding to the two kinds of B horizons in each profile. Adsorption of organic matter by clays is suggested by the second maxima in the Bt horizons deep in the Blue Lake profiles.

Total nitrogen depth functions have the same shape as organic carbon functions. In Figure 7 the scale for carbon is 20 times that for nitrogen. For any horizon, when the point representing per cent nitrogen lies to the left of the point representing per cent carbon, the carbon/nitrogen weight ratio is over 20, and *vice versa*. The carbon/nitrogen ratios are over 20 in all of the horizons of the three youngest soils plotted and in all of the horizons of the two Blue Lake soils plotted except the A2 and Bh horizons which range from 17 to 18. The carbon/nitrogen ratios of the surface horizons of the soils in the order they occur in the figure (some not plotted) are 27, 26, 17, 17, and 17. It is 28 for the Kalkaska Bhm.

Available phosphorus and exchangeable bases

Available phosphorus and exchangeable bases are plotted in Figure 8. Exchangeable base contents are always highest in the organic matter-rich Al horizons, but this does not hold true for available phosphorus which usually reaches maxima in the lower part of the podzol B and in the textural B horizons. Total amounts of available phosphorus and bases in the solum (areas under the curves) do not change much with the age of the soil. In fact, except for somewhat greater amounts of nutrients in the Al of Blue Lake II, this soil is about as impoverished as Eastport. This despite the fact that Blue Lake II is the finest textured soil of the group.

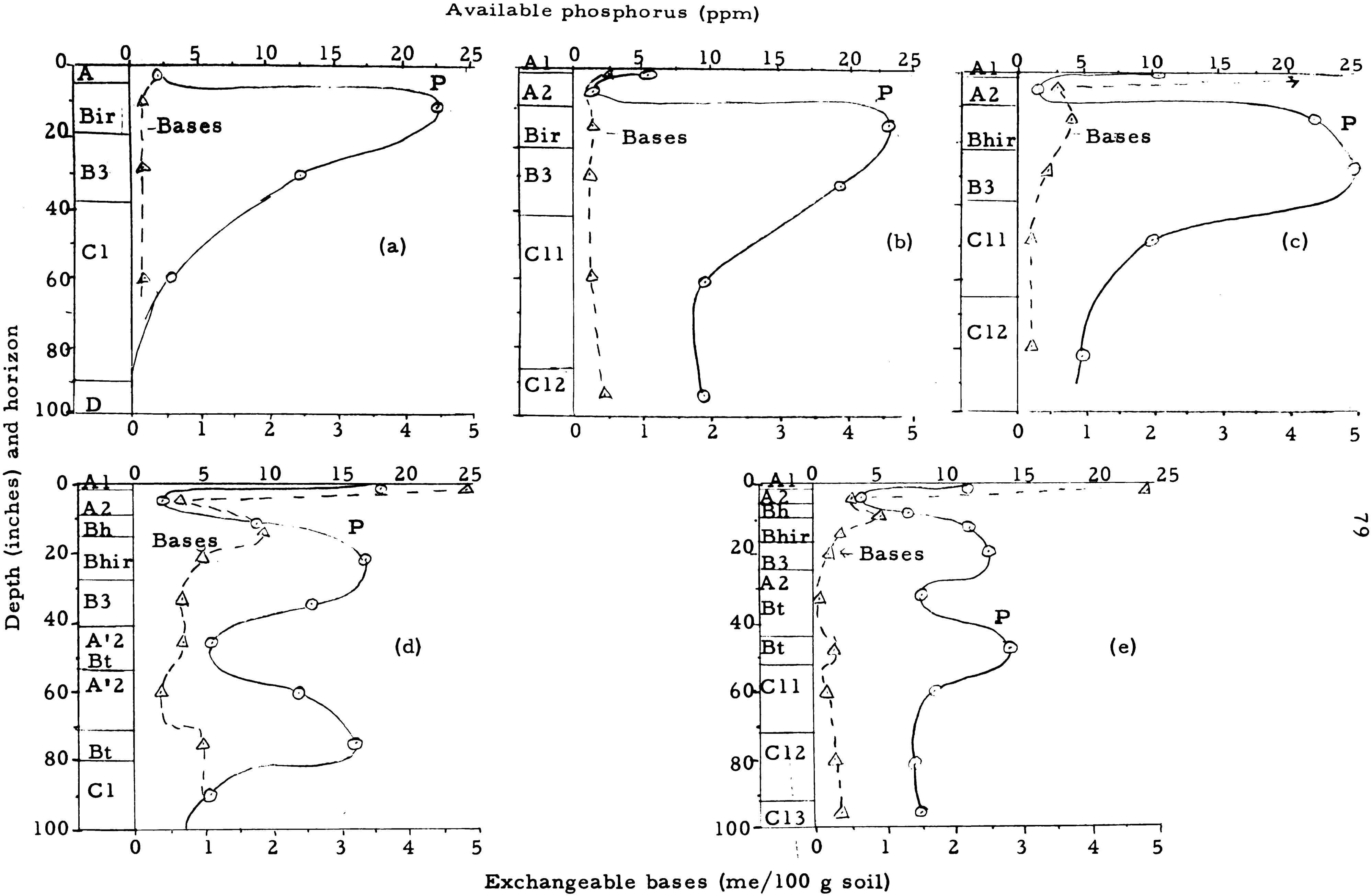


Figure 8. Available phosphorus and exchangeable base contents as functions of depth and horizon for five soils: a, Eastport; b, Rubicon; c, Kalkaska; d, Blue Lake I; and e, Blue Lake II. (Both scales apply to all graphs).

The more abundant supply of bases (largely calcium) in the Blue Lake I profile than in the Blue Lake II profile is reflected by the vegetation growing on the two sites. The species, in order of abundance, on the "I" site are sugar maple, beech, yellow birch, basswood, and elm, and on the "II" site are sugar maple, big tooth aspen, and beech with bracken as ground cover. Basswood and elm leaves are known to contain relatively large amounts of calcium (Lutz and Chandler, 1946, p. 146) and, by implication (p. 340), are thought to have large requirements for this element. These two species appear only on the Blue Lake I site.

The exchange capacities of all soils are low. Because of the low values for exchangeable cations in any given horizon, base saturation values for individual horizons would be of little significance. But if the exchange capacity was summed for a profile, horizons with the largest and most reliable exchange capacity values would make the largest contribution to the totals, resulting in more reliable figures. The cation exchange capacity and exchangeable hydrogen of a column of soil 1 cm square by 60 inches deep was calculated for each soil. Columns of Eastport, Rubicon, Kalkaska, Blue Lake I and Blue Lake II soils had exchange capacities of 0.7, 1.2, 2.8, 4.0, and 4.0 m.e. and base saturations of 74, 47, 48, 55, and 21%, respectively. When the cation exchange capacity is expressed as $CaCO_3$ equivalent per acre to 60 inches deep assuming that all the exchange sites held calcium, the values would be 1.6, 2.7, 6.3, 9.0, and 9.0 tons $CaCO_3$ equivalent/acre. Multiplying these figures by the base saturation values gives 1.0, 1.3, 3.0, 4.9, and 1.9 tons of $CaCO_3$ equivalent/acre if all bases were calcium.

Available phosphorus extracted by the Bray test (0.025 $\underline{N}$ HCl, 0.03 $\underline{N}$ NH_4F) shows minima in all of the A2 and A'2 horizons and maxima in the Bh or Bir and Bt horizons. This is especially pronounced in the three youngest soils, implying phosphorus mobilization early in the chronosequence. Assuming that the solum developed from a uniform parent material, there is a greater accumulation of extractable phosphorus in the B horizons than there is loss from the A2 horizons. This implies a net conversion from a form of phosphorus not soluble in Bray's extracting solution to one that is soluble. Suzuki *et al*. (1962) found that phosphorus extracted by Bray's solution correlated well with aluminum phosphates but poorly with calcium phosphates, iron phosphates, and organic phosphorus present in some soils of Michigan. Thus it is likely that much of the phosphorus extracted from the soils studied here occurs in a combination with aluminum. The horizons of phosphorus minima (A2) range in pH from 4.4 to 4.8 and the horizon of phosphorus maxima (not considering Bt horizons) range in pH from 5.1 to 6.2. Teakle (1928) has shown that calcium, aluminum, and manganese phosphates were considerably more soluble in the more acid pH range (4.4 to 4.8) than in the less acid range (5.1 to 6.2) while iron phosphate was slightly less soluble in the more acid range. Buehrer (1932) calculated that in the pH range of 4 to 6 practically all (80-100%) of the phosphate was in the $H_2PO_4^-$ form. Hemwall (1957) reviewed the literature of phosphorus fixation in soils. He concluded that "phosphorus fixation in acid soils is due to the formation of insoluble iron and aluminum compounds of the nature of $M(H_2O)_x (OH)_y H_2PO_4$. The iron- and aluminum-containing soil minerals, including the clay minerals, are the source of the iron and aluminum. The formation of these compounds is governed by the solubility product, the common ion, and the salt affect principles. Under certain conditions, a precipitate is formed, whereas under other conditions the compounds are adsorbed." Variscite, an aluminophosphate, dissolves according to the equation $\underline{Al(OH)_2H_2PO_4} \rightleftharpoons Al^{3+} + 2OH^- + H_2PO_4^-$ with the solubility product, $k = [Al] \cdot [OH]^2 \cdot [H_2PO_4]$, having a value of 2.8×10^{-29} according to Cole and Jackson (1950).

From this evidence a model explaining the apparent mobilization of phosphorus early in the development of the soil can be tentatively proposed. Organic acids contained in rainwater after it has passed through the forest canopy and through litter on the soil surface may contain some phosphorus and may also dissolve phosphorus-containing primary minerals in the A2 horizons. The $H_2PO_4^-$-saturated solution is washed down the profile until it encounters a zone of higher pH and/or higher "free aluminum" content. Here, because $[OH^-]$ and/or $[Al^{3+}]$ are higher than in the horizon above and because $[Al^{3+}] \cdot [OH^-]^2 \cdot [H_2PO_4^-]$ must remain constant, $[H_2PO_4^-]$ is decreased and variscite--or some number of the variscite-barrandite-strengite series, $(Al,Fe)(OH)_2 H_2PO_4$ (Cole and Jackson, 1950)--is precipitated. It appears that either a sesquioxide or a pH gradient must be established before $H_2PO_4^-$ can move. Judging from the gradient of the pH and sesquioxides functions between the A2 and B horizons of Eastport, it is likely that the pH gradient was well-established by the Eastport stage, while the sesquioxide gradient was just beginning. The possibility that phosphate accumulated in the young B horizon first and caused precipitation of aluminum as it moved downward in solution is unlikely because the molar ratio of extractable aluminum to extractable phosphorus is 14 in the Eastport B(ir), indicating a surplus of aluminum.

There are many interactions which may affect this generalization. For instance, as the pH increases beyond a certain point, Al^{3+} precipitates as $Al(OH)_3$ causing $[H_2PO_4^-]$ to increase (Cole and Jackson, 1950). The point of minimum solubility of $H_2PO_4^-$ in an aluminum system was found to be around 6.5 by Teakle (1928) and around 4.0 by Cole and Jackson (1950).

The differentiation of extractable phosphorus into horizons of the podzol sequum appears to be completed early in the chronosequence--around Eastport (2250 years) age--and is then degraded. The decrease

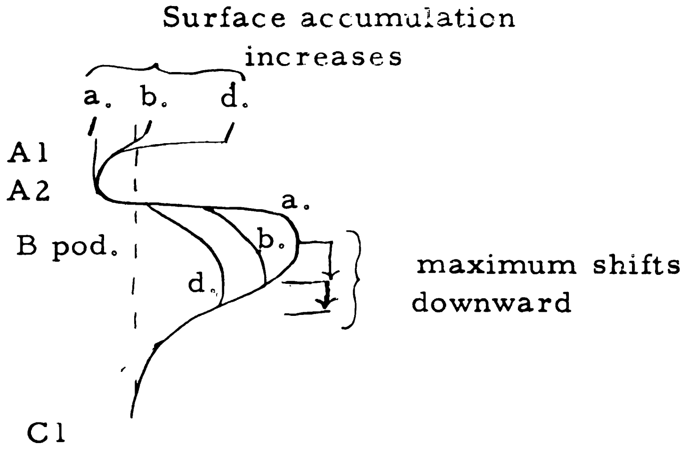


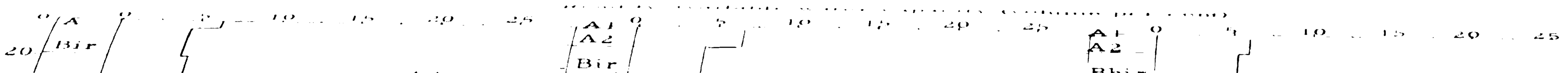
Figure 9. Diagrammatic representation of changes in extractable phosphorus distribution in three stages of development of the podzol sequum relative to the C1 horizon: a, Eastport; b, Rubicon; and d, Blue Lake I.

with time of the available phosphorus accumulation in the podzol B, relative to the C1 horizon, the downward shifting of the phosphorus maximum in the profile, and the increase of phosphorus at the surface, all with increasing age of the soil, might be explained as shown diagrammatically in Figure 9. Uptake of $H_2PO_4^-$ by tree roots in the upper part of the podzol B, where the roots are abundant, causes more phosphate to be ionized, gradually reducing the amount of fixed phosphorus in the B horizon. This phosphorus is cycled through the tree and returns to the soil surface as leaf fall. Loss of extractable phosphorus from the podzol B horizon with time could be due to conversion from an extractable form to a non-extractable form (possibly through an organic route) or to a removal of phosphorus from the ecosystem, as in logging. Assuming a yield of red pine of 5,300 cu. ft./acre, a specific gravity of wood of 31.6 lb./cu. ft., 0.4% ash content, and 4% P_2O_5 in the ash (Rudolf, 1957, p. 18; Hodgman et al. 1959; Lutz and Chandler, 1946, pp. 143-144) one logging of red pine would remove about 12 pounds of phosphorus per acre. For comparison, the amounts of available phosphorus in the podzol sequa are: Eastport, 185; Rubicon, 230; Kalkaska, 230; Blue Lake I, 155; and Blue Lake II, 72 pounds per acre.

Available water

Readily available water capacity (RAWC) has been defined as the difference in weight percentage between the water content of an undisturbed soil sample at 0.06 atmospheres tension and that of a disturbed sample at 6 atmospheres tension (Franzmeier et al., 1960). These weight percentages are reported in the Appendix and they have been converted to volume percentages in Figure 10. The increase of RAWC in the upper horizons relative to the lower ones can be attributed to more silt, very fine sand, and/or organic matter in the upper horizons. Differences among soils in RAWC of the lower horizons can be explained by shifts among the fine, medium, and coarse sand fractions.

The ability of a soil to supply water for plant growth can be estimated by totaling the volume percentages of RAWC for a certain depth in the profile. These capacities are 2.8, 2.9, 2.7, 4.7, and 4.4 inches of water in the upper 60 inches of soil for Eastport, Rubicon, Kalkaska, Blue Lake I, and Blue Lake II, respectively. Since undisturbed samples were not taken in the A1 horizon, the 60 inches represented are 0-60, 2-62, 1-61, 1-61, and 1½-61½ inches, respectively, for the five soils. In order to make the calculations for the Blue Lake II, it was estimated that the 45-61½ inch layer had the same RAWC as the 25-45 inch layer (dotted line in Figure 10). The figures for RAWC of the 60 inch profile separate the soils on the moraine from those on the beach deposits. Much of this difference could be explained by the total amounts of silt in the profiles (see Figure 3). The Kalkaska is somewhat out of place in the series of successively greater amounts of readily available water with increasing age. The low value for this soil is due largely to the low RAWC of the C1 horizon which contains a large percentage of coarse sands. The surface organic horizons, thicker in Kalkaska than in the two younger soils, might make a significant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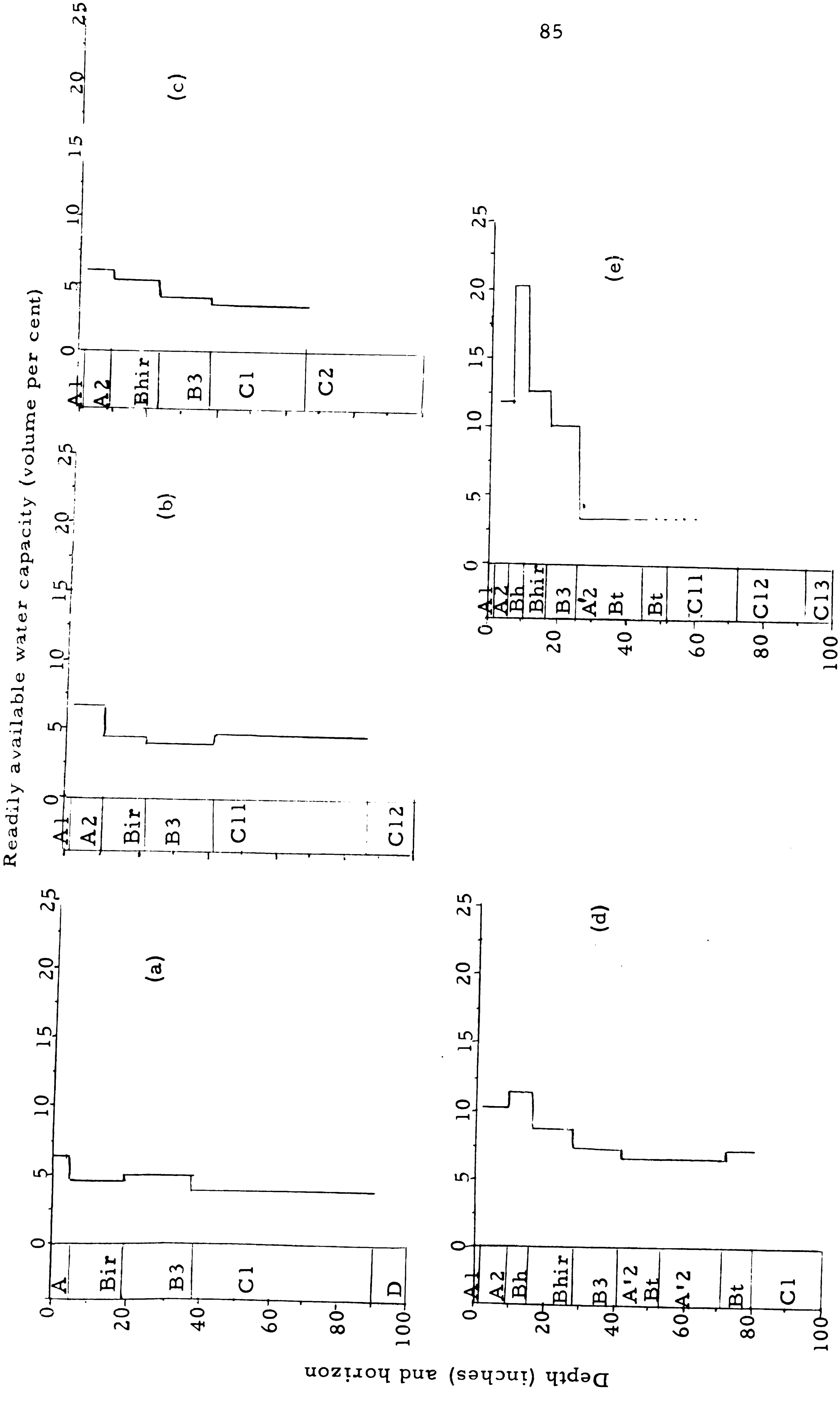

Figure 10. Readily available water capacity ($W_{0.06} - W_{5.}$ atm) as a function of depth and horizon for five soils: a, Eastport; b, Rubicon; c, Kalkaska; d, Blue Lake I; and e, Blue Lake II.

contribution to the available water supply and give Kalkaska more actual available water than Rubicon or Eastport.

The RAWC of the Bt of the Blue Lake soil was only slightly greater than the A'2 horizon above it. If it had occurred within the depths considered in the calculations, it would have resulted in only a small increase in the profile's ability to supply water for plant growth.

Heavy Minerals of the Fine Sand Fraction

The content of heavy minerals in the fine sand fraction, their distribution according to mineral species in the profile, and some mineral ratios are shown in Table 7 for the five soils. The only two resistant minerals present in quantities large enough to warrant attention are garnet and magnetite. In the Eastport, even the percentages of these minerals are so low that their ratios would be meaningless. Garnet/magnetite ratios in the Rubicon and two Blue Lake soils vary by a factor of about two within each soil indicating non-uniformity of parent materials. These ratios in the Kalkaska profile, however, are 0.24, 0.19, and 0.29, indicating somewhat greater uniformity of the original material. For this reason the Kalkaska profile is used to illustrate the weathering of fine sand materials in the profile.

By analogy from radioactivity counting, (Willard, Merritt, and Dean, 1958, p. 377), the standard deviation, D, can be estimated from the number of grains, N, of a species counted by:

$$D = \sqrt{N} .$$

If the limits around N are set at ± two standard deviations and, in calculating a mineral ratio, if the largest limit of the numerator is divided by the smallest limit of the denominator and <u>vice versa</u>, the two values would give an approximation of the probable range of the ratio at about

) and ratios of heavy minerals (s. g. > 2.80)

Table 7. Content by weight, distribution by count (per cent of total number), and ratios of heavy minerals (s. g. > 2.80) in the fine sand fraction of major horizons of five soils.

	Eastport			Rubicon			Kalkaska			Blue Lake I					Blue Lake II				
	Al+A2	Bir	Cl	A2	Bir	C1	A2	Bhir	C1	A2	Bh	A'2	Bt	Cl	A2	Bh	A'2	Bt	C12
Per cent Heavies	4.7	6.2	4.1	2.8	2.2	3.2	2.5	4.3	3.8	0.6	1.4	1.0	1.4	1.5	1.2	1.7	2.3	4.1	1.2
Distribution																			
"Chlorite"	62.2	63.4	69.2	49.1	48.6	48.8	13.8	36.3	45.6	11.9	26.8	55.2	34.4	38.8	4.6	26.8	17.8	9.7	27.0
Augite	13.2	8.8	8.2	4.0	8.0	4.1	4.7	4.7	7.3	4.7	5.6	4.8	6.7	3.9	4.5	5.5	5.5	3.2	4.2
Diopside	4.6	6.3	5.1	2.5	5.4	6.9	0.7	4.2	3.4	1.7	3.2	4.4	6.4	3.0	0.9	5.0	3.2	2.0	4.2
Hornblende	3.3	5.8	6.0	9.8	5.7	2.5	8.5	4.7	3.1	4.7	9.8	8.9	7.6	5.7	8.2	7.1	5.3	4.2	6.7
Garnet	3.0	2.8	4.8	6.1	8.5	5.5	12.0	7.0	8.0	7.5	7.2	3.8	6.4	5.9	9.8	5.2	5.5	6.0	7.7
Epidote	5.6	2.3	3.3	7.7	4.1	8.0	4.7	3.5	2.7	12.8	6.7	8.3	7.9	4.9	5.0	6.9	3.4	3.2	4.6
Magnetite	3.3	5.0	1.2	17.2	14.5	16.5	49.4	36.1	27.2	48.9	36.4	12.1	27.1	34.0	59.0	39.2	53.2	66.6	37.2
Hematite	1.3	3.3	1.2	1.5	3.4	5.0	3.1	1.0	0.9	4.4	1.5	0.6	1.2	1.6	3.6	1.9	2.0	2.2	2.1
Hypersthene	0.3	0.8	0.6	0.9	0.3	0.3	0.4	0.5	0.0	0.3	0.3	0.0	0.0	0.4	0.4	0.2	0.4	0.2	0.4
Tourmaline	1.0	0.2	0.3	0.0	0.3	0.3	0.4	0.2	0.3	1.7	0.3	1.3	0.3	0.8	1.2	0.7	0.2	0.5	1.8
Zircon	0.3	0.2	0.0	0.3	0.5	0.6	0.7	0.5	0.3	0.0	1.2	0.0	0.9	0.2	0.9	1.0	1.2	0.7	0.6
Others	2.0	1.3	0.3	0.9	0.8	1.7	1.6	1.4	1.2	1.4	0.8	0.6	1.2	0.8	2.0	0.4	2.4	1.2	3.3
Number counted	304	399	331	326	387	363	449	403	327	360	593	315	343	492	561	421	506	401	671
Ratios																			
Diopside/magnetite	1.4	1.3	1.2	0.15	0.37	0.42	0.01	0.12	0.12	0.03	0.08	0.36	0.24	0.09	0.02	0.13	0.06	0.03	0.11
Garnet/magnetite	0.9	0.6	4.0	0.35	0.59	0.33	0.24	0.19	0.29	0.15	0.20	0.32	0.24	0.17	0.17	0.13	0.10	0.09	0.21

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the 95% confidence interval. From the ratios with their estimated errors plotted in Figure 11 it is seen that the hornblende/magnetite, garnet/magnetite, and epidote/magnetite ratios are relatively uniform throughout the Kalkaska profile, while the diopside/magnetite, and "chlorite"/magnetite ratios decrease with proximity to the soil surface. Apparently, magnetite, garnet, epidote, and hornblende have weathered very little in the profile, while diopside has weathered in the A2 horizon and "chlorite" has weathered slightly in the Bhir horizon but to a greater extent in the A2.

Even though there is a considerable amount of variation among ratios of resistant minerals in the Blue Lake soils (Table 7), diopside and "chlorite" are conspicuously scarace in the A2 horizons, especially, relative to the adjacent Bh horizons.

Generally, in the deeper, little-weathered portions of the soil profile, "chlorite" content decreases, magnetite content increases, and the percentage of heavy minerals decreases with increasing age of the soil surface.

The mineral grains identified here as "chlorite" appeared to be composed of aggregates of crystals. Their refractive index was < 1.66. They appeared a dull, dark gray color and were nearly opaque except around the edges of the grain using transmitted light and white to light greenish brown under reflected light. Under crossed Nicols the edges of the grain exhibited a mosaic of bright interference colors. Using a strong light with the Nicols crossed, light passed through the center of the grains, giving a dusky green-brown appearance. Some of the "chlorite" grains were picked out of the fine sand fraction of the Eastport C horizon using a binocular microscope, ground and used for X-ray diffraction measurements of the spacing of crystal planes. The lines >3 Å obtained are compared in Table 8 with lines tabulated in the ASTM index (1954). Usually only one line of a known mineral--instead of all three given--coincide with the lines of the unknown mineral.


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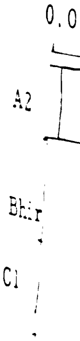
Bhir
C1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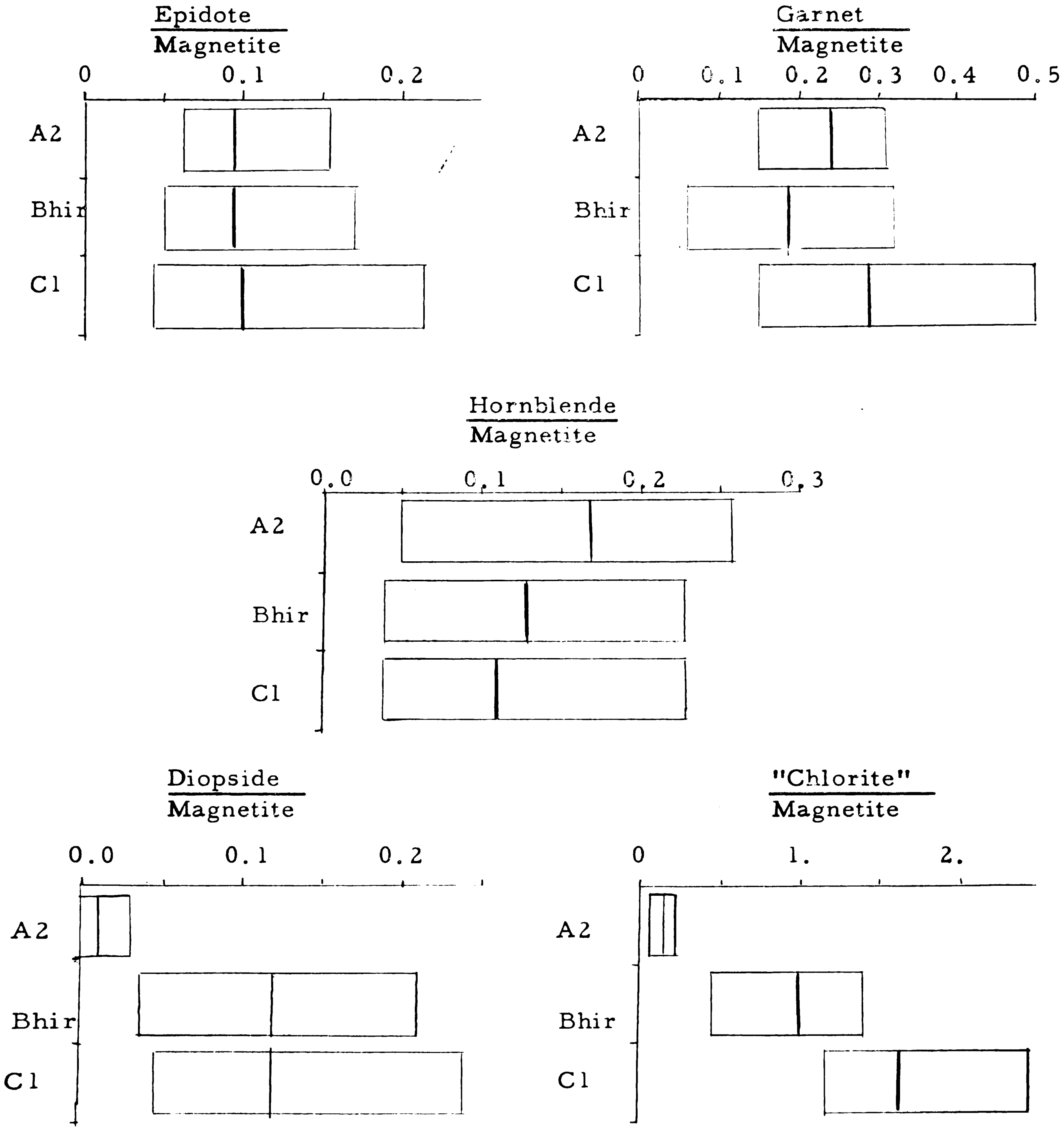


Figure 11. Heavy mineral ratios (center lines) and their errors estimated at about the 95% level (outside lines) for the fine sand fractions of major horizons of Kalkaska sand.

Table 8. Possible sources of x-ray diffraction lines from the fine sand mineral identified optically as "chlorite." (Data for knowns from ASTM index, 1954)

Source	Spacing (Å)											
	8.90- 8.80	8.80- 7.35	7.35- 7.25	7.25- 5.20	5.20- 5.10	5.10- 4.20	4.20- 4.12	4.12- 3.50	3.50- 3.40	3.40- 3.36	3.36- 3.26	<3.26
Unknown ("chlorite")	*8.84		7.30		5.17		*4.16		3.45		*3.31	3.05
Calcium silicate hydrates	8.87					4.57		3.56				
Magnesium silicate hydrates			7.31- 7.28					3.65- 3.62				2.55- 2.45
Calcium aluminate hexahydrates					5.16- 5.13							2.03- 2.30
Calcium silicate hydrate							4.18				3.27	2.41
Calcium aluminum ortho silicate							4.17	4.11				3.21
Geothites							4.18- 4.17					2.69- 1.73
Chlorites				6.90- 6.77					3.48- 3.49			2.00- 1.55
Magnesium aluminum silicate		8.29									3.34	3.00
Quartz						4.26					3.34	1.82
Micas											3.34- 3.30	

*Most distinct lines.

All the lines of "chlorite," however, could be accounted for by lines originating from known chlorites or from various combinations of calcium, magnesium, aluminum, silicon, and oxygen in compounds or minerals (some hydrated) as listed. These aggregate grains could be alteration products of amphiboles and pyroxenes.

Quartz Contents of the Silt and Sand Fractions

In the Kalkaska and Blue Lake soils the greatest quartz contents of the silt and total sand fractions occur in the A2 horizons (Table 9). This is evidently due to the weathering of less resistant mineral species in the A2 horizon.

Table 9. Quartz contents (percent) of silt and total sand fractions of five soils.

Soil and horizon		Sand	Soil and horizon		Silt	Sand
Eastport	A1 A2	82	Kalkaska	A2	49	88
	B(ir)	88		Bhm	45	81
	B3	88		Bhir	47	88
	C1	82		B3	--	82
				C11	--	80
Rubicon	A2	90	Blue Lake I	A1	62	88
	Bir	91		A2	70	88
	B3	88		Bh	59	82
	C11	81		Bhir	63	86
				B3	--	82
				A'2	--	84
				Bt	62	82
				C1	51	84
			Blue Lake II	A2	74	95
				Bh	59	83
				Bhir	--	80
				B3	--	91
				A'2 Bt	--	87
				C12	--	82

Mineralogy of the Clay Fraction

All soils

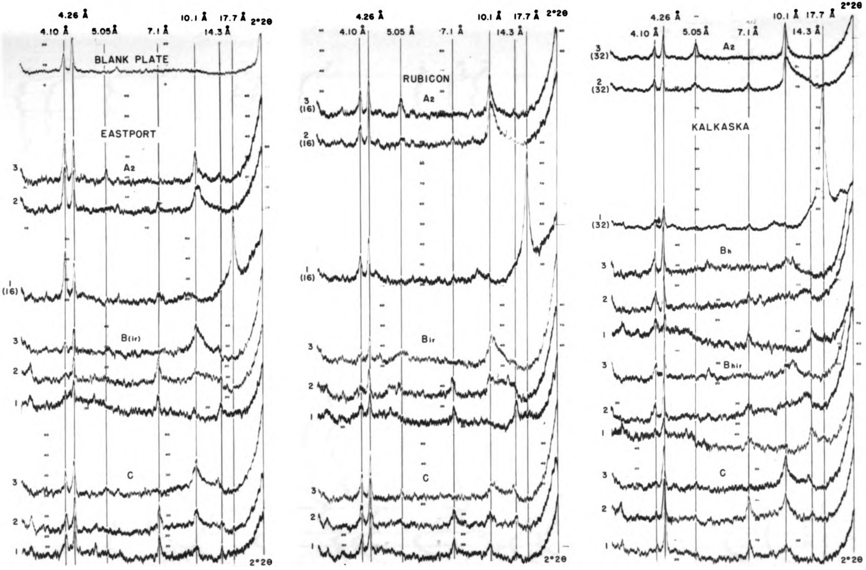
According to X-ray diffraction patterns (Figure 12) of the < 2μ fractions, the distribution of layer silicates shows the same pattern in all five profiles. The layer silicates of the parent material are composed of kaolinite, chlorite, and illite. In the Bt horizon of the Blue Lake soils the same three minerals persist, but with possible random interstratification of chlorite and montmorillonite. In the podzol B horizon, relative to lower horizons, the degree of interstratification increases, montmorillonite and vermiculite (Rubicon) may appear, while peaks due to chlorite and illite decrease in intensity, especially in the upper B (Bh) horizons. Montmorillonite is the dominant clay mineral in the A2 horizons with some X-ray patterns indicating that it is about the only layer silicate present. However, peaks due to small amounts of illite and kaolinite may be present in the A2 horizons.

The < 0.2μ fraction of the Blue Lake I Bh and Bt horizons give peaks in the same positions as did the < 2μ fraction. The finer clays produce much broader peaks, however.

Diffraction recordings of the clays of the Bir horizon of Rubicon (and possibly the Bhm and Bhir of Kalkaska) indicate possible aluminum interlayers in vermiculite. The Mg-glycerol treatment shows a symmetrical 14 Å peak. Replacing Mg^{++} with K^{+} and heating the X-ray plate to 110°C produces a broad maximum between 14 and 10 Å and further heating to 550°C shifts the peak to around 10-11 Å. Similar curves were interpreted by Shawhney (1960) to be due to aluminum interlayers in vermiculite.

The pattern of clay mineral distribution in the profiles indicates that the weathering sequence is from illite and chlorite, possibly through vermiculite, to montmorillonite. This pattern is established early in the development of a Podzol.

Figure 12. X-ray diffraction tracings of oriented soil clay films on porous ceramic plates. Treatments: 1, Mg-saturated, glycerol-solvated, no previous heat treatment; 2, K-saturated, and previously heated to 110°C; 3, K-saturated and previously heated to 550°C. Scale on horizontal axis is linear for degrees 2θ. Vertical axis is radiation intensity. Scale factor is 8 unless indicated otherwise in parentheses under treatment number.


4.26 Å
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17.7 Å
2°2θ
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EASTPORT
A2
B(ir)
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RUBICON
Bir
KALKASKA
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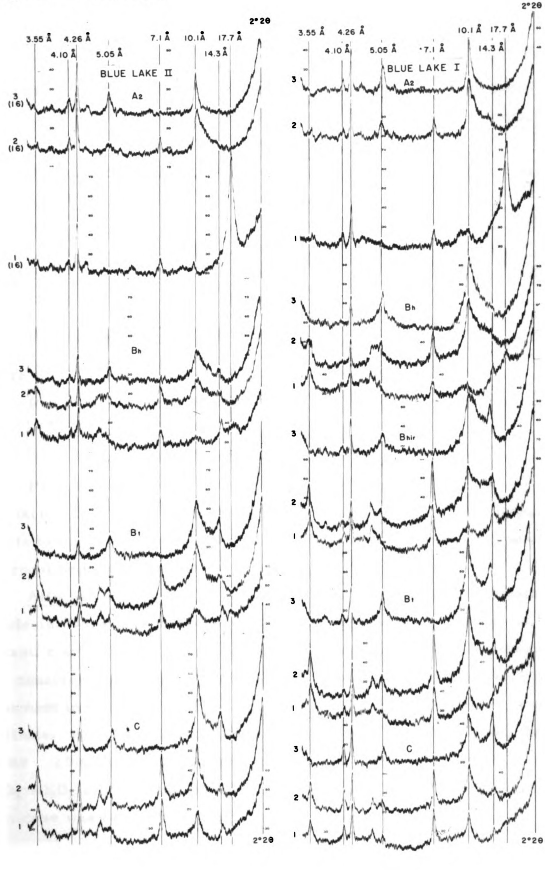
Figure 12

Figure 12 - Continued



Blue Lake I

The mineralogical composition of the clay fraction of major horizons of the Blue Lake I soil was estimated (Table 11) from differential dissolution, total chemical, and X-ray diffraction analyses as explained below.

Quartz. The quartz content of the clay fraction was determined by X-ray diffraction.

Potassium feldspars. The content of potassium feldspars in the clay fractions ($< 2\mu$) was calculated using the X-ray diffraction curves obtained in the quartz determination by the following equation:

$$\text{Per cent Kf} = 2.93 \cdot \frac{I_{Kf}}{I_Q} \cdot \text{Per cent Qtz}$$

where

Per cent Kf = potassium feldspar content of soil clay
I_{Kf} = intensity of 3.25 Å peak of soil clay
I_Q = intensity of 3.35 Å peak of soil clay
Per cent Qtz = quartz content of soil clay.

The factor 2.93 is the ratio of the intensity of the 3.35 Å peak of pure quartz to the average intensity of the 3.25 Å peaks of orthoclase and microcoline as determined by Bailey et al. (1957, p. 435).

Allophane, kaolinite, free silica. Differential dissolution data (Table 10) were used to estimate allophane and kaolinite contents of the soil clay. The SiO_2 and Al_2O_3 extracted after the 110°C treatment was considered to be from allophane, and that extracted after the 525°C treatment in excess of that extracted after the 110°C treatment, from kaolinite. Allophane and kaolinite contents were calculated using the formulas $2SiO_2 \cdot Al_2O_3 \cdot 3.28\ H_2O$ (Jackson, 1956, p. 540), and $2SiO_2 \cdot Al_2O_3 \cdot 2H_2O$ (Grim, 1953, p. 47), respectively. Excess SiO_2 in each case was called "free SiO_2."

Table 10. Results of differential dissolution analysis and total chemical analysis of the clay fractions (< 2 μ) of several samples (per cent of oven dry weight).

Soil and horizon		Differential dissolution						Total Analysis					
		Pretreatment:											
		110°C		400°C		525°C							Molar
		SiO_2	Al_2O_3	SiO_2	Al_2O_3	SiO_2	Al_2O_3	SiO_2	Al_2O_3	Fe_2O_3	K_2O	MgO	SiO_2/R_2O_3
Blue Lake I	A2	3.54	0.85	4.40	0.98	7.30	3.20	63.7	13.2	2.74	3.52	0.96	7.2
Blue Lake I	Bh	5.86	2.24	6.33	2.07	8.20	3.86	59.5	14.0	4.86	3.16	1.71	5.9
Blue Lake I	Bt	7.34	3.03	7.76	2.64	10.52	4.42	59.5	13.7	4.90	4.06	2.19	6.0
Blue Lake I	C	5.85	2.45	6.72	3.44	8.98	3.97	60.0	12.1	4.86	4.25	2.14	6.7
Kalkaska	Bhm	9.05	2.11	9.98	2.89	11.55	2.78	60.0	14.2	3.93	2.68	1.24	6.1

Illite. When potassium from the feldspars (16.8% K_2O) was subtracted from the total potassium content (Table 10), the remainder was considered to be from illite. Assuming that illite contains 10% K_2O (Jackson, 1956, p. 544), the illite contents of the clays were calculated. The results obtained using this method agreed in general with the intensities of the 10 Å X-ray diffraction peak due to illite.

Chlorite. No 14 Å peak was produced by the clay from the A2 horizon so the entire MgO content of that clay (0.96%) was considered to be from minerals other than chlorite. As an approximation, 1% MgO was assigned to non-chlorite minerals in the other horizons and the remainder assigned to chlorite. Because the magnesium content of the clays was low while relatively intense 14 Å peaks persisted in their X-ray diffraction patterns, a low value, 6%, was assigned as the MgO content of the chlorite in the soil clays (Grim's values (1953, p. 372) range from 38 to 2.3% MgO). Chlorite contents were calculated by multiplying the adjusted MgO contents by the factor 100/6.

Vermiculite and Montmorillonite. The remaining percentages of the total clay were allotted to vermiculite and montmorillonite. Their relative abundance was judged by the relative intensities of the X-ray diffraction peaks.

Molar SiO_2/R_2O_3 ratios of the clay fraction of the Blue Lake I soil (Table 10) are higher than those reported in the literature review. The ratio is smaller in the podzol B horizon than in the A2 or C horizons, in agreement with a criterion for the spodic B horizons (Soil Survey Staff, 1960).

The estimated percentages of the various components of the clay fraction (Table 11) show these relations in the Blue Lake I soil:

1.) Quartz and free silica are uniform throughout the profile.
2.) Allophane is somewhat less abundant in the A2 horizon than in the rest of the profile.
3.) Kaolinite and potassium feldspars are somewhat more abundant in the A2 than in the rest of the profile.

Table 11. Estimated mineralogical composition of the clay fractions from the major horizons of the Blue Lake I soil.

Horizon	Free SiO_2	Allophane	Kaolinite	Quartz	K-feldspars	Illite	Chlorite	Vermiculite	Montmorillonite
	gm/100 gm clay								
A2	4	2	6	22	7	13	0	0	46
Bh	4	6	4	17	5	14	12	19	19
Bt	5	8	4	18	4	34	20	3	4
Cl	4	7	4	20	5	34	19	3	4 .

4.) Illite and chlorite are most abundant in the deeper horizons, Bt and C, and decrease with proximity to the soil surface; chlorite is practically non-existent in the A2 horizon.

5.) The vermiculite maximum occurs in the Bh horizon.

6.) The montmorillonite maximum occurs in the A2 horizon.

Net Changes in Profiles

All Soils

Net changes in weight and volume which have occurred during the formation of each horizon were calculated according to the method of Marshall and Haseman (1942). Their equation is:

$$Wa' = Wa \frac{Ra}{Rp}$$

where:

Wa' = weight of the original layer which gives rise to the present day layer.

Wa = weight of present day layer

Ra = per cent (weight) of resistant mineral in horizon under question

Rp = per cent (weight) of resistant mineral in parent material.

Non-clay quartz was used as the resistant mineral in this study since it has been shown that this mineral is relatively resistant to weathering and because it is present in large quantities. If during soil formation, physical disintegration of non-clay quartz to clay-size particles had occurred to a great extent, one would expect to find a greater increase of clay-size quartz near the soil surface than in deep horizons. This is not the case in the Blue Lake I soil as seen by comparing the quartz figures in Table 13.

The assumption was made that silt does not move between horizons in these soils. Whether or not this assumption is true is difficult to evaluate. However, because of the small amounts of silt present in these soils, some movement of silt would not greatly affect the results obtained.

In order for results obtained by these calculations to be valid, it must be ascertained that the material from which the solum developed was uniform. Marshall's criteria to test this were (1.) that ratios of resistant minerals be constant throughout the profile, and (2.) that the particle size distribution of a given resistant mineral be the same throughout the profile. As was seen in Table 7, the garnet/magnetite ratios in the fine sand varied in most of the soils. Quartz, however, because of its abundance, is more uniformly distributed in the profile than are other resistant minerals. In other words, the parent materials may have been stratified in respect to the accessory minerals, but uniform according to the much more plentiful quartz.

St. Arnaud (1961) observed a marked disintegration of coarse-sized (coarse, medium and fine sand size) minerals in the Ae horizon of a Grey Wooded soil and a subsequent increase of intermediate-sized (very fine sand, coarse silt and medium silt size) minerals. This trend in size distribution was evident in quartz as well as in the total soil. This would rule out the second criterion of Marshall in such soils. Further, if only one size class of quartz were used as the resistant mineral in calculating changes in that profile, errors would result from such shifts in particle size. However, using the quartz content of the entire non-clay fraction avoids these errors.

Calculated net changes in weight and volume are shown in Table 12. Eastport and Rubicon profiles show a net loss in both weight and volume, Kalkaska has undergone a net loss in weight but a net gain in volume, while the Blue Lake soils gained in both weight and volume. In all soils the net change in volume is algebraically greater then the net change in weight. This has been shown to be due to increased porosity of the

Table 12. Calculated net changes in total weight, total volume, and weights of several components in a column of soil one cm^2 in cross section, based on non-clay quartz.[1, 2]

Soil, horizon and depth (in.)	Total Weight gm	Total Weight %	Total Volume cm^3	Total Volume %	Silt gm	Clay gm	Org. C gm	Ext. Fe_2O_3 gm	Ext. Al_2O_3 gm	Av. P mg
Eastport										
A1 + A2 0-5	+0.1	+1	+1.6	+14	+.08	+.07	+.06	.00	.00	-.02
B(ir) 5-19	-4.2	-7	-2.0	-5	+.06	+.04	+.03	+.01	+.01	+.99
B3 19-38	-5.6	-7	-3.5	-7	.00	+.01	+.03	+.01	+.01	+.64
Δ Profile	-9.7	-6	-3.9	-4	+.14	+.12	+.12	+.02	+.02	+1.61
Rubicon										
A2 2-11	-2.8	-9	+1.2	+4	+.20	+.11	+.05	.00	-.01	-.17
Bir 11-22	-6.3	-13	-3.3	-11	+.03	+.13	+.05	+.04	+.03	+.63
B3 22-42	-6.5	-8	-2.5	-5	+.02	+.07	+.04	+.04	+.04	+.95
Δ Profile	-15.6	-9	-4.6	-4	+.25	+.31	+.14	+.08	+.06	+1.41
Kalkaska										
A2 1-9	-2.2	-8	+1.7	+9	+.57	+.10	+.05	.00	-.01	-.24
Bhm 9-23[3]	+0.4	+4	+0.7	+11	+.05	+.12	+.08	+.03	+.05	+.13
Bhir 9-23[3]	-1.8	-4	+3.0	+12	+.65	+.68	+.20	+.13	+.12	+.47
B3 23-38	-0.5	-1	+2.4	+7	+.06	+.17	+.09	+.03	+.08	+.84
Δ Profile	-4.1	-3	+7.8	+9	+1.33	+1.07	+.42	+.19	+.24	+1.20

Blue Lake I										
A2 1-9	-1.4	-5	+1.7	+9	+2.0	-.07	+.10	+.01	-.01	-.12
Bh 9-15	+1.4	+7	+2.5	+20	+.4	+.57	+.11	+.07	+.03	+.07
Bhir 15-28	-0.2	-1	+2.8	+9	+.7	+.66	+.19	+.06	+.10	+.52
B3 28-41	+1.6	+3	+2.5	+8	+.4	+.42	+.07	+.02	+.06	+.36
A2 41-71[4]	-1.8	-2	-1.1	-1	-.3	-.50	+.06	.00	+.04	+.71
Bt 71-80	+1.7	+5	+0.6	+3	+.4	+.97	+.05	+.02	+.04	+.38
Δ Profile	+1.3	+.4	+9.0	+5	+3.6	+2.05	+.58	+.18	+.26	+1.92
Δ Pod. seq.					+3.5	+1.58	+.47	+.16	+.18	+.83
Blue Lake II										
A2 1½-6	-0.8	-5	+1.4	+14	+1.4	+.06	+.04	+.01	-.01	-.07
Bh 6-10	+1.8	+19	+4.1	+67	+0.8	+.64	+.14	+.08	+.05	.00
Bhir 10-17	+3.8	+20	+5.9	+50	+1.3	+.94	+.21	+.06	+.12	+.13
B3 17-25	-0.8	-3	+1.2	+5	+0.3	+.23	+.02	+.01	+.02	+.14
ΔPod. seq.	+4.0	+5	+12.6	+27	+3.8	+1.87	+.37	+.16	+.18	+.20

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[1] Quartz contents of silt fractions of horizons low in silt were estimated as follows: Eastport (all) 50%; Rubicon (all) 50%; Kalkaska B3, Cl, 50%; Blue Lake I B3, A2, 62%; Blue Lake II Bhir, B3, A2, 60%.

[2] Reference horizons are: Eastport Cl, Rubicon C11, Kalkaska C11, Blue Lake I Cl, Blue Lake II A2-Bt.

[3] Thicknesses of these two horizons alloted according to their estimated volume.

[4] Assume 41-71" layer has same properties as 53-71" horizon.

sola relative to the parent materials. The large net losses in weight and volume calculated for the Eastport and Rubicon soils are probably more apparent than real. In both of these soils the quartz contents (see Table 9) of the thicker horizons of the sola are markedly higher than the quartz contents of the parent material. Some of these calculated losses, then, might be attributable to original differences in materials.

Eluvial-illuvial relations are not evident in the two younger soils but they are evident in the Kalkaska and become more pronounced in the Blue Lake soils. Weight and volume gains become as great as 19 and 67%, respectively, in the podzol B of Blue Lake II.

Differences between the podzol and textural B horizons can be seen in the relative weight and volume changes of the Blue Lake I B horizons. Whereas the per cent volume change in the podzol B horizons is about 3 times as great as the per cent weight change, in the textural B the weight change is greater than the volume change. This is probably due to more root activity and greater severity of freeze-thaw cycles in the podzol B horizons.

The amounts of organic matter, silt, clay, extractable sesquioxides, and available phosphorus in the entire sola of all five soils increased during soil formation according to calculations made using the method of Marshall and Haseman. Table 12 shows these amounts of increase in g per sq. cm. column down to the C or A'2 horizons. They are expressed on a pounds or tons per acre basis graphically in Figure 13. In order to compare similar depths in the five profiles, the podzol sequum of the Blue Lakes should be used instead of the entire profile which includes, in addition, the A'2 and Bt horizons. The results in Table 12 do not consider the organic or A1 horizons.

When the net changes of silt, clay, organic carbon, extractable Fe_2O_3 and Al_2O_3, and available phosphorus are calculated for each horizon, it is seen that a net loss of any of these components from any horizon occurs quite infrequently. Clay was lost from the A2 and A'2 horizons of Blue Lake I suggesting eluviation from these horizons and accumulation in lower horizons because the horizons beneath them showed net gains of clay. The A2 horizons of all soils showed small net losses of extractable aluminum and showed relatively greater losses of phosphorus, also suggesting eluviation of these two elements.

Net gains of the extractable form of some element such as iron, aluminum or phosphorus in the B horizon does not necessarily imply that the element weathered from a mineral source in overlying horizons and was immediately translocated downward and immobilized in the B or that it was transformed directly from a mineral source in the B horizon. It could have been incorporated into organic matter first and then translocated downward. Annual additions of mineral elements to the soil surface in leaf fall can be estimated. Pollen studies cited earlier suggest that pine was the most plentiful genus during the time of formation of these soils. From Scott's (1955) data one can estimate that the annual weight of leaf fall under pine is about 2,000 pounds dry matter per acre and that these leaves contain approximately 0.06% P, 0.02% Fe, and 0.01% Al. This amounts to annual additions of 1.2 pounds P, 0.4 pounds Fe, and 0.2 pounds Al per acre. The accumulated additions of sesquioxides in the leaf fall for the time intervals estimated at each site amount to only about 1/2 to 1/8 of that accumulated in the profiles, but around 20 to 600 times more P has fallen on the soil surface in leaves than has accumulated in the profiles (see Figure 13). (If data for maple is used instead of data for pine, the figures for annual additions of P would be about three times greater; for Fe, about one-third greater.) Thus, all the available phosphorus accumulated in the solum could possibly have been in a leaf at one time.

Table 13. Total P_2O_5 contents (per cent) of some sandy soils of northern Michigan (McCool *et al.*, 1923).

		Horizon				
		1	2	3	4	5
Soil	Lab. no.	*(Ao or A1)	(A2)	(Bh or Bhir)	(Bir or B3)	(C)
Transitional soil; sand	3001-04	0.14	0.12	0.14	0.09	---
Transitional soil; sand	3005-08	0.20	0.19	0.17	0.07	---
Typical north. profile; sand	3019-22	0.09	0.04	0.09	0.09	---
Sand, poor drainage	3023-26	0.19	0.07	0.05	0.04	---
Transitional soil; sand	3035-38	0.07	0.04	0.10	0.05	---
Sandy soil; poor drainage	3044-47	0.08	0.02	0.04	0.04	---
Sandy soil; well drained	3048-51	---	0.08	0.13	0.07	0.07
Dry sandy soil	3057-60	0.12	0.05	0.10	0.09	---

*Horizon designations in parentheses are this author's interpretations.

However, even if all the iron and aluminum arriving on the soil surface as leaf fall were translocated to the B horizon and remained there, the amounts thus accumulated would not account for all of the net increase of these elements. In the cases of the sesquioxides, only a small part of the net increases could have come from outside the solum via the vegetation. If each iron or aluminum ion deposited on the soil surface as leaf fall were cycled through the vegetation only once, it is estimated that these ions originally in the vegetation would account for 1/2 to 1/8 of the net gain of extractable sesquioxides in the sola. If, as is probably true, an ion in a leaf has been in a leaf previously, these fractions would be much smaller. Most of the net increase must have come directly from a weathering mineral source. The most likely source is the A2 horizon, judging from the observed weathering of Fe-Al-silicate minerals occurring there, Figure 11.

The reported distributions of total phosphorus in the profiles of sandy soils of northern Michigan show about the same relations as the depth-functions of available phosphorus in this study. McCool, Veatch, and Spurway (1923) reported total chemical analyses data for some northern Michigan soils. Some of their data is presented in Table 13. Data for the Ao or A1 was presented for seven of the eight soils and all of these surface horizons contained the same or a higher percentage of total P_2O_5 than did the deepest horizon of the profile reported (Bir, B3 or C); four of the A2 horizons contained more phosphorus, and four contained less, than the deepest horizon; and all of the podzol B horizons had total phosphorus contents as high as or higher than the deepest horizon of the profile. (Similar results were reported by Wicklund (1955) for some medium textured Podzols of New Brunswick.) Since several of these soils had higher total phosphorus contents in all of the horizons above the reference horizon, a net gain of phosphorus in the solum is probable. A gathering of phosphorus by the vegetation from a volume greater than that assumed for the solum might account for this increase.

Since trees might garner phosphorus from strata deeper than the solum or Podzol sequum, as suggested above for total phosphorus, the net changes of available phosphorus calculated in this study using the C horizons as reference horizons may not be strictly representative of the true situation. It may be better to consider absolute amounts of available phosphorus in the solum. The Eastport, Rubicon, Kalkaska, Blue Lake I, and Blue Lake II contained 2.1, 2.6, 2.6, 1.7, and 0.8 mg of available phosphorus in a column of soil 1 cm square from the top of the A2 to the bottom of the B3 horizons.

Considering the absolute amounts of available phosphorus, rather than the amounts relative to the C1 horizon, and the probability that trees garner phosphorus from volumes of soil greater than the sola, it appears that phosphorus must be gathered from relatively great depths. After it cycles through the vegetation, perhaps many times, it accumulates in the solum as extractable phosphorus until about the Rubicon or Kalkaska stage of the chronosequence. The change from accumulation of available phosphorus in the podzol B to its depletion may take place because the source of phosphorus for vegetation other than that extractable by Bray's solution (probably calcium phosphate) becomes scarce and the trees feed on the Bray-extractable phosphorus (probably aluminum phosphate) in the solum. This decrease is illustrated by the low values for available phosphorus in the sola of the Blue Lake soils.
Net loss of extractable forms with time could be due to their eventual transformation into non-extractable forms (probably iron phosphates), or to their loss from the system by leaching, logging, etc. The former explanation is more likely, but the contents of extractable forms are so small relative to the total phosphorus content that such transformations would be difficult to demonstrate.

Clay fraction of Blue Lake I

When the net changes in the weight of each component of the clay fraction are calculated for each horizon (Table 14), these changes, relative to the change of the entire clay fraction in each horizon are as follows:

Bt: All components have increased and each has increased by about the same amount as the total fraction.

Bh: All components have increased, but the amounts of increase are not all the same. Illite and chlorite have increased relatively less while vermiculite and montmorillonite have increased relatively more than has the total fraction.

A2: Some components have increased, some have decreased. The amounts of free SiO_2, kaolinite, quartz, feldspars, and vermiculite in this horizon have remained virtually unchanged during soil formation. Allophane, illite, and chlorite have decreased relatively more than the total fraction, while montmorillonite has increased.

If a greater decrease or a smaller increase is interpreted to mean weathering of this component and greater increase or an increase when the total fraction decreased is interpreted to mean formation of the component, one can make some generalizations concerning clay mineral weathering and formation. Allophane weathers in the A2 horizon; illite and chlorite weather in both the A2 and Bh horizons; vermiculite weathers in the A2 but accumulates in the Bh; and montmorillonite accumulates in the A2 and Bh horizons. Reasoning that weathering procedes from the more complex to the simpler substances, allophane would weather to the free oxides or to ions while the weathering sequence in the 2:1 silicates may be

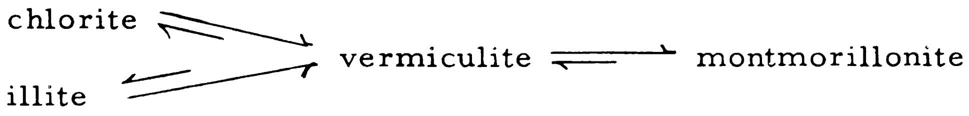


Table 14. Original and present weights (mg.) of total and component clay minerals in major horizons of a column of Blue Lake sand I 1 cm^2 in cross section.

Horizon and depth	Total Clay	Free SiO_2	Allophane	Kaolinite	Quartz	K-Feldspar	Illite	Chlorite	Vermiculite	Montmorillonite
A2, 1-9 in.										
original	350	14	24	14	70	18	120	66	10	14
present	280	11	6	17	62	20	36	0	0	128
Bh, 9-15 in.										
original	240	10	17	10	48	12	81	45	7	10
present	810	32	49	32	140	40	114	97	153	153
Bt, 71-80 in.										
original	420	17	29	17	84	21	143	80	13	17
present	1390	70	110	56	250	56	472	278	42	56

with the equilibrium to the left in the Bt and C, at the center-right in the Bh, and to the right in the A2 horizon. In the A2, Bh, and Bt horizons, the ratio of all 2:1 clay minerals now present to those present at time zero is 2.4, while the ratio of all clay-size minerals now present to those present at time zero is 2.5. This might indicate that the net changes undergone by the 2:1 minerals have occurred within the clay system rather than from additions to the clay system.

Ratios of the present content of other clay minerals to the contents at time zero are: free SiO_2, 2.8; allophane, 2.4; kaolinite, 2.6; and quartz, 2.2. Since each component or group of components (2:1 minerals) increased by approximately the same factor, it is likely that the apparent changes are largely due to differences in the clay content of the original material rather than formation of the clay minerals. The latter explanation would necessitate, for example, the formation of 2:1 clays, 1:1 clays; quartz, and potassium feldspars in the B horizons. The former seems much more likely.

Additions to the soil surface, such as the deposition of wind blown materials, is possible. However, if this was proposed as the source of all the increase of clay in the profile, translocation of the clay materials from the soil surface to the Bt horizon (71-80 inches deep) would have to be explained.

Micromorphology

Kubiena (1938, pp. 127-129) used the term fabric for the arrangements of the constituents of the soil and their role in relation to each other. He distinguished two groups of component units, the skeleton which consists mainly of rock minerals and organisms not decomposable or only slowly decomposing, and fabric plasma, the finely dispersed and highly active, newly formed ingredients of the soil. His terminology will be used here in describing the micromorphology of the soils. The descriptions are based on observations of dissected soil cores and thin sections of undisturbed fragments from these cores.

Since the A1, A2, and C horizons were each micromorphologically similar in the five soils, it would be repetitious to describe each of them five times. One description of each of these three horizons will be given, noting minor variations between soils.

C or A'2 horizons

The C horizon of Eastport, Rubicon, and Kalkaska, and the A'2 of the Blue Lake soils consist only of skeletal components with no fabric plasma evident. Sand grains are packed more closely in these horizons than in the upper ones. The degree of roundness and sphericity of the grains can best be judged from photomicrographs of other horizons since these properties appear to be much the same throughout the profile.

B horizons

Eastport, B(ir). A few thin coatings, light yellowish brown to dark orange yellow (10 YR 6/6) in thin section with transmitted light, are apparent on some parts of the skeletal sand grains but thin out to nothing on other parts.

Rubicon, Bir (plate 2). About 80-90% of the surface area of the sand grains is covered with a thin coat of fabric plasma, strong yellowish brown (7.5 YR 5/8) in color with transmitted light. These coatings are about 0.002 to 0.005 mm thick, show little fracturing and have a variegated color density. They are occasionally slightly birefringent. There is no material in the intergranular spaces.

Kalkaska, Bhir. This horizon is similar to the Rubicon Bir horizon in appearance of the thin sections except that the grain coatings are darker in color (strong yellowish brown, 7.5 YR 5/8 to strong brown, 5 YR 4/6) with transmitted light and somewhat thicker (around .005 to .01 mm). Some of the coatings are moderately birefringent, evident when the coated sand grain is at extinction. It indicates the presence of crystalline material in the coating of fabric plasma.

Kalkaska,Bhm (plate 2). This cemented horizon resembles very closely Kubiena's description (1953, p. 259):

> (The micromorphology of the ortstein layer) is extraordinarily characteristic, so that ortstein formation can generally be determined from a single quartz grain. Each sand grain is painted as with a dye and shows a uniform skin of sepia brown, highly dispersed humus substances. Owing to the great shrinkage of the skin, drying out causes its breakdown into irregularly formed tiles separated from each other by a network of light fissures which allow the bare grain to be seen. In thin section, the humus coating appears as a dark brown line round the contour of the grain. The intergranular spaces are completely empty. With a very high soil permeability and with intense eluviation the remains of droppings and more or less washed dropping skeletons also are carried by the percolating waters and become deposited between sand grains. In the normal humus ortstein they are missing. The individual sand grains are glued to each other for their coatings show a collar-like thickening at the points of contact, due to the precipitation of more humus colloidal substances at the corners. The coatings are mineral deficient. The mineral substances contained in them are readily apparent if the humus substances are ignited. The individual tiles of the coatings are then seen to consist only of sparse remains of mineral substances. They are only slightly reddened (ferric oxide colour) and often are completely white.

Coatings on the grains studied here contain significant amounts of iron and in this respect the Kalkaska Bhm horizon is more similar to the B horizon of Kubiena's iron-humus podzol (1953, p. 261). These coatings are usually about 0.01 to 0.03 mm thick and range in color from strong brown (5 YR 4/6) to moderate reddish brown (2.5 YR 3/4) with transmitted light. They cover approximately 70-80% of the surface area of the skeletal minerals. They are occasionally slightly birefringent near the mineral surface, but this birefringence is less prominent than in the Bhir horizon. Some gaps between grains of about 0.08 mm are bridged by this fabric plasma. Most of the "tiles" are 0.02 to 0.05 mm in diameter with intervening fissures < 0.01 mm wide. The thicker coatings are usually darkest brown in color (dark grayish reddish brown, 2.5 YR 2/2). It appears as if some of these coatings may have peeled off the sand grain and now occupy intergranular spaces, although these scattered small aggregates in the spaces (usually <0.05 mm in diameter) may be the remains of droppings of small organisms carried downward by percolating waters as suggested by Kubiena.

Blue Lake I, Bt (plate 3). The Bt horizon consists of skeletal grains many of which are joined by birefringent intergranular braces. In well developed braces the surfaces adjacent to intergranular spaces are concave. In these cases, the extinction bands remain normal to the tangent of the brace-pore interface as the microscope stage is rotated (see plate 3). This is indicative that the braces are composed of well-oriented clay particles which were deposited between sand grains in successive layers.

Blue Lake I and II, Bhir. The description of the Kalkaska Bhir horizon also fits these horizons. An exception is that examination of soil debris shows that more silt grains are pasted onto the skeletal sand grains by the fabric plasma in the Blue Lake soils.

Blue Lake I and II, Bh (plates 2 and 3). These horizons are characterized by the high percentage of uncoated sand grain surfaces--probably greater than 50%--and by the abundance of intergranular material. The coatings are dark in color--largely dark grayish brown (5 YR 2/1) with transmitted light--and thick (often 0.08 mm). The intergranular aggregates or pellets may be as large as 0.2 mm in diameter and are usually the same color as the dark coatings on sand grains. Most of the aggregates are 0.02 to 0.1 mm in diameter, however.

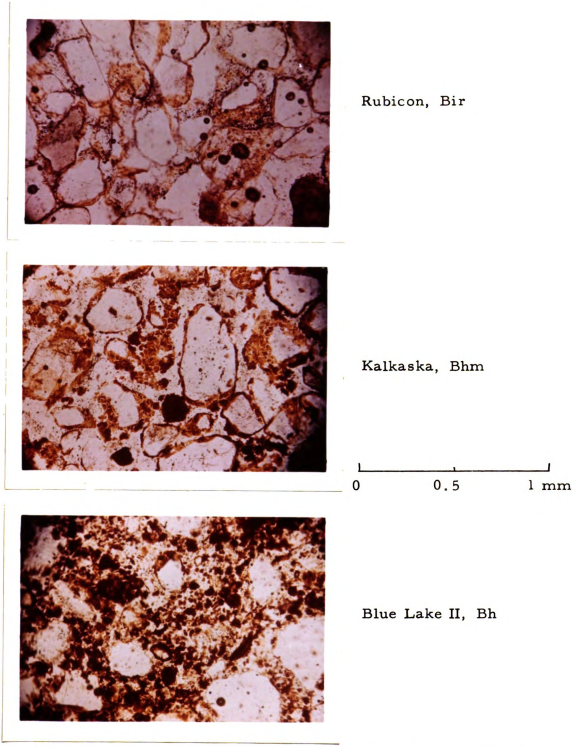
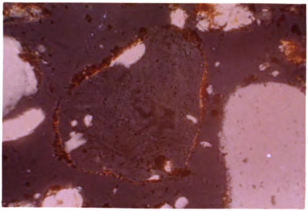
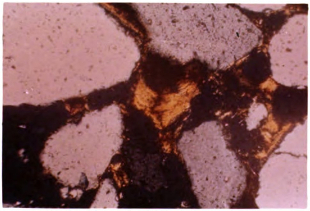


Plate 2. Photomicrographs of thin sections of a sequence of podzol B horizons. Note the increased thickness of coatings on sand grains of the Kalkaska Bhm relative to the Rubicon Bir horizon; the bridging of sand grains with reddish-brown plasma material in the Kalkaska Bhm; and the scarcity of coatings and abundance of intergranular material in the Blue Lake II Bh horizon. The patch of reddish-brown tiles in the center of the photo of the Kalkaska Bhm represents coatings on the top surface of sand grains.



Blue Lake I, Bh



Blue Lake I, Bt

0 0.25 0.50 mm

Plate 3. Photomicrographs of thin sections of Blue Lake I Bh and Bt horizons using crossed Nicol prisms. The photo of the Bh represents a birefringent rim around a quartz grain at extinction with amorphous material on the outside of the rim. The photo of the Bt shows oriented clay particles (gold) forming bridges between sand grains (white or gray) and around pores (black).

Much more of the fabric plasma occurs as intergranular deposits than as coatings on the soil skeleton. In the Blue Lake II, especially, some parts of the thin section would be more accurately described as skeletal material interspersed in the aggregates of fabric plasma rather than the other way around. The shape of these aggregates ranges from round to polygonal but they are generally more rounded than those in the Kalkaska Bhm. Occasionally a thin birefringent band occurs between the skeletal mineral grain and the darkest part of the coating (see plate 3), but because of the scarcity of tightly adhering coatings the occurrence of these bands is limited.

A2 horizons

The sand grains in the A2 horizons are again clean and reflective. There are considerably fewer aggregates of organic matter in the A2 than in the A1 of each soil, but there are more of these aggregates in the A2 horizons of the two oldest soils than in the A2 horizons of the other three. In the Kalkaska and two Blue Lake soils, in which there is more silt present than in the other soils, most of the silt adheres loosely to the surface of sand particles in a dry state or appears as space deposits when the soil is saturated. Many of the roots present in this horizon are in intimate contact with silt-size materials, the mineral material being held to the root by fungi. Also, some small roots (about 0.05 to 0.1 mm in diameter) have short, slender, shiny-brown filaments projecting from them with a clump of fine (about 0.01 to 0.02 mm) white material on the end of the filament.

The fabric of this horizon is similar to Kubiena's bleached sand fabric (1938, pp. 147-148) except that there is no evidence of coatings--originally from a former Bh horizon (Kubiena, 1953, p. 259)--which Kubiena described in his bleached sand fabric.

A1 horizons

In all five profiles the sand grains are predominately quartz on which the corners and edges have been rounded, characteristic of the action of water on angular sand grains. In the A1 horizon, however, there is a greater proportion of sand grains having a more spherical shape and a pitted or frosted surface, typical of wind blown sands, than in the rest of the profile.

The sand grains in the A1 horizons are reflective (with direct light under the binocular microscope) and almost entirely free of coatings of any sort. Occasionally a small rootlet adheres to the surface of a quartz grain and some silt size mineral particles adhere to the surface of a sand grain. In the latter case, the silt grains occur as small aggregates on the surface rather than as individual particles.

Pieces of charcoal are found in the A1 horizons of all five soils and it is especially abundant in the Kalkaska sand. It is likely that all sites had been burned over in the past. The presence of charcoal has significance in the determination of total carbon or organic matter since it is not readily oxidizable by most methods. It is oxidized by dry combustion, however, and is included in the results obtained by this method.

Most of the organic matter is in aggregates with silt-size minerals, the aggregates being generally smaller in size than the medium sand grains. Some of the organic matter still retains its original form, especially short sections of small roots. The aggregates are most abundant in the three oldest profiles, decreasing markedly in going to the Rubicon and to the Eastport. In the latter, most of the organic matter present reflects its original form.

The fabric of this horizon is most similar to Kubiena's agglomeratic fabric (1938, p. 146), except that the formation of somewhat coherent complexes or aggregates takes place more than just sporadically in these soils.

Conclusions

From these observations and considering other data, the following sequence of development of these Podzol sequa is proposed:

1.) Iron and aluminum are mobilized in the A2 horizon by reacting with organic materials in the leachates; phosphorus--either a part of the organic component or weathered in the A2--is translocated downward; and all three components are deposited on sand grains in the B horizon because of evaporation of the solvent, precipitation, or other mechanisms. Eastport represents this stage.

2.) Weakly birefringent coatings are formed on skeletal grains as iron, aluminum, and possibly some silicate clay are deposited on them as crystalline materials. Humus accumulation at this stage is not evident either in thin sections or as a bulge of the organic matter curve in the B horizon. The Rubicon Bir represents the first appearance of this stage and evidence of it remains in later stages--the Bhir horizons of Kalkaska and the Blue Lakes.

3.) Initiation of eluviation and illuviation of humus occurs, resulting in the appearance of thick dark brown coatings on the outside of the lighter reddish brown, birefringent coatings. Some of these dark brown amorphous coatings may form intergranular braces causing the skeletal grains to adhere. The Kalkaska Bhm represents the first appearance of this stage.

4.) These coatings grow in thickness and gradually flake off. This is beginning in the Kalkaska Bhm.

5.) Intergranular aggregates grow in size and increase in number. Once fabric plasma occupies the intergranular

> spaces, it--rather than skeletal sand grains--can be the material causing additional organic matter to be removed from suspension or solution in the percolating waters. Mechanisms by which this is accomplished could be the saturation of active organic groups with metallic cations and their precipitation, adsorption, sieve action, or others. While this is occurring, sand particles may actually be losing their coatings in the upper part of the Podzol B horizon.

About the same developmental sequence is noted in observing the upper B horizon of the chronosequence of soils as in observing a sequence of B horizons progressively higher in the podzol sequum of the oldest soil.

Intergranular braces in the Bt appeared to have resulted from translocation of clay. Whether it came from upper horizons or it was translocated within this horizon could not be determined from these observations.

Classification by Seventh Approximation

(Soil Survey Staff, 1960)

Diagnostic horizons

The A2 horizons of all soils meet the requirements for albic horizons in that they all have chromas of 3 or less and moist color values higher than the underlying spodic (or spodic-like) horizons. The A'2 horizons have chromas higher than 3 and therefore do not qualify as albic horizons.

Horizons meeting the requirement of the spodic horizon of more than 0.29% organic carbon are the six podzol B horizons described for the Kalkaska and Blue Lake soils. Only one horizon, the Blue Lake II Bh exceeds the 1% total sesquioxide criterion. Since the other requirements are fulfilled (or assumed to be fulfilled) by these six horizons, and since they must meet either the organic carbon or sesquioxide requirement, these six are called spodic horizons. Although the amount of allophane in the Blue Lake I Bh has apparently increased during soil formation, its percentage increase is smaller than the percentage increase of total clay in the Bh horizon and smaller than the percentage increase of allophane in the Bt horizon (Table 14). If it is true that some of the apparent increase in clay content of the Blue Lake I soil is due to original differences in the material from which the soil formed, as has been proposed, the role of allophane in this spodic horizon (Bh) may be minor.

The Bt horizons of the Blue Lake soils both have the necessary 3 percentage point increase in clay over the overlying A'2 horizons and the necessary thickness to meet the requirement for argillic horizons. Blue Lake I Bt has oriented clay deposits among the sand grains and the same is thought to be true of the Blue Lake II Bt. Therefore both Bt horizons are called argillic horizons. The requirement that oriented clays constitute 10% of the area of the solid portion of a cross (thin) section suggested on page 45 of the Seventh Approximation (Soil Survey Staff, 1960) could not apply to coarse-textured soils. If a soil contained 10% clay, all of the clay would have to be oriented to make 10% of the solid cross sectional area.

Classification by subgroups

Because both the Eastport and Rubicon soils have only the albic diagnostic horizon, and meet the requirements of the subgroup, they are classified Spodic Orthopsamments (1.22-6). The adjective, spodic, suggests the resemblance of these soils to Spodosols. Since the contrast between the A2 and B horizons of these weakly developed Podzols is more pronounced in the purity of the spectral color (chroma) than in their color values, it may be desirable to give contrasts in chroma at least as much weight as contrasts in value in defining the limits of this subgroup.

The Ortstein in the Kalkaska soil is not continuous enough to meet the requirements for the central concept of the Orthod suborder. The Kalkaska is, therefore, classified Entic Typorthod (6.33-1), indicating that in addition to the properties of the Typorthod great group, it also has properties of the Entisol order.

The two Blue Lakes soils fall into two different subgroups because of differences in the base saturation of their argillic horizons. The Blue Lake I Bt has a base saturation of over 35% and is therefore an Alfic Typorthod (6.33-7), while the Blue Lake II has a base saturation of less than 35% and is an Ultic Typorthod (6.33-8).

Differences between podzol and textural B horizons are brought out by the ratios of some components of these horizons. Organic carbon/clay percentage ratios of the podzol B horizons with letter subscripts range from 0.14 to 0.55 and these ratios for the Bt horizons are 0.04 and 0.05. Wurman's data (1959) for a Montcalm and Wallace soil showed that these ratios were from 0.08 to 0.20 for the podzol B horizons and 0.02 for several textural B horizons. In the soils of the study reported here the "free Fe_2O_3"/clay ratios of the podzol B horizons range from 0.06 to 0.30; of the textural B, 0.03 to 0.05. Wurman's data ranged from 0.09 to 0.11 and from 0.05 to 0.06 for the two kinds of horizons, respectively. Considering the data from these two Michigan studies, it appears that organic carbon/clay ratios and "free Fe_2O_3"/clay ratios each having values of about 0.06 separate the two kinds of horizons.

Bulk density data may also separate the two kinds of horizons. The Bt horizons consist of clay particles occupying the spaces between skeletal sand grains. The arrangement of the latter is probably not greatly different from that of the parent material. On the other hand, in the podzol B horizon the skeletal sand grains are farther apart. This interpretation is based on bulk density and porosity data and observations of thin sections.

It is here proposed for further consideration that in defining the spodic horizon the requirement of "more than 1 percent free sesquioxides in some part" (no. 3, p. 49) be changed to "more than twice as high a free sesquioxide content as the parent material." The B horizon of the Eastport and Rubicon soils would then be spodic horizons and these two soils would be classified in the Spodosol order with the genetically similar Kalkaska and Blue Lake soils. Within the Spodosol order, the present requirement of 1% free sesquioxides could be maintained for the Aquod, Humod, Orthod, and Ferrod suborders, but a new suborder could be established for those soils in which the spodic horizon contained at least twice as much free sesquioxides as the parent material but less than 1% free sesquioxides. Making such a separation at the suborder level is in line with the idea (p. 13) that the differentiae in the suborder category may be chemical or mineralogical properties which are related to the degree of soil development. Defining the spodic horizon by some property relative to such a property of the parent material would be of greater genetic significance than defining it by some arbitrary value of the property.

VII. CONCLUSIONS AND SUMMARY

Time Functions

As shown in the introduction, a soil system, or pedon, is defined when its properties, s_1, s_2, $s_3 \ldots s_n$ are stated. The equation

$$s = f(t)_{cl,\ o,\ p,\ r}$$

represents the relation between a pedon property, s, and time, t, when the other soil-forming factors are held constant. Several pedon properties are plotted as functions of time in Figure 13. The properties shown are the net changes of some constituent of the Podzol sequum or entire bisequum occurring during soil formation calculated using the method of Marshall and Haseman (see Table 12). Since no net change had occurred at time zero, all functions pass through the origin.
In addition to those plotted, some trends of other properties were noted but there was not enough data to plot the function. The net changes are discussed below according to the shapes of their time-functions.

Continuously increasing functions

This type of function is illustrated by the curves for net changes of clay, silt, and organic matter in the sequa. The curve showing the net change in organic matter in the podzol sequum shows a linear increase from 0 to 8000 years and then it levels off, approximating equilibrium conditions, or

$$\frac{\Delta\, 0.m.}{\Delta\, t} = 0$$

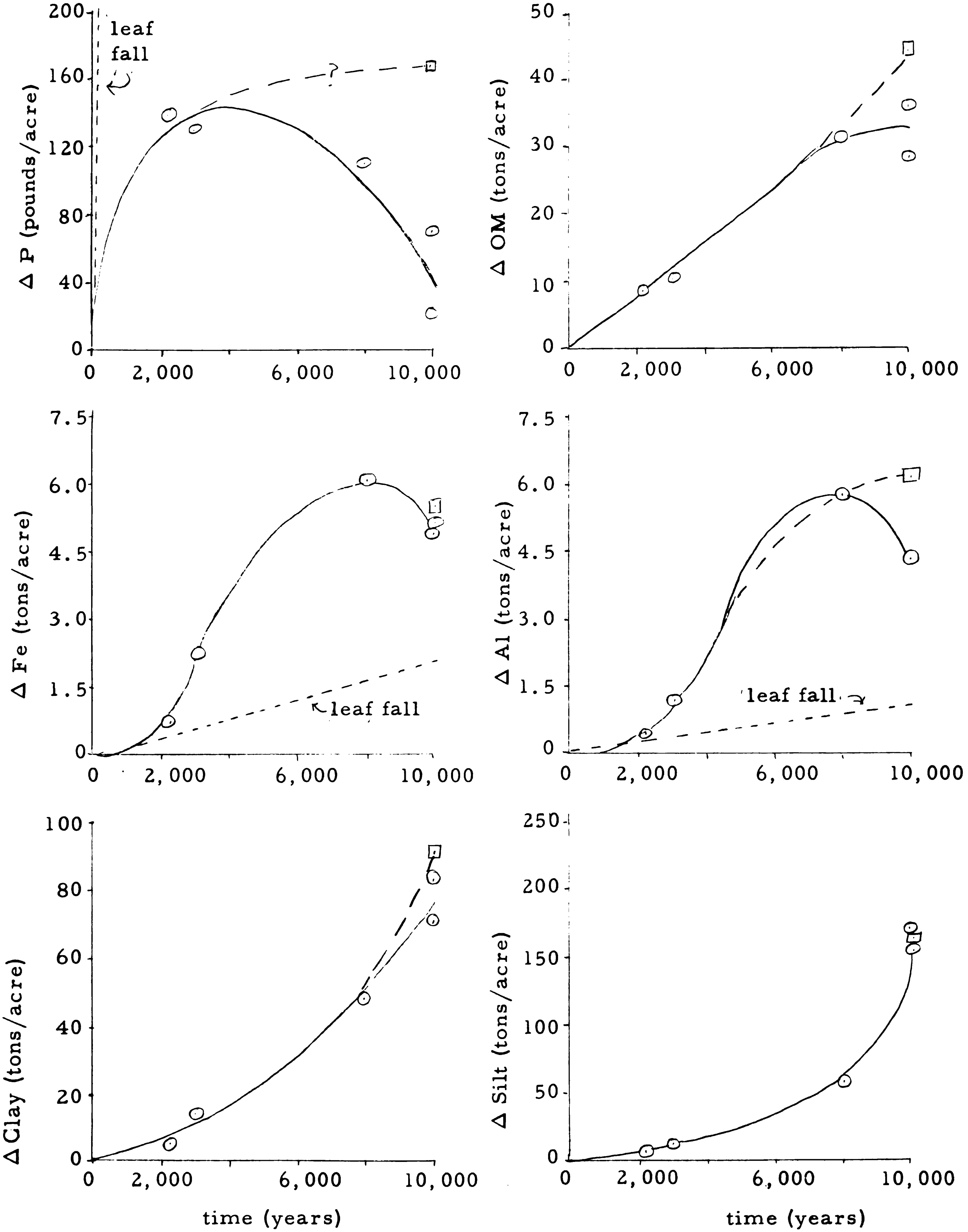


Figure 13. Net changes in available phosphorus, organic matter, extractable Fe_2O_3 (as Fe) and Al_2O_3 (as Al), clay, and silt in the podzol sequum (circles) and in the entire bisequum (squares) as functions of time; and cumulative additions of P, Fe, and Al in leaf fall as functions of time.

If the entire solum of Blue Lake I is considered, the increase in organic matter is linear with time to 10,000 years. These calculations exclude the surface accumulations of organic matter which are subject to destruction by fires. Assuming bulk densities (Wicklund, 1955) of the Aoo, Ao, and A1 horizon are 0.13, 0.14, and 0.58 respectively, and organic contents of the Aoo and Ao are 90% and 80% (Alway et al., 1933) respectively, contributions of organic matter not included in the calculations are Eastport, none; Rubicon, 3; Kalkaska, 25; Blue Lake I, 18; and Blue Lake II, 9 tons per acre. However, these sites are not suitable for the evaluation of these portions of the profile. At best they indicate that a large part of the organic matter in the Podzol profile may be above the mineral soil.

Jenny et al. (1949) observed that surface accumulations of organic matter reach an equilibrium in a much shorter time. According to Jenny, the time required for near equilibrium in the accumulation of the forest floor is 30 to 60 years under oak and 100 to 200 years under pine in the mountains of California.

Some properties have apparently not yet attained equilibrium in 10,000 years. The curves representing changes of silt and of clay in the solum are still increasing at this time. Some of the apparent increase in the clay content of the Blue Lake I solum may have been due to original differences in the material from which the soil developed and thus the points representing this soil, shown by a square in Figure 13, may be too high.

Other properties which have shown generally increasing values with time are the readily available water holding capacity and cation exchange capacity of a 60 inch column of soil and the total and capillary pore space of the solum. Exchangeable bases increase through the Kalkaska stage. However, Blue Lake I contains more exchangeable bases, and Blue Lake II contains less, than does Kalkaska. Exchangeable calcium may show a double maximum--one at time zero before leaching has occurred, and another later at the Kalkaska or Blue Lake stage.

Continuously decreasing functions

None of these curves are plotted, but several are suggested by the data. One is removal of carbonates from the solum. Because of the ubiquitous occurrence of calcareous drift in northern Michigan and because calcareous materials were found below the solum in two of the soils studied, it is assumed that the materials from which the soils developed were calcareous. In this case, the time function of net change in carbonates would begin at the origin, decrease rapidly, and approach a limit sometime before 2, 250 years.

The change in diopside content of the solum is also likely to show a continuous decrease, although the data is not sufficiently complete to calculate this change. Diopside was shown to have weathered from the fine sand fractions of the Kalkaska soil. In the light of the evidence of St. Arnaud (1961) that fine, medium, and coarse sands weather to finer sizes, it is likely that diopside weathers from the entire sand fraction in at least the A2 horizon. In the Kalkaska profile under consideration, the decreasing trend of diopside could not be reversed unless it was formed in the soil. Since diopside is not considered to be an alteration product, such reversal is unlikely. The total sand content also decreases.

Coupled increasing and decreasing functions

In the horizons of the Blue Lake I soil in which the clay fractions were analyzed in greater detail it was found that while chlorite and illite contents showed a small increase, vermiculite and especially montmorillonite showed a large increase, with the result that all 2:1 minerals increased the same amount as did the total fraction. It was further shown that each component or group of components (2:1, 1:1, and primary minerals) underwent about the same apparent increase as did the entire clay fraction. This is interpreted to mean that the material from which these horizons formed was not the same as the horizon selected as the parent material and that in reality the latter contained less clay than the former. If this were true, chlorite plus illite would have decreased and montmorillonite and vermiculite would have increased, and this would be represented by time-functions similar except for opposite signs.

Increasing, then decreasing functions

Time-functions of net changes in extractable aluminum, iron, and phosphorus in the podzol sequum each reach a maximum between 0 and 10,000 years. Another pedon property which apparently attains an early maximum is the pH difference between the A2 and B horizons. It is zero at time zero, reaches its maximum value, 1.1, at the Eastport stage and is low again, 0.4 and 0.5, at the Blue Lake stage. The intervening stages, Rubicon and Kalkaska have gradients of 0.3 and 0.9, respectively, making it difficult to establish the trend in this region of the curve.

The establishment of a large pH difference between the A2 and B horizon early in the chronosequence is thought to be the cause of apparent phosphorus movement from the A2 to the B horizon. This necessitates a greater solubility of available phosphorus at pH 4.4 than at pH 5.5. When the net change of available phosphorus is calculated relative to the C horizon as is shown in Figure 13, the maximum in the subsoils occurs around 2250 to 3000 years. However, if tree roots absorb phosphorus from depths greater than those assigned for the solum, the C horizon no longer represents the material from which the solum developed in regard to phosphorus. In this case it may be better to look at absolute amounts of available phosphorus in the solum rather than the amounts relative to some horizon. Doing this, it is seen (Figure 8) that the maximum in the solum occurs around 3,000 to 8,000 years and is followed by a sharp decrease.

The possibility that the curves would not show a maximum should a forest fire occur and release inorganic phosphate to the mineral soil should be explored. The estimations of the weight of organic matter in the surface horizons show that Kalkaska contains more than any other soil. Thus, assuming the phosphorus contents of the original forest floors were not greatly different among the soils studied here, after a fire Kalkaska should still contain more available phosphorus in the solum and the curve would essentially not change shape. (Assuming that the forest floor contains about 0.2% P_2O_5--Alway et al., 1933--and using the organic matter contents of the surface horizons estimated previously, total phosphorus contents in the organic horizons are Eastport, 0; Rubicon, 4; Kalkaska, 43; Blue Lake I, 32; and Blue Lake II, 16 lb. P per acre.)

If an amount of mineral P equivalent to that in the Kalkaska Ao and A1 has already been released into the Eastport and Rubicon profiles by fires this may account for a part of the apparent early maximum of available P in the podzol sequa.

Whether the maximum of available phosphorus in the podzol sequum occurs at around 2,250 to 3,000 years or 3,000 to 8,000 years, the change in directions must be explained. The explanation rendered here is this: Trees absorb most of their phosphorus originally from a source not extractable by Bray's solution which is either entirely or partially within the present solum. It is circulated through the trees and falls to the soil surface in leaves. Some of the phosphorus in the fallen leaves remains in the surface organic horizons, but most of it is released as the leaves decay. Most of this released phosphate, in turn, is again utilized by trees but some of it is translocated down the profile and immobilized in the B horizon in forms extractable by Bray's solution, probably largely aluminum phosphates. When the available phosphorus in the solum reaches a maximum the sources other than extractable forms have become scarce and the trees utilize extractable forms, depleting their supply by eventual loss to non-extractable forms or from the ecosystem entirely. Since neither calcium phosphate nor iron phosphate is readily extracted by the method used here (Suzuki et al., 1962), it is likely that the original non-extractable form is largely calcium phosphate and the final non-extractable form is iron phosphate.

Curves representing extractable sesquioxides increase to 8,000 years and then decrease slightly in the case of the podzol sequum or level out when the Gray Wooded sequum is also considered in the calculations. Contributions to the current extractable sesquioxide content from sources outside the podzol sequum via vegetation are small because of the low gross accumulation and likely much smaller net accumulation of sesquioxides as leaf fall relative to the extractable sesquioxide content.

Summary of Soil Formation

Instead of considering each stage of the sequence, the author's interpretation of the formation of a Blue Lake soil will be summarized by beginning with the material at time zero and following it through to the present day.

The assumption was made that the parent material was originally calcareous. Pioneer vegetation, probably mosses and lichen at first, and later fireweed and alder became established on the barren sands. The vegetational succession went through a spruce stage, then through a stage in which pine was predominant, followed by a long stage of pine mixed with hemlock, birch, beech, oak, and maple. The organic materials produced by this vegetation contributed organic matter to the pedon and reactive organic chemical groups to the percolating solutions. The acid groups neutralized the carbonates and leached the products from the solum. Eventually basic cations on the exchange complex were exchanged for hydrogen or aluminum ions, establishing a pH gradient between the A2 and B horizons. This resulted in dissolution of phosphate in the A horizons and its precipitation in the B.

The movement of phosphorus marked the beginning of the inorganic-accumulation phase of soil formation. In this phase iron and aluminum were also mobilized in the A horizons and accumulated in the B horizon as slightly crystalline coatings on sand grains as indicated by the birefringence at the coatings.

After this inorganic phase had been in existence a few thousand years, the organic-accumulation phase commenced and humus began to accumulate, forming a Bh horizon. Sesquioxides and probably silicate clays continued to be mobilized and immobilized in this organic phase. Several mechanisms of mobilization and various combinations of the active components were no doubt operative during this phase. These active components were adsorbed or precipitated as amorphous coatings on the previously deposited slightly crystalline coatings in the B horizon. The thickness of the amorphous coatings gradually increased until they flaked off and became intergranular deposits. Here, acting as nuclei for further precipitation and adsorption of material from solution, they caused an increase in the amount of intergranular material. Since these aggregates were relatively weakly held together, chemical, physical, and biological agents prevented them from growing indefinitely. Most of the aggregates were about 0.02 to 0.1 mm in diameter. As the large pores become filled with this debris, the capillary pore space, readily available water capacity, exchange capacity, and exchangeable bases increased. Conditions were thus made more mesophytic and the maple-beech association succeeded the pine-broad-leaved association.

It is possible that the beginning of this organic phase coincided with the entrance of broad-leaved species into the succession. Harper (1918) observed that forest fires had occurred much more frequently in pine-spruce forests, than in hardwood forests in northern lower Michigan. If this were the case an increase in the hardwood component of a forest should have resulted in fewer fires and in a greater amount of organic matter remaining on the soil surface to decompose biologically and to release organic compounds capable of moving down the profile. When the forest-type changed to almost entirely hardwood species, this effect was intensified. The general increase in exchangeable bases with time might be due to the introduction into the vegetational succession of tree species which were more deeply rooted and/or more efficient foragers of bases than were earlier species of the succession.

During the entire course of soil formation, physical weathering was causing a breakdown of medium and coarse sand grains to finer sizes. This occurred to the greatest extent near the soil surface. Diopside and "chlorite" were weathered from the fine sand fraction, probably by physical and chemical means. Chemical processes were largely responsible for illite and chlorite weathering to vermiculite and montmorillonite in the clay fractions. Chemical weathering was also more severe near the surface of the soil, but its effects apparently did not decrease as sharply with greater depth as did the effects of physical weathering.

During the entire course of soil formation the total clay content of the solum was also increasing. Apparently after the clay content reached a threshold point, and after the Podzol sequum was well formed, a second, Gray Wooded, sequum began to form below the Podzol sequum. This final stage is the Blue Lake soil. (If the Blue Lake I soil was originally slightly higher in clay than the other soils, as was postulated, one would come to the same conclusion because a trend of increasing clay content with time was already established in the Eastport, Rubicon, and Kalkaska stages. The slightly higher original clay content would have only hastened the appearance of the final stage.)

This sequence, of the Podzol sequum forming prior to the Gray Wooded sequum, is different from the sequences on finer textured materials in which the Podzol has apparently formed later than or simultaneously with the Gray Wooded sequum (see Literature Review).

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APPENDIX

Table 15. Physical and chemical data for Eastport sand.

Property	Horizon and depth (inches)				
	A1+A2	B(ir)	B3	C1	D
	0-5	5-19	19-38	38-90	90+
Particle size dist. (%)					
Very coarse sand 2-1 mm	0.0	0.0	0.2	0.2	10.6
Coarse sand 1-0.5	8.8	9.7	26.8	13.0	47.1
Medium sand 0.5-0.25	80.0	79.6	65.2	75.7	36.2
Fine sand 0.25-0.1	9.4	10.4	7.2	10.3	2.6
V fine sand 0.1-0.05	0.2	0.0	0.0	0.0	0.1
Silt 0.05-0.002	0.49	0.14	0.04	0.04	0.02
Clay < 0.002	0.44	0.24	0.17	0.16	0.16
Total < 2 mm	99.3	100.1	99.6	99.2	96.8
> 2 mm	0.0	0.0	0.0	0.0	27.8
USDA textural class	s	s	s	s	gr cs
Bulk density (gm/cc)	1.33	1.49	1.52	1.52	--
Water retention (%)					
saturated	35.5	28.2	26.8	26.9	--
0.01 atmospheres	31.2	26.4	25.2	25.4	--
0.02	23.6	22.0	20.7	21.3	--
0.03	11.0	9.1	6.3	8.3	--
0.04	7.4	4.5	7.5	3.6	--
0.06	5.9	3.3	3.6	2.8	--
0.33	5.0	2.7	2.5	2.4	--
1.0	4.4	2.3	2.0	2.1	--
5.0	1.2	0.2	0.2	0.1	--
15.0	1.3	0.4	0.2	0.2	--
Available H_2O (0.06-5)	4.7	3.1	3.4	2.7	--
Total carbon (%C)	0.44	0.12	0.10	0.06	--
Carbonate carbon (%C)	--	--	--	--	0.53
Organic matter (%)	0.76	0.21	0.17	0.10	--
Total nitrogen (%N)	0.016	0.005	0.004	0.002	--
Carbon/nitrogen ratio	27	24	25	30	--
Extractable sesquioxides					
Iron (%Fe_2O_3)	0.03	0.06	0.05	0.03	0.01
Aluminum (%Al_2O_3)	0.011	0.049	0.034	0.023	0.006
Exchangeable cations					
Hydrogen (me/100g)	0.3	0.1	0.1	0.0	--
Potassium	0.01	0.01	<.01	0.01	--
Calcium	0.4	0.2	0.2	0.2	--
Magnesium	<.1	<.1	<.1	<.1	--
Cation exchange capacity	0.7	0.3	0.3	0.2	--
pH (water suspension)	4.4	5.5	5.6	6.0	8.3
Avail phosphorus (p^{P}pm)	2	22	12	3	0

Table 16. Physical and chemical data for Rubicon sand.

Property	Horizon and depth (inches) A1 0-2	 A2 2-11	 Bir 11-22	 B3 22-42	 C11 42-86	 C12 86-102
Particle size dist. (%)						
Very coarse sand 2-1 mm	0.1	0.2	0.2	0.2	0.2	0.4
Coarse sand 1-0.5	20.7	20.3	32.8	16.0	17.2	20.4
Medium sand 0.5-0.25	56.9	60.6	49.7	63.4	59.6	65.1
Fine sand 0.25-0.1	16.4	15.7	15.8	19.4	22.3	13.2
V fine sand 0.1-0.05	0.6	0.4	0.1	0.0	0.0	0.0
Silt 0.05-0.002	1.65	0.72	0.11	0.06	0.03	0.06
Clay <0.002	0.90	0.52	0.46	0.26	0.14	0.19
Total <2 mm	97.2	98.4	99.2	99.3	99.5	99.4
>2 mm	0.0	0.0	0.0	0.0	0.0	1.3
USDA textural class	s	s	s	s	s	s
Bulk density (gm/cc)	--	1.31	1.52	1.51	1.56	--
Water retention (%)						
saturated	--	33.6	27.7	27.9	25.2	--
0.01 atmospheres	--	30.8	26.0	26.3	24.2	--
0.02	--	23.7	21.6	21.0	22.2	--
0.03	--	12.7	9.8	9.2	13.5	--
0.04	--	7.9	4.7	4.4	5.0	--
0.06	--	6.2	3.7	3.3	3.2	--
0.33	--	5.4	3.0	2.6	2.9	--
1.0	--	4.7	2.6	2.3	2.4	--
5.0	--	1.0	0.7	0.5	0.2	--
15.0	--	0.9	0.6	0.5	0.2	--
Available H_2O (0.06-5)	--	5.2	3.0	2.8	3.0	--
Total carbon (%C)	1.38	0.24	0.18	0.12	0.06	--
Carbonate carbon (%C)	--	--	--	--	--	0.02
Organic matter (%)	2.38	0.41	0.31	0.21	0.10	--
Total nitrogen (%N)	0.054	0.009	0.006	0.005	0.002	--
Carbon/nitrogen ratio	26	27	30	24	30	--
Extractable sesquioxides						
Iron (%Fe_2O_3)	0.05	0.04	0.14	0.09	0.04	0.02
Aluminum (%Al_2O_3)	0.019	0.015	0.115	0.098	0.047	0.049
Exchangeable cations						
Hydrogen (me/100gm)	3.0	0.2	0.3	0.2	0.1	0.0
Potassium	0.04	0.01	0.02	0.02	0.01	0.01
Calcium	1.0	0.2	0.3	0.2	0.2	0.4
Magnesium	<.1	<.1	<.1	<.1	<.1	<.1
Cation exchange capacity	4.0	0.4	0.6	0.4	0.3	0.4
pH (water suspension)	4.7	4.8	5.1	5.8	6.2	6.4
Avail phosphorus (p^{P}pm)	6	2	23	20	7	7

Table 17. Physical and chemical data for Kalkaska sand.

Property	Horizon and depth (inches)						
	A1 0-1	A2 1-9	Bhm	Bhir 9-23	B3 23-38	C11 38-66	C12 66-113
Particle size dist. (%)							
Very coarse sand 2-1 mm	0.5	0.8	0.3	0.6	0.2	0.6	0.2
Coarse sand 1-0.5	27.6	34.8	23.9	26.6	25.9	41.3	30.9
Medium sand 0.5-0.25	36.8	43.5	48.2	42.9	52.0	43.5	53.4
Fine sand 0.25-0.1	15.6	16.4	21.6	22.4	19.3	13.6	10.8
V fine sand 0.1-0.05	1.0	0.8	0.4	1.0	0.2	0.2	0.2
Silt 0.05-0.002	5.2	2.2	0.5	1.8	0.2	0.1	0.1
Clay < 0.002	2.1	0.7	1.4	2.1	0.6	0.3	0.4
Total < 2 mm	88.8	99.2	96.3	97.5	98.4	99.6	96.0
> 2 mm	0.0	0.0	0.0	0.0	0.0	0.0	0.0
USDA textural class	cs	cs	s	cs	s	cs	s
Bulk density (gm/cc)	--	1.34	1.51	1.35	1.47	1.58	--
Water retention (%)							
saturated	--	34.8	27.1	34.7	30.0	24.6	--
0.01 atmospheres	--	31.5	24.6	32.0	27.8	23.2	--
0.02	--	20.4	19.7	22.7	21.3	19.3	--
0.03	--	11.7	14.2	12.1	9.4	8.4	--
0.04	--	8.1	7.5	8.3	5.3	3.8	--
0.06	--	6.1	5.9	6.5	3.8	2.6	--
0.33	--	4.2	4.3	4.7	2.3	1.9	--
1.0	--	4.0	3.9	3.9	2.1	1.5	--
5.0	--	1.3	2.5	2.5	1.0	0.3	--
15.0	--	1.2	2.0	2.0	0.9	0.3	--
Available H_2O (0.06-5)	--	4.8	3.4	4.0	2.8	2.3	--
Total carbon (%C)	3.98	0.24	0.77	0.58	0.22	0.06	--
Carbonate carbon (%C)	--	--	--	--	--	--	0.01
Organic matter (%)	6.85	0.41	1.33	1.00	0.38	0.10	--
Total nitrogen (%N)	0.236	0.012	0.028	0.024	0.009	0.002	--
Carbon/nitrogen ratio	17	20	28	24	24	30	--
Extractable sesquioxides							
Iron (%Fe_2O_3)	0.11	0.04	0.33	0.37	0.09	0.03	0.04
Aluminum (%Al_2O_3)	0.05	<.01	0.54	0.36	0.18	0.04	0.02
Exchangeable cations							
Hydrogen (me/100 gm)	10.0	0.1	0.5	2.0	0.3	0.0	0.0
Potassium	0.14	0.01	0.03	0.03	0.01	0.02	0.03
Calcium	6.3	0.6	1.3	0.8	0.4	0.2	0.2
Magnesium	0.5	<.1	<.1	<.1	<.1	<.1	<.1
Cation exchange capacity	16.9	0.7	1.8	2.8	0.7	0.2	0.2
pH (water saturation)	4.7	4.8	6.0	5.7	6.2	6.4	6.4
Avail phosphorus (p^{P}pm)	10	2	22	23	25	10	5

Table 18. Physical and chemical data for Blue Lake sand I.

Property	Horizon and depth (inches)									
	A1	A2	Bh	Bhir	B3	A'2-Bt	A'2	Bt	C1	C2
	0-1	1-9	9-15	15-28	28-41	41-53	53-71	71-80	80-106	106+
Particle size dist. (%)										
Very coarse sand 2-1mm	1.2	1.6	2.2	2.2	1.0	1.1	1.2	2.0	3.9	4.6
Coarse sand 1-0.5	20.1	22.7	24.0	25.0	19.1	18.4	32.0	27.4	37.7	33.4
Medium sand 0.5-0.25	26.4	33.8	33.2	36.3	38.4	37.8	32.6	34.2	34.4	35.9
Fine sand 0.25-0.1	22.2	28.2	26.9	27.0	33.7	34.2	30.4	27.2	19.6	20.0
Very fine sand 0.1-0.25	4.0	4.7	4.4	3.4	3.0	3.9	2.0	2.9	1.2	1.7
Silt 0.05-0.002	10.6	8.0	3.2	2.2	1.6	2.0	0.6	1.8	0.8	1.0
Clay <0.002	3.4	1.0	3.8	2.6	2.0	2.2	0.8	3.8	1.2	1.0
Total <2mm	87.9	100.0	97.7	98.7	98.8	99.6	99.6	99.3	98.8	97.6
>2mm	0.8	4.2	4.2	2.3	2.2	1.7	0.8	3.3	8.7	18.2
USDA textural class	ls	s	cs	cs	s	s	cs	cs	cs	cs
Bulk density (gm/cc)	--	1.38	1.41	1.44	1.51	--	1.58	1.61	--	--
Water retention (%)										
saturated	--	33.6	34.2	32.2	28.6	--	25.8	22.9	--	--
0.01 atmospheres	--	30.5	31.6	30.0	26.4	--	23.2	19.8	--	--
0.02	--	24.2	26.6	25.2	22.1	--	18.9	16.2	--	--
0.03	--	16.2	18.9	18.0	15.6	--	12.1	12.4	--	--
0.04	--	12.3	14.1	11.7	9.2	--	6.9	8.9	--	--
0.06	--	9.1	10.5	7.7	6.0	--	4.6	6.1	--	--
0.33	--	6.1	7.2	4.8	3.5	--	2.8	4.0	--	--
1.0	--	5.0	6.3	4.3	3.0	--	2.4	3.4	--	--
5.0	--	1.8	2.6	1.8	1.4	--	0.6	1.8	--	--
15.0	--	1.8	2.0	1.5	1.2	--	0.4	1.6	--	--
Available H_2O (0.06-5)	--	7.3	7.9	5.9	4.6	--	4.0	4.3	--	--

Total carbon (%C)	4.98	0.40	0.55	0.44	0.18	0.08	0.09	0.17	0.16	--
Carbonate-carbon (%C)	--	--	--	--	--	--	--	--	0.12	0.48
Organic matter (%)	8.58	0.69	0.95	0.76	0.31	0.14	0.15	0.29	0.07	--
Total nitrogen (%N)	0.297	0.022	0.032	0.018	0.009	0.004	0.004	--	0.002	--
Carbon/nitrogen	17	18	17	24	20	20	22	--	20	--
Extractable sesquioxides										
Iron (%Fe_2O_3)	0.22	0.08	0.39	0.17	0.08	0.07	0.05	0.11	0.05	0.04
Aluminum (%Al_2O_3)	0.06	0.02	0.18	0.24	0.16	0.06	0.07	0.16	0.04	0.01
Exchangeable cations										
Hydrogen (me/100gm)	12.0	0.2	4.0	0.4	0.3	0.1	0.1	0.3	--	--
Potassium	0.26	0.05	0.10	0.09	0.09	0.09	0.09	0.07	--	--
Calcium	4.3	0.6	1.7	0.9	0.6	0.6	0.3	0.8	--	--
Magnesium	0.3	<.1	0.1	<.1	<.1	0.1	<.1	0.1	--	--
Cation exchange capacity	16.9	0.8	5.9	1.4	1.0	0.9	0.5	1.3	--	--
pH (water saturation)	4.4	4.5	5.0	5.4	5.6	5.6	5.9	5.4	7.2	8.3
Avail phosphorus (p^Ppm)	18	2	9	17	13	8	12	16	6	2

Table 19. Physical and chemical data for Blue Lake sand II.

Property	Horizon and depth (inches)									
	A1	A2	Bh	Bhir	B3	A2-Bt	Bt	C11	C12	C13
	0-1½	1½-6	6-10	10-17	17-25	25-45	45-52	52-72	72-92	92-105+
Particle size dist. (%)										
Very coarse sand 2-1mm	1.0	1.4	1.8	1.7	0.7	1.4	3.8	0.2	1.0	1.4
Coarse sand 1-0.5	15.1	21.6	17.4	19.0	22.0	30.2	29.4	23.7	36.0	22.4
Medium sand 0.5-0.25	26.2	32.0	31.2	29.8	45.2	46.0	36.5	52.0	40.8	44.7
Fine sand 0.25-0.1	21.8	26.3	25.0	28.4	24.7	18.8	17.4	19.4	18.7	28.6
V fine sand 0.1-0.05	4.8	5.7	5.6	5.8	2.6	1.2	1.7	1.6	1.0	0.9
Silt 0.05-0.002	13.6	9.5	8.0	6.2	1.8	0.7	2.2	1.0	0.7	0.5
Clay <0.002	4.4	1.4	6.4	4.9	1.8	1.0	7.0	1.6	1.4	1.0
Total <2mm	86.9	97.9	95.4	95.8	98.8	99.3	98.0	99.5	99.6	99.5
>2mm	1.4	3.8	4.9	3.8	0.8	0.5	23.6	0.3	1.1	1.2
USDA textural class	ls	s	ls	s	s	cs	gr cs	s	cs	s
Bulk density (gm/cc)	--	1.35	1.14	1.30	1.49	1.62	--	--	--	--
Water retention (%)										
saturated	--	33.7	46.0	37.5	28.5	24.2	--	--	--	--
0.01 atmospheres	--	30.5	41.6	34.8	27.0	22.2	--	--	--	--
0.02	--	24.0	37.6	30.2	22.9	17.4	--	--	--	--
0.03	--	18.7	32.6	23.6	16.6	7.6	--	--	--	--
0.04	--	14.2	27.4	17.3	10.8	3.9	--	--	--	--
0.06	--	11.2	23.2	13.4	7.9	2.7	--	--	--	--
0.33	--	8.6	20.0	8.9	5.2	1.7	--	--	--	--
1.0	--	7.4	17.5	8.1	4.2	1.4	--	--	--	--
5.0	--	2.2	5.0	3.3	1.0	0.5	--	--	--	--
15.0	--	2.0	3.8	3.0	0.9	0.4	--	--	--	--
Available H_2O (0.06-5)	--	9.0	18.2	10.1	6.9	2.2	--	--	--	--

Total carbon (%C)	5.82	0.40	1.28	1.00	0.22	0.12	0.38	0.05	--	--
Carbonate carbon (%C)	--	--	--	--	--	--	--	--	--	--
Organic matter (%)	10.03	0.69	2.20	1.72	0.38	0.21	0.65	0.09	--	--
Total nitrogen (%N)	0.336	0.024	0.070	0.044	0.010	0.005	0.019	0.003	--	--
Carbon/nitrogen ratio	17	17	18	23	22	24	20	17	--	--
Extractable sesquioxides										
Iron (%Fe_2O_3)	0.18	0.09	0.74	0.31	0.08	0.04	0.35	0.06	0.04	0.05
Aluminum (%Al_2O_3)	0.08	0.02	0.51	0.59	0.18	0.09	0.40	0.06	0.04	0.04
Exchangeable cations										
Hydrogen (me/100gm)	11.0	0.3	6.0	4.0	0.5	0.3	5.0	0.2	0.2	0.1
Potassium	0.18	0.05	0.12	0.11	0.06	0.04	0.16	0.09	0.06	0.10
Calcium	4.3	0.6	0.9	0.3	0.1	0.1	0.1	0.1	0.2	0.3
Magnesium	0.4	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1	<.1
Cation exchange capacity	15.9	1.0	7.0	4.4	0.7	0.4	5.3	0.4	0.5	0.5
pH (water saturation)	4.6	4.6	5.0	5.1	5.2	5.2	4.9	5.0	5.3	5.7
Avail phosphorus ($p^{P}pm$)	12	4	7	12	13	8	14	9	8	8

ROOM USE ONLY

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~~MAY 26 1963~~
~~JAN 9 1964~~
DEC 12 1964
~~FEB 3 1965~~
~~FEB 19 1965~~
~~MAR 10 1965~~
~~APR 17 1965~~
~~APR 11 1966~~
~~APR 25 1966~~
~~MAY 11 1966~~
~~MAY 25 1966~~
~~JUN 8 1966~~
~~JUN 21 1966~~

~~OCT 31 1966~~
~~NOV 14 '66~~
~~NOV 26 '66~~
~~DEC 16 1966~~
~~DEC 16 1966~~
~~JAN 4 1967~~
~~JAN 20 1967~~
~~FEB 4 1967~~
~~JUN 14 1967~~

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