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ARGILLIC HORIZON FORMATION IN THE

SOILS OF A HYDROSEQUENCE

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DAVID LYNN CREMEENS

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By

David Lynn Cremeens

A THESIS

Submitted to
Michigan State University
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ABSTRACT

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Four hydrosequences occurring in loamy till were investigated in order to gain insight into the influence of the depth and duration of the zone of saturation on argillic horizon development.

Field descriptions and laboratory data indicated that the well-drained pedons were characterized by a well developed argillic horizon. Two of the somewhat-poorly drained pedons and two of the poorly drained pedons had argillic horizons that were less developed than the well-drained pedons. Two of the somewhat-poorly drained and two of the poorly drained pedons were characterized by a lack of argillic horizon development.

Vermiculite, illite, and kaolinite were all translocated to a significant extent in the well drained pedons, while in the somewhat-poorly drained pedons with argillic horizons illite appears to have been preferentially translocated. In the poorly-drained pedons with argillic horizons montmorillonite and illite were translocated. These pedons appeared to have similar water table regimes as

the poorly drained pedons without argillic horizons. Zones of saturation behave as physical barriers to the throughflow of moisture fronts.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The proper mapping, classification, and management of soils is guided by a knowledge of the processes involved in soil genesis. This knowledge is in part gained by the recognition of the products of soil genesis. These products frequently occur in the form of diagnostic horizons. Diagnostic horizons give a soil its most distinguishing properties, and can be formed by different processes. Differentiating the relative importance of these processes is important in the proper classification of soil.

The purpose of this study was to gain insight into the genesis of argillic horizons in the soils of a hydrosequence as influenced by the depth and duration of the zone of saturation. The following objectives served to guide the research process throughout this study:

1. To characterize the degree of expression of argillic horizon formation in the soils of a hydrosequence. The degree of expression is based on clay content differential between adjacent horizons and on the clay particle arrangement in the argillic horizon. A more strongly expressed argillic horizon will have a greater content of clay, relative to the eluvial zone, and in the form of more oriented clay films, as compared to a more

weakly developed argillic horizon.

2. To determine whether the soils in the poorly drained positions, with aquic moisture regimes, are characterized by having argillic horizons, or any zones of clay illuviation. This is based on the hypothesis that zones of saturation present barriers to downward moving soil water systems.

3. To determine whether the clay mineralogy of clay films in the argillic horizon differ from the mineralogy of the fine clay fraction of the eluvial and illuvial horizons of the soils of a hydrosequence. Certain clay minerals may translocate more easily than others, resulting in a difference.

An argillic horizon is a diagnostic horizon in which layer-lattice silicate clays have accumulated to a significant extent by the process of illuviation (Soil Survey Staff, 1975). Illuviation in this system refers to the movement of clay size particles with the downward percolating water in the form of a colloidal suspension. In an argillic horizon the clays have accumulated to the extent that:

1. The ratio of clay in the argillic horizon to that in the eluvial horizon must be 1.2 or more when the eluvial horizon contains between 15 and 40 percent total clay. If the eluvial horizon has less than 15 percent total clay then the increase must be at least 3 percent more clay. If the eluvial horizon

has more than 40 percent total clay then the argillic horizon must contain at least 8 percent more clay, or 8 percent more fine clay if the total clay content of the eluvial horizon exceeds 60 percent.

2. In cases where the clay content of the eluvial horizon is less than 40 percent, the ratio of fine clay to total clay in the argillic horizon is generally greater than that in the eluvial horizon or underlying horizon by about one third or more.

In addition to the clay increase criteria there are additional properties that should be met for the designation of a B horizon as an argillic horizon. The argillic horizon should be at least 15 cm thick where the solum extends below 1.5 m depth, or if the argillic horizon is sand or loamy sand. The argillic horizon should be at least 7.5 cm thick when it is loamy or clayey. Generally, it should be at least one-tenth as thick as the cumulative thickness of all overlying horizons. The clay increase must be morphologically recognizable in addition to textural differences. In structureless soils this takes the form of oriented clay bridging between sand grains and in some pores. In pedal soils the argillic horizon should have clay films on some of both the vertical and the horizontal ped surfaces and in some fine pores. Oriented clay, determined in thin section observation, meets the criteria if it occupies one percent or more of the cross section. The clay film requirement is waived where the argillic horizon is clayey and is dominated by 2-to-1 lattice clays.

B horizons that are characterized by an increase (or maximum) in the relative clay content are not necessarily argillic horizons. Other mechanisms have been suggested as a cause for the clay maximum occurring in the B horizon (Birkeland, 1974; Smeck et al., 1981). In most soils the maximum clay content in the B horizon is a result of a combination of processes. The relative importance of each process will vary from soil to soil. If evidence shows that clay has moved from one horizon to another or from one point to another within a horizon, then certain mechanisms are involved in initiating and stopping the movement.

Young glacial landscapes, such as in central Michigan, often have complex soil landscape relationships within a small geographic area. Thus, soils characterized by contrasting diagnostic properties are often associated together. This is especially true for soils with contrasting drainage classes and soil moisture regimes. Such soils are said to occur in a topographical hydrosequence. In central and southern Michigan, a common hydrosequence consists of well drained and moderately well drained soils occupying higher landscape positions with somewhat poorly and poorly drained soils occupying the lower positions and depressions. The well drained are commonly characterized by a typic subgrade of a udic moisture regime. Moderately-well drained soils are characterized by an aquic subgrade of a udic moisture regime. The poorly drained soils are characterized by a typic subgrade of an aquic moisture regime, while the somewhat poorly drained soils occur as intergrades between udic and aquic moisture regimes. This topographic hydrosequence is a naturally occurring product of young glacial landscapes and the immature drainage networks that develop on them.

Chapter 2. LITERATURE REVIEW

A. Soil Classification

a. United States

Argillic horizons, or zones of clay accumulation are recognized and incorporated into soil classification systems throughout the world. In the United States, criteria are applied to the properties of argillic horizons in order to give a genetic implication. The criteria imply clay accumulation resulting from clay particle translocation, as opposed to stratification or in situ weathering. Argillic horizons contain more total clay, and have a greater fine clay to total clay ratio than overlying eluvial horizons (Soil Survey Staff, 1975). Where a lithologic discontinuity occurred between the argillic horizon and the eluvial zone, the B/C total clay difference and B/C fine clay to total clay ratios was used as criteria for defining an argillic horizon (Smith and Wilding, 1972).

The clay increase is reflected in the form of clay films coating ped faces of structural soils, as clay bridges between sand grains of structureless soils, or as one percent oriented clay in a cross section. Soils with a clayey particle-size family dominated by 2:1 expandable clays are an exception to the clay film criteria. Argillic horizons must be at least 7.5cm thick.

In the Soil Taxonomy argillic horizons are diagnostic at the Order level for Alfisols and Ultisols, the Suborder level for Aridisols, the Great group level for Mollisols, and at the subgroup level for Entisols, Inceptisols, and Spodosols (Soil Survey Staff, 1975).

b. Canada

In the Canadian system of soil classification a Bt horizon is recognized without having a diagnostic name. The criteria for a Bt horizon differ from those listed for an argillic horizon in the United States system by lowering the minimum thickness to 5 cm. and by maintaining the clay film requirement for clayey structured soils (McKeague et al., 1981). It has been suggested that a B horizon meeting the particle-size and clay film criteria should be considered a Bt horizon in spite of the fact that micromorphological evidence indicated less than one percent oriented clay (McKeague et al., 1978; and McKeague et al., 1981). The criterion for a Bt horizon designation requires one percent or more oriented clay in a cross section. Suggestions for lowering the oriented clay requirement resulted from the observation that many horizons, which did not meet the micromorphological criteria, did contain much more clay than the associated eluvial horizon and a higher proportion of fine clay than the associated C horizon (McKeague et al., 1978).

In the Canadian system the Bt horizon is diagnostic at the order level for the Luvisolic Order, the Luvic great group for the Gleysolic Order, the Eluviated subgroup for the Brunisolic and Chernozemic Orders, and indirectly, the Solod great group of the Solonetizic Order (Canada Soil Survey Committee, 1978). The latter Bt horizon is similar in characteristics to the natric horizon in the United States system.

c. Australia

The key developed for use in the classification and recognition of Australian soils describes a B horizon as a master horizon of one or more layers of mineral soil material with a concentration of clay, and/or iron, and/or aluminum, and/or translocated organic matter among other structural and color properties (Northcote, 1971). The first or primary division of all soils are the primary profile forms, largely textural in character. Gradational primary profile forms show increasingly finer texture in passing down through the solum, with the textural difference between consecutive horizons being less than 1.5 texture groups. This form allows for an increase in clay content with depth with a subsequent decrease as one leaves the solum and enters the parent material. Where the textural difference between the A and B horizons span more than 1.5 texture groups a Duplex primary profile form is recognized. The B horizons in these soils are described as clayey B horizons, or clayey subsoils. A genetic inference is not given in the description of these horizons.

The 1968 Australian system of soil classification recognized the role of translocated clay material in the formation of a clay enriched B horizon, but places greater

emphasis on a combination of processes (Stace et al., 1968). Brewer (1968) reported that the micromorphological data for most horizons exhibiting particle-size differentiation indicates that the proportion of illuviated (oriented) clay is small, or even lacking.

Great Soil Groups in the 1968 Australian system are grouped in an order that represents an overall progressive increase in the degree of leaching and profile development (Stace et al., 1968). The clayey B horizon is best represented in the "mildly to strongly acid and highly differentiated" soils. The Grey-Brown Podzolic soils, Red Podzolic soils, Yellow Podzolic soils, and Brown Podzolic soils are all characterized by a blocky clay enriched B horizon. It is suggested that the role of illuviation is small, and a combination of other processes, most notably the destruction of clay in the eluvial zone, is responsible for the textural differences. Illuvial clay features are commonly found in all horizons though. The only soils believed to have developed largely from clay illuviation are the Gleyed Podzolic soils; characterized by strongly contrasting A and B horizons and gley properties.

d. Soviet Union

Soviet soil classification schemes have developed out of the genetic factor approach to soil classification, associated most notably with Dokuchayev and Glinka (Liverovskiy, 1969). A great deal of importance was attached to podzolization and the formation of podzolic soils. Basically, podzolization referred to the mobilization, translocation, and deposition of various humus mineral assemblages by the downward flow of acid soil solutions. The diagnostic horizon resulting from this process is the podzolic horizon, an eluvial horizon. The equivalent horizon in the United States system is the albic horizon designated E (A2).

Ivanova and Rozov (1970) have worked on a more modern soil classification system for the U.S.S.R.. In this system soils are originally divided into large geographic zonal units, based on climate and vegetation. These units are further subdivided based on their moisture status. Automorphous soils, semihydromorphous soils, and hydromorphous soils are recognized in increasing order of wetness. Alluvial soils are also recognized in this category. As a division within this category soil types are described based on the overall morphology of the soil. Podzolic soils are a soil type of the automorphous soils of the Taiga forest region soils. Soil types are then divided into subtypes based on environmental subzonal facies, or additional morphologic properties.

The division in which diagnostic B horizons are described is the soil type. Diagnostic B horizons include those described as illuvial, referring to accumulations of iron, aluminum, humus, and clay. A textural, or clay rich, B horizon is given the designation of Bt. Soil types among the automorphous and semihydromorphous soils of the Taiga forest regions have been described as having a Bt horizon. Automorphous and semihydromorphous soils of the Brown soil forest regions also have soil types characterized by a Bt horizon. Automorphous, semihydromorphous, and hydromorphous soils of the Steppe region all have soil types containing a Bt horizon. Two soil types in the automorphous soils of the semi-desert and desert regions have Bt horizons. Four soil types characterized by having Bt horizons occur in the soils of the humid subtropical regions, and in the soils of the semiarid subtropical regions.

e. France

In the French soil classification system the concept of "sol lessive" broadly indicates a soil where eluviation of clay and of bound iron results in minimum clay and iron contents in the A horizons and a maximum in the Bt horizon. Losses from the A horizon were thought to approximately balance gains in the Bt horizon (Duchaufour, 1978). The mechanical translocation of fine clay particles together with their iron oxide coatings is the implied concept. Eluviated soils employ this concept and are approximately equivalent to the Alfisols in the United States system. Illuvial Bt horizons are also described in the lessive subdivisions of the Fersialitic Soils.

f. FAO

The Food and Agricultural Organization of the United Nations developed a classification system used in the preparation of a world soil map. The diagnostic horizon definitions and horizon nomenclature of the United States Soil Conservation Service (Soil Survey Staff, 1975) were used in developing the legend of the FAO system. The basic

unit of classification is the soil unit. Two soil units are characterized by having an argillic horizon. Luvisols and Acrisols designate soils in which the essential characteristic is the illuvial accumulation of clay under conditions of, respectively, high or low base saturation (FAO, 1974). The adjective "luvic" designates soils in which there is evidence of clay illuviation, although other soil forming processes are acknowledged. Soil units in which the luvic adjective appear are the Arenosols, Kastanozems, Phaeozems, Xerosols, and Yermosols.

g. Summary

The concept of a clay enriched illuvial B horizon, identified by various morphological, physical, and chemical properties, is recognized throughout the world. Various workers have pointed out weaknesses in the concept, resulting from application of the various criteria by pedologists. McKeague et al. (1981) reported that pedologists from various regions in Canada seem to use varying criteria for Bt horizon designations; the criteria being dependent on the soil being examined. The need for all pedologists to consistently use the same criteria was stressed. Particle-size data, used alone, resulted in designating horizons as Bt even though they lacked clear evidence of illuvial clay. Soils thought to have B horizons by previous work on Prince Edward Island yielded data that failed to meet the requirements for argillic horizons in the United States classification system (McKeague et al., 1973).

It was pointed out, however, that some evidence of clay translocation can be found in most soils of humid lands. Clay content was found to be one of the least variable soil horizon properties in Udalfs and Aqualfs of Ohio (Wilding et al., 1965).

Disagreements pertaining to argillic horizon criteria seem to be centered around the morphological and micromorphological evidence. McKeague et al (1981) suggested that little evidence is available to indicate that pedologists can consistently identify clay films, or that soil micromorphologists can consistently estimate oriented clay in thin section. Many horizons considered to be Bt horizons in the field had very little illuvial clay as estimated in thin section studies. Some horizons having more than the required one percent oriented clay did not appear to have the higher ratios of clay in the B horizon to clay in the A horizon (McKeague et al., 1978). These horizons consistently lacked higher proportions of fine clay to total clay relative to the C horizon as compared to B horizons of other soils. Many of the soils thought to have a B horizon by field evidence, and lacking the one percent oriented clay, were from semiarid areas or were soils of very high clay content. Estimates of Bt horizon identification differed in their degree of consistency depending on the soil order. Luvisols were approximately 70% consistent, Gleysols were approximately 40% consistent, and Chernozemic and Solonetzic orders were much less consistent (McKeague et al., 1981). It is suggested that until standards can be developed for quantitative thin section analysis, the one percent oriented clay criteria should be flexible and serve as a guideline only.

Brewer and Sleeman (1969) reported the lack of a consistent correlation between frequency of oriented illuvial clay, and the degree of particle-size differentiation or percent clay in the Bt horizon. The frequency of oriented clay may account for varying proportions of the clay lost from the eluvial horizon. Oriented illuvial clay was reported as occurring in all horizons: A2, B2, and C horizons. The authors concluded that perhaps oriented illuvial clay does not quite serve as a definite quantitative indicator of clay translocation, as they may be disrupted by pedoturbation.

The coefficient of linear extensibility (COLE) has been found to be significantly correlated with surface area, but not with clay content (McKeague et al., 1981).

B. Argillic Horizon Morphology

a. Ped interiors and ped exteriors

The morphology of the argillic horizon, along with textural differences, are the basic field observation used in its identification. Soil materials have been described by Brewer and Sleeman (1969) as consisting basically of relatively inert skeleton grains, organic fragments, and relatively easily rearranged plasma. The plasma is rearranged by the processes of pedogenesis. Ped surfaces are thought to sensitively reflect soil developmental processes in addition to providing much of the contact area between the root and the soil. Grossman et al. (1964) sampled the zone of maximum clay content in horizons of Illinois soils in order to analyze ped surfaces. In examining the entire pedon it was found that the structural specific surface, the planer ped surface per unit weight, decreased with depth while the disparity, or difference between the ped surface and the ped interior increased. Field observations during the study indicated two types of ped surfaces; degradational and accretive. Degradational surfaces are identified by an abundance of uncoated sand and silt grains, and were more common in the B1 horizons. Accretive surfaces show evidence of accumulated clay sized material, and were more common in the B3 and C1 horizons. The B2 horizons contained nearly equal proportions of both. Khalifa and Buol (1968) described an Ultisol in which accretive surfaces (clay films) were lacking in the A2 horizon, occurred as discontinuous patches in the B2H horizon, and as continuous thick coatings on the peds of the B22t horizon.

A complex pattern of ped alteration over short lateral and vertical distances was common in the Illinois soils examined by Grossman et al. (1964). Changes from strongly degradational to strongly accretive were found to occur over short distances. Particle-size analysis data indicated that ped surfaces seemed to have a bimodal clay distribution; more fine clay associated with accretive surfaces, and more coarse clay associated with degradational surfaces, as compared to bulk ped material. Differences between ped interiors and ped surfaces of a B horizon in a somewhat more arid soil were investigated by Heil and Buntley (1965). The differences appeared to occur in the form of an orientational distribution of major constituents and soil properties. Soil color, clay films, form and amount of $CaCO_3$, along with the size, number, and abundance of pores are among the oriented ped features thought to represent the genetic evolution of horizons. Particle-size analysis indicated that ped surfaces in the B2H horizon were characterized by a loss of clay while underlying subhorizons of the B horizon had accumulations of clay on ped surfaces. Soluble magnesium was greater for the ped surfaces than for the ped interiors in the B22t and underlying B horizon subdivisions. Soluble calcium showed a similar trend except that the higher ped face-interior differentials occurred deeper in the profile. The suggested accumulation of soluble Ca and Mg on the ped surfaces is thought to indicate that ped surfaces are a more humid climate while ped interiors are a more arid climate; as compared to the macroclimate of the entire profile. The profile of the ped surface would represent a higher stage of development than the interior.

Soviet work has shown similar observations (Targul'Yan, 1964). In mountain-tundra and mountain-taiga soils accumulations of brown clayey material in the form of crusts on the upper sides of blocks and rock debris was observed in the lower most rocky and blocky horizons. The coatings were found to adhere to their respective surface

whether wet or dry, and upon analysis, were found to have a finer texture than the general mass of the fine earth from the same horizon.

b. Clay films

Several investigators in the United States have physically separated clay films from ped surfaces and analyzed them for various constituents and properties (Buol and Hole, 1959; Thorp et al., 1959; and Khalifa and Buol, 1968). Clay films in the Miami silt loam occurred from the B horizon into the C horizon along joints in the parent material. Closer examination revealed that the dark brown color of the clay films resulted from their association with organic matter (Thorp et al., 1959). Clay films were removed from air dried peds of the B3 horizon of an Al-fisol (Gray-Brown Podzolic soil) and analyzed for N, C, clay, reductant soluble Fe, total Fe, Na, K, Ca, Mg, Si, Al, P, Mn, and Ti (Buol and Hole, 1959). The clay films had much higher contents of N, C, clay, free Fe, P, and Mn than the bulk sample of the same horizon. A greater proportion of reductant soluble Fe than total Fe in the clay films was thought to suggest independent movement of some Fe with regard to clay or organic matter. Release of Fe from mineral weathering was also suggested.

Clay films were removed from ped surfaces of a Typic Hapludult for analysis (Khalifa and Buol, 1968). Particle-size analysis, cation exchange capacity, X-ray mineralogy, and thin section determinations were made in addition to tests similar to those performed by Buol and Hole (1959).

The clay films from the B22t horizon peds were found to contain more fine clay, Al, Fe (free and total), N, P, K, and less Si than the bulk B22t sample. The highest CEC values were found in the fine clay of the A2 horizon and the fine clay of the clay films from the B22t horizon had weak diffuse X-ray diffraction peaks. The fine clay from the bulk B22t horizon and the C1 horizon clay films had more well defined and intense peaks. Maximum clay accumulation occurred on the face of peds from the B22t horizon of soils developed from till investigated by Heil and Buntley (1965). It appeared that the accumulation of clay acted as a barrier to weathering of the interior of the ped, as higher amounts of exchangeable Ca were found in the interior of the peds.

Work in the Soviet Union indicates that clay films occur in almost all horizons of Brown mountain-forest soils as compared to Mountain forest podzolic soils in which the clay accumulations are concentrated in the illuvial B horizon (Minashina, 1958). In soils formed from coarse textured material accumulations of clay have been described as coatings on upward facing horizontal surfaces of sand grains. The clay accumulated on these surfaces more than any other side, although it also occurred as bridges between individual grains (Dijkerman et al., 1967).

A clay film volume study by thin section analysis, and a soluble salt concentration study was performed on the entire profile of an Alfisol (Buol and Hole, 1961). The maximum concentration of both occurred in the C1 horizon. The maximum accumulation of clay films in the C horizon

represented conditions adjacent to joints and interstices which, with increasing depth, were spaced further apart. In addition, the C horizon contained much thicker clay films which accounted for the greater volume occupying the thin section filed. In Wisconsin it was found that clay films were formed in soils having an adequate supply of clay, relatively stable aggregates, and root channels (Buol and Hole, 1961). Clay films found in the C horizon occurred mainly in the root channels and on ped surfaces, while those in the overlying horizons were increasingly remote from the ped. Wenner et al. (1961) investigated parent materials and soils of calcareous Wisconsin till in Ohio indicated that the upper 60-75cm of the calcareous material has been altered to such an extent that it should be considered part of the solum.

The formation or occurrence of clay films is not universal over the entire argillic horizon. Daniels et al. (1968) found eluvial bodies, degradational surfaces, existing side by side with clay films in Ultisols. Similar observations were reported from work in Illinois (Grossman et al., 1964). In the Ultisols, clay films deeper in the solum than the eluvial bodies were grayish and covered redder and browner films. This was interpreted as indicating that the last clay moved in that part of the solum was iron poor coming from the gray areas of the Bt horizon--the eluvial bodies. Another explanation proposed that the eluvial bodies were actually C horizon that had been bypassed by the illuviational accumulations.

Some authors feel that perhaps clay films are not indicative of clay accumulation or that they cannot be regularly identified as such (Brydon, 1965; Nettleton et al., 1969; and McKeague et al., 1978, 1981). Work in Canada and the southwest United States suggests that clay films are not easily distinguished from pressure faces or stress-oriented clay formed in place on ped surfaces. This appeared especially true for moderately fine and fine-textured Bt horizons and soils dominated by expandable clay minerals having a large shrink swell potential (Nettleton et al., 1969). In the soils of the arid and mediterranean climates of the United States the clay films were present predominantly in soils containing less than 40% clay, <20% 15 bar water retention, and < 4% linear extensibility. In horizons exceeding these values clay films were absent. In Orthic Podzols in eastern Canada organic matter and sesquioxides may have prevented the formation of or masked clay films (Brydon, 1965).

c. Cutans

Early on it was recognized that various surface coatings broadly described as "clay skins" were actually composed of a variety of constituents and arrangements of these constituents (Brewer, 1964). These coatings were originally described in reflected light under slight magnification; a procedure easily done in the field. Upon closer examination in the laboratory the varying nature of these coatings came into view. Brewer (1960) has defined the cutan in order to cover a broad group of surface

features. Basically cutans are "a broad group of pedological features associated with the surfaces of skeleton grains, peds, and various kinds of voids within soil materials." Cutans are a surface modification of texture, structure, or fabric primarily due to a concentration of particular constituents or in situ modifications of the plasma (Brewer, 1964). The definition of cutan covers a broader range of features and materials than clay films, clay skins, etc. The broadness of the definition allows all features identified in the field as clay films, or clay skins to be recognized as cutans. Upon closer examination cutans can be differentiated according to the surfaces they are associated with, their mineralogical nature, and their fabric. These features represent a segregation and reorganization of some of the constituents, and thus are important indicators of the pedogenic process (Brewer, 1960). The definition of cutan includes all variations of coatings on the walls of voids, as well as in situ plasma modifications. It is necessary to be able to distinguish plasma concentrations resulting from deposition or diffusion of plasma material, and plasma separations formed by in situ surface modifications.

For the deposited constituents cutans indicate sites that were suitable, both physically and chemically, for deposition. Cutans are viewed as a record of the environments of mobilization and deposition of specific constituents. It is important to locate and chemically characterize the source areas for the mobilized constituents

since similar pedological features may be formed by different processess under different environmental conditions (Brewer, 1973). Cutans composed of different materials may reach a maximum degree of development in different horizons of the same profile. Simple cutans are interpreted as indicating uniform conditions during their formation; whereas, compound cutans indicate a more complex formation involving the operation of changes in conditions (Brewer, 1960). Plasma separations are thought to suggest reorganization of plasma materials by differential movement possibly resulting from irregular wetting and drying (Brewer and Sleeman, 1969).

Cutans have also been subdivided into four groups based on an interpretation of the formation process. Illuviation cutans, diffusion cutans, stress cutans, and complex cutans are recognized; the latter formed by various combinations of the three processes. Distinguishing between the first three subtypes is the real difficulty in interpretation. The sharpness of the boundary between the cutanic and noncutanic material has been used as an indicator (Brewer, 1960). The sharper the boundary the more definite the diagnosis as an illuviation cutan. The more diffuse the boundary the more definite the diagnosis as a diffusion or stress cutan. Stress cutans can be mistaken for illuviation cutans, and illuviation cutans can eventually be incorporated into the soil matrix appearing to be unrelated to any natural surface (McKeague and St. Arnaud, 1969). Work in northeastern Ohio has indicated the occurrence of complex

cutans consisting of alternating layers or bands indicative of illuviation, diffusion, and stress processes (Ritchie et al., 1974). These cutans occurred in the B horizons of Aqualfs.

Morphological descriptions of plasma fabric, especially cutans, is greatly enhanced by optical methods in thin section utilizing the petrographic microscope. The interpretation of the extinction patterns of various kinds and arrangements of plasma can give a good indication of the origin of the fabric (Brewer, 1964). If the individual grains of the plasma material are unoriented with regard to surrounding grains, or surfaces they appear isotropic in thin section. This is the result of the extremely small size of the grains as compared to the thickness of the thin section. Most constituents of plasma are crystalline and anisotropic. Anisotropy of the plasma is due to translucent, anisotropic plasma grains exhibiting some degree of preferred orientation to adjacent surfaces. Description of plasma fabric is then based on interpretation of optical properties with regard to polarized light. Especially important are extinction phenomena caused by orientation patterns of the plasma grains, the kind and degree of preferred orientation of domains (a cutan is a plasma domain), and the development of plasma separations (Brewer, 1960).

d. Argillans

A cutan composed dominantly of clay minerals is an argillan (Brewer, 1964). Crystalline oxides, carbonates, and sulfates are excluded from the definition. Clay minerals refer to the layer-lattice aluminosilicates. In reflected light thick argillans have an uneven ropy appearance with a waxy luster while thin argillans have a more smooth glazed surface (Brewer, 1960). Clay minerals with organic matter, an organo-argillan, give gray to dark gray colors. Argillans composed of clay minerals closely associated with iron oxides and hydroxides, ferri-argillans, give shades of yellow, red, green, or blue.

Argillans occurring as highly separated, strongly oriented bands or coatings on skeleton grains, ped surfaces, or void walls are taken as evidence for deposition of clay minerals from an aqueous suspension after drying (McCaleb, 1953; Brewer, 1956; Brewer and Haldane, 1957; Dijkerman et al., 1967; Khalifa and Buol, 1968; Brewer and Sleeman, 1969; Brewer, 1973; Pawluk and Dudas, 1978). Buol and Hole (1961) have defined "clay skin" as an "assemblage of optically oriented clay sized particles with included coarser particles, exhibiting abrupt internal and external boundaries, forming on the walls of interstices." The Soviets have defined optically oriented clays as consisting of aggregates of individual clay particles all possessing the same orientation. Such a plasma concentration, or aggregate would behave as one crystal when viewed with polarized light (Minashina, 1958). Soils have been described with various forms of oriented clay including scales, fibers, and clay material surrounding particles. The orientation is caused by the flaky shape of the particles; upon placement they tend to occupy the most stable position possible; with their c-axes normal to the surface of deposition. McCaleb (1953) used thin section evidence of oriented clay material along walls as an indication that clay had been mobilized and transported through eluviation-illuviation. Comparing corresponding horizons of two soils; Brewer (1956) noticed that one had less clay, but the clay it did have occurred as strongly optically oriented layers coating primary grains and pore spaces. Further experimentation using puddled soils indicated that the finest clay was strongly oriented while the coarser clay was only partially oriented. Dijkerman et al. (1967) investigating coarse textured soils with fine textured lamellae suggested that strongly oriented clay bridges may have indicated that oriented clay was deposited as interstitial water was evaporated. Khalifa and Buol (1968) described B22t horizon argillans under polarized light and concluded that the clay films were indicative of illuvial crystalline colloids of clay with iron oxides. The authors also described oriented clay bodies frequently imbedded in the soil matrix, and stress cutans present around both free and plasma embedded quartz grains. Pawluk and Dudas (1978) described void argillans as occurring throughout the entire profile, but most abundant in the B horizon, of an Acid Luvisolic soil. An attempt has been made to quantify the extent to which clay movement and

accumulation has occurred in a horizon based on the surface area occupied by the illuviation features as a percentage of the area of the thin section, the degree of reworking of such features due to biologic and pedoturbidic processes, and the horizon thickness (Miedema and Slager, 1972). It is felt that such an approach may offer possibilities for quantifying the requirements for an argillic horizon.

Work in Canada has shown that interpretation of argillans, particularly quantitative interpretation, is difficult at best. It was felt that quantitative micromorphological estimates were not comparable unless they were compared with common reference standards (McKeague et al., 1981). Both the methods of estimating the amounts of illuvial clay and distinguishing illuvial clay contribute to differences among various workers. The latter has the larger influence since it determines the first. Illuvial clay may be impossible to estimate in materials with inherited bodies of oriented clay, or with oriented clay derived from in situ weathering such as shale lithorelics. During investigations of a catena of soils McKeague et al. (1973) recorded the presence of weakly oriented, ferruginous, clayey laminae in the parent material which made the estimation of translocated clay difficult. Interpretation of the clayey laminae as translocated clay would have essentially doubled many of the values reported for translocated clay. Many of the argillans also had incorporated silty materials. In reviewing micromorphological evidence of illuvial clay in field designated Bt horizons McKeague et al. (1978) pointed out several problems in estimating illuvial clay; relatively weakly oriented argillans or silty argillans not strongly differentiated from the matrix, apparent flows of silty and clayey material associated with planar voids that have segregated silty and clayey bodies in the C horizon, the occurrence of weakly oriented apparently silty argillans which have been interpreted as weathered argillans, and the occurrence of birefringent organic material that resembles illuviation argillans. In addition it is suggested that the limit between apparent stress cutans and apparent illuviation cutans is ambiguous. Micromorphological criterion proved less consistent in identifying Bt horizons than were estimates by the other criteria (McKeague et al., 1981).

Minashina (1958) reported very small quantities of optically oriented clays in the form of extremely fine aggregates in the basic mass of the illuvial horizons and the upper horizons occurring in podzolic soils. Clay in the form of incrustations was noted. Embedded argillans within the matrix have been suggested as outlining what appear to be former structural units, an indication of considerable physical disturbance perhaps occurring during wetting and drying cycles (Ritchie et al., 1974). This was found to be especially true for finer textured soils. In the same study it was reported that argillans are often superimposed on surfaces from which clay and iron have been stripped. It is thought that this implies alternate cycles of stripping and accumulation of clay. Grossman et al. (1964) reported that well-expressed oriented clay coatings in ped interiors were associated with strongly altered ped surfaces, both accretive and degradational in type.

Cutans, or argillans, are important from a different standpoint than being merely indicators of pedogensis. Their large surface area per unit volume, in the horizons in which they occur dominates the plant root environment (Brewer, 1960). Soil material without cutans behaves as a porous medium allowing movement and reorganization of soil constituents. As surfaces become cutanic in nature the soil material undergoes changes, many of its properties approximating those of a colloidal membrane adhering to a relatively inert matrix. The bulk of the soil material within the ped is protected from such processes as leaching, mass movement, and root uptake. This is in agreement with conclusions reached by Heil and Buntley (1965) and Grossman et al. (1964). In soil materials with strongly developed cutans analysis should recognize the cutanic material in addition to the bulk (Brewer, 1960).

Clay film, or argillan evidence of clay illuviation has one problem in that the surface accumulations may not be stable over a period of time (Birkeland, 1974). Clay films are sometimes destroyed shortly after formation. Gile and Grossman (1968) described a Bt horizon in an aridic zone as being relic and suggest the waiver of the clay film requirement. It is thought that the large forces generated during wetting and drying cycles in the high tension moisture range of the aridic climate may lead to disruption of the fabric. Surfaces of peds can be abraded during expansion and new ped surfaces formed during contraction. Fragments of former clay films may be incorporated in the new peds and still retain their strong optical orientation. Clay films appear to be the most stable on the surfaces of sand and coarse fragments. Calcium carbonate accumulation can lead to the destruction of clay films. Shrinking and swelling associated with moisture cycles can lead to clay film destruction in soils of the southwestern United States (Nettleton et al., 1969). Soils with greater than 40% clay and a high shrink-swell potential were found to be particularly susceptible to clay film destruction. Soil mixing by roots and fauna can also lead to clay film destruction (Birkeland, 1974). Khalifa and Buol (1974) suggested that clay film destruction would be greater in the B22t horizon as compared to the C1 horizon. The C1 horizon would be subject to a lower magnitude and frequency of wetting and drying, and of mixing. Stress cutans in the B22t horizon are offered as evidence.

C. Mechanisms of Argillic Horizon Formation

Several mechanisms have been proposed by various workers in order to account for clay maxima occurring in B horizons. Smeck et al. (1981) have suggested five possibilities in order to account for clay accumulation in poorly drained soils of western Ohio: clay illuviation, in situ formation of clay sized particles, stratification inherited from parent materials, physical disintegration of coarse grained materials, and residual concentration of clay due to the leaching of more soluble constituents such as carbonates. Cline (1949) suggested translocation of soluble weathering products as a precursor to in situ clay particle formation, in addition to illuviation, and residual concentration due to the loss of more soluble constituents. The suggestions of Buol and Hole (1959) agree with those of Cline (1949) and Smeck et al. (1981). In addition they add that clay films may be formed in situ from constituents released by decomposing plant roots, and from constituents released from the in situ weathering of primary minerals. The occurrence of textural subsoil lamellae or bands have been proposed as resulting mainly from illuviation, with in situ clay formation playing a minor role (Dijkerman et al., 1967). Field investigations showed that in some cases illuviation can be strongly influenced by parent material stratification. Birkeland (1974) suggested three processes; illuviation, translocation of soluble weathering products with in situ clay particle formation, and in situ mineral weathering. Most argillic horizons probably result from a combination of more than one process.

In Soil Taxonomy (Soil Survey Staff, 1975) the definition of the argillic horizon indicates that illuviation is the dominant process by which clay accumulates in the horizon. Illuviation has been defined as the process of deposition of soil material moved from one horizon to another; usually from an upper to a lower horizon (SSSA Committee, 1979). In the Soviet Union illimerization was used to define the process in which the clay fraction is transferred, without destruction, from the upper horizons (Fridland, 1958). This process has also been termed lessivage.

Several authors have attributed illuviation as the cause of the relative enrichment of clay in the argillic B horizon (McCaleb and Cline, 1950; Brydon, 1965; McKeague and St. Arnaud, 1969; and Brewer and Sleeman, 1969). A higher clay content in the B horizon is not sufficient evidence for clay translocation. Higher ratios of fine to total clay in the B horizon suggest that fine clay has preferentially moved, especially if lower ratios occur both in the eluvial zone and the parent material. The maximum total clay content and relative enrichment of fine clay in the respective B horizon was interpreted as being due to illuviation of clay from the Ae horizon with deposition in the underlying B horizon (Brydon, 1965). McKeague and St. Arnaud (1969) indicated that clay translocation is thought to be the major factor in argillic horizon formation in post-Wisconsin soils, although some evidence may show that it is not a major factor. The authors suggest that clay translocation in soils is mainly a simple physical process evidenced by a higher ratio of fine clay to total clay in the argillic horizon, along with argillans developed on the surfaces of grains and peds. Void and ped argillans are usually attributed to illuviation although it has been suggested that some may result from crystallization from solution (Brewer and Sleeman, 1969).

Jenny and Smith (1935) proposed that claypan formation was the result of translocation and subsequent deposition. It was concluded, after an analysis of the clays from various horizons in the claypan profile, that the particles migrated as a whole rather than in the form of colloidal sesquioxides and SiO_2 with later recombination. Similar conclusions were reached by Culver and Gray (1968) in their investigations of clay-pan soils in Oklahoma. Their data indicated that larger amounts of coarse-clay were trapped in the upper B horizon while the fine clay, higher in exchangeable bases, tended to move into the lower B horizon. The authors suggested that the translocation of inherited fine clay was simply physical movement down numerous pores and channels. Kunze and Oakes (1957) studied claypan formation in east Texas. Their conclusion was that, although particle size distribution and clay films in the B horizon indicate eluviation of fine clay from the A horizon with subsequent accumulation in the B horizon, clay formation in combination with a swelling type clay mineral, high sodium and magnesium content were also responsible. The authors were unable to assign a relative importance to each process.

Evidence in the form of low A2 horizon, high B22t horizon fine clay/coarse clay ratios along with B22t horizon clay films, and similar mineralogy of A2 horizon fine clay and B22t clay film fine clay, indicated that the eluvial site for clay film material in a Typic Hapludult was in the A2 horizon and its deposition in the B horizon was mainly through physical transport (Khalifa and Buol, 1968). The particle size distribution for mountain-tundra and mountain-taiga soils in the Soviet Union indicate the relationship between two processes: the formation of fine earth as a result of the transformation of the original solid rock, and the migration of its suspensions down the profile (Targul'Yan, 1964). Mineralogical and micromorphological studies of the soils gave clear indications of the movement of a suspension of heterogeneous composition through the profile. Soils with an acid reaction, a nonsaturated exchange comple, a leaching water regime, and the proper substances for stabilizing the suspension have the necessary conditions. It is concluded that the movement of suspensions cannot be considered a process peculiar to some soil zone or soil group, nor a preliminary stage in development of another process. Polygenesis may be involved in the morphology of Udolls, although it could be accounted for by translocation of the inherited clay fraction as influenced by the availability of channels and pores through which the particles may be physically moved (Arnold, 1965). Ballagh and Runge (1970) concluded that fine clay horizons over limestone were illuvial rather than residual after ^{14}C dating of carbon complexed with clay, X-ray diffraction, and particle-size analysis.

a. Dispersion

In order for fine clay to accumulate in the argillic horizon by illuviation there must be a mobilization mechanism at the source area, a transporting mechanism, and an through physical transport (Khalifa and Buol, 1968). The particle size distribution for mountain-tundra and mountain-taiga soils in the Soviet Union indicate the relationship between two processes: the formation of fine earth as a result of the transformation of the original solid rock, and the migration of its suspensions down the profile (Targul'Yan, 1964). Mineralogical and micromorphological studies of the soils gave clear indications of the movement of a suspension of heterogeneous composition through the profile. Soils with an acid reaction, a nonsaturated exchange comple, a leaching water regime, and the proper substances for stabilizing the suspension have the necessary conditions. It is concluded that the movement of suspensions cannot be considered a process peculiar to some soil zone or soil group, nor a preliminary stage in development of another process. Polygenesis may be involved in the morphology of Udolls, although it could be accounted for by translocation of the inherited clay fraction as influenced by the availability of channels and pores through which the particles may be physically moved (Arnold, 1965). Ballagh and Runge (1970) concluded that fine clay horizons over limestone were illuvial rather than residual after ^{14}C dating of carbon complexed with clay, X-ray diffraction, and particle-size analysis.

a. Dispersion

In order for fine clay to accumulate in the argillic horizon by illuviation there must be a mobilization mechanism at the source area, a transporting mechanism, and an accumulation mechanism. For the mobilization mechanism a process to consider is the differential dispersion of the fine clay in the eluvial source area (Gorbunov, 1961; Buntley, 1965; Daniels et al., 1967; and Gile and Grossman, 1968). Formation of oriented clay coatings in the argillic horizon of desert soils required the prior dispersion of the fine clay (Gile and Grossman, 1968). The question as to whether dispersion takes place with or without decomposition of the particles has been addressed by Soviet work (Gorbunov, 1961). It is acknowledged that both processes occur, the first being termed podzolization, the latter illimerization or lessivage. The objective evidence for distinguishing these two processes was thought to be debatable and insufficient in most cases. The A2 horizon of Podzols commonly displayed the presence of residual silica powdering at the surface of aggregates, an important sign of movement of clay and colloids. Heil and Buntley (1965) reported that ped faces of a B21t horizon were being stripped of their clay be eluviation as the argillic horizon was degraded.

Dispersion was thought to occur by the forces generated during the wetting of an originally dry soil (Thorp et al., 1959; Arnold, 1965; Daniels et al., 1967; Grossman and Lynn, 1967; and Hudson, 1977). The influx of organic acids and water-soluble leaf materials (Throp et al., 1957; Smith and Wilding, 1972), the leaching of exchangeable bases (Cline, 1949; Hallsworth, 1963; Marshall, 1964; and Powell and Dillon, 1972), and the thawing of frozen soil layers (Powell

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and Dillon, 1972) are also thought to contribute to the mobilization of clay. Daniels et al. (1967) proposed that clays are more likely to mobilize during the initial wetting following a period of dessication. There is thought to be little translocation of clay in well drained soils during wet periods, unless there are dry periods between moisture influxes. A similar conclusion was reached by Thorp et al., (1959) following leaching experiments in which it was proposed that dry clay disperses upon wetting. A gel-like air-water interface film that formed as dry soil material is moistened, was reported by Grossman and Lynn (1967). Drying was necessary to the formation of the film. Drying the soil material between wetting episodes yielded successive films, whereas soil kept moist yielded little or no film material upon rewetting. During the wetting process it is thought that disaggregation occurs near the surface of the ped. Film formation is apparently not restricted to natural ped surfaces as it was observed from fragmented soil material. The authors emphasized that the air-water interface film does not itself mobilize clay for movement. The active agent is the wetting process.

Hudson (1977) has reviewed many investigations concerning clay movement in coastal plain soils of North Carolina. Moisture already present in the soil is suggested as somehow inhibiting clay mobilization by percolating water. The theory is based on the forces of adhesion and cohesion, resulting from hydrogen bonding between soil solids and water. The major force holding hydrated soil

particles together is thought to be cohesion; the attraction of adjacent water films for one another. As a wet soil dries the films thin out, and at some point become so thin that the cohesive forces cannot be maintained. Less force would be required to remove clay particles from a surface at a drier state than if the material were moist and the cohesive forces maintained. The higher frequency of wetting and drying cycles on an older morainal landscape was suggested as the reason that clay translocation by illuviation occurred to a greater extent on morainal soils, than on lake plain soils in southeast Michigan and northwest Ohio (Smith and Wilding, 1972).

Electrochemical forces are thought to have an influence on dispersion. Jenny and Smith (1935) reported dispersion of a claypan upon removal of the electrolytes. If the potential, which results from isomorphous substitution in the clay mineral lattice, is not neutralized by cations with its field of influence, the clay system exists in a dispersed state. Dispersion occurs because the negatively charged clay particles repel one another. In the clay-soil solution system some cations will be absorbed at each clay mineral surface, and others will be diffusely distributed in the electrical field near each particle. An electrical double layer exists at each particle-solution interface. As the concentration of cations increases, there is a point at which the net negative charge of the clay minerals becomes neutralized, and the particles no longer repel one another. Random collisions between the neutralized particles results

in flocculation. In the reverse sense, once the concentration of cations surrounding the clay particles decreases past a certain point, the system will disperse.

Dispersion is at a maximum when the zeta potential is at a maximum; as in an extremely dilute soil solution. Zeta potential decreases with increasing electrolyte concentration. Neutralization occurs very quickly for tightly held trivalent and divalent cations, and slowly for loosely held monovalent cations. Monovalent cations in the normal highly hydrated condition tend to stabilize dispersed clay systems. The results of Oster et al. (1980) suggested that a small amount of adsorbed Na markedly increased the dispersivity and mobility of a clay fraction in dilute solutions. The dispersivity of montmorillonite and illite clays are very sensitive to a low fraction of Na on the exchange complex. Shainberg et al. (1981) proposed that the response of soil to exchangeable Na during leaching with distilled water (simulated rainwater) depends on the concentration of electrolyte that the solid phase of the soil maintains. Clay dispersion and movement can be caused by low levels of electrolytes even at low levels of exchangeable Na.

Iron and aluminum oxyhydroxides may provide flocculating or dispersing effects on a clay system depending on which hydroxide, the surface reactivity of that hydroxide (a function of pH), and the clay mineral with which it may be associated (El-Swaify, 1976). Generally, the two hydroxy polymers provide equal enhancement of clay in flocculation. In the reverse sense, once the concentration of cations surrounding the clay particles decreases past a certain point, the system will disperse.

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suspension stability above their isoelectric points (high pH) where they both exist as negatively charged complexes. Below their isoelectric points both exist as positively charged species, capable of being adsorbed on the clay surface and reducing the zeta potential. Hydroxy-Al polymers, formed during the potentiometric titration of Al- and Fe-montmorillonite suspensions with NaOH, were found to apparently act as cementing agents preventing the dispersion of the aggregates (Frenkel and Shainburg, 1980). When an excess of NaOH was added the hydroxy-Al polymers disintegrated and the entire system dispersed. Jenny and Smith (1935) reported that precipitated iron-clay colloids in the form of aggregates would readily disperse with the addition of humus and mixing by gently shaking.

Hallsworth (1963) investigated factors affecting clay migration including quantity of clay, clay mineralogy, size distribution of the mineral skeleton, pH of the leaching solution, and the nature of the cations present. Generally, high pH was found to move more clay, both montmorillonite and kaolinite, all other factors being conducive to movement. The increase in mobilization of kaolinite in the presence of Na ions was twice that which it was with Ca ions, while Mg ions gave no measurable effect. The movement of kaolinite was thought to be much more sensitive than that of montmorillonite to the concentration and nature of the saturating cation. It was felt that the different clay types might behave differently; the known effects of an ion on the hydration of a clay and

on the stability of its sol may be mutually antagonistic in regard to its movement. The ions in solution may have a negligible effect at the time of maximum water throughflow. As the soil dries, the solution becomes more concentrated, probably with a rise in pH. This may encourage mobility.

Cline (1949) investigated a developmental sequence of soils in New York and found that as the profile acidity increased, the A2 horizon became very acid and encroached on the B21 horizon. The B22 horizon became the horizon of maximum clay accumulation and rested abruptly on the calcareous parent material. Similar work in the Soviet Union (Fridland, 1958) suggested that a significantly lower intensity of eluviation and illuviation might be associated with a high degree of base saturation on the adsorption complex and a considerably less acid profile. The work also indicated that possible stabilizers which maintained clay particle suspensions include organic substances and colloidal silica. Evidence for this was cited in the increased organic matter and silica contents in clay rich illuvial horizons.

Rowell and Dillon (1972) suggested that, upon thawing, the resuspension of aggregates held in frozen layers is nearly identical to that for aggregates produced by drying. It is felt that the similarity results from the fact that both processes remove pure water from the suspension. A similar conclusion was reached by Gorbunov (1961).

Some authors felt that illuviation was insignificant in

Oertel, 1968). Oertel (1968) suggested that illuvial clay dominated by the fine clay fraction has the inherited weakness in the implicit assumption that these small particles exist as such in the soil rather than as fairly stable aggregates. Jenny and Smith (1935) found that clay from a claypan soil in contact with water and not mechanically disturbed formed a coacervate - neither a sol nor a true gel, but a gel like system in which the particles possess individual mobility.

b. Translocation

Once the clay fraction disperses into a somewhat stable sol it must be translocated into the illuvial horizon where it is deposited. The availability of channels and pores through which particles may be physically moved influences the translocation of inherited clay (Arnold, 1965). Movement is possible for clay particles in the soil as the dimensions of soil pores and voids, generally, are hundreds of times greater (Fridland, 1958). Clay migration requires reasonably good permeability in the solum as the nature of the sol requires relatively large channels for movement (Brewer, 1956). The upper portion of the soil with its increased wetting and drying and numerous biological pedoturbations, favors eluviation; whereas, the lower portion favors illuviation (Arnold, 1965). Brewer (1960) reported that illuviation cutans are nearly always associated with conducting voids, while diffusion cutans can be associated with voids of any size. Hallsworth (1963) suggested that the quantity and perhaps the type of clay in

any horizon of the profile might determine the rate of percolation of water through the soil. During column studies the amount of clay moved was observed to be roughly proportional to the volume of water passing through. High clay soils tended to have severely restricted clay migration; little movement of clay was observed in the columns with kaolinite contents of 40% or more, or montmorillonite contents of 20% or more. Hallsworth concluded from the column studies that if the clay content of a system is low, a stable suspension could be easily translocated. With rising clay content the expanded sol would increasingly block pores. Smaller noncolloidal particles could possibly reduce the pore space of a system, causing a reduction in the ability of the soil to conduct a moving suspension. In experiments designed to examine the factors affecting clay orientation in soils, it was found that infiltration of dilute clay suspensions into sand columns was rapid at first and then quickly decreased (Brewer and Haldane, 1957). Heil and Buntley (1965) reported higher organic carbon on ped faces, possibly resulting from a greater downward translocation of colloidal materials in percolating waters along between-ped voids. The retarded downward movement of air, water, and plant roots through the mass of the ped per se resulted from the low permeability of glacial till.

Percolating water moves the clay suspension and deposits the clay where the percolation is arrested (Arnold, 1965). Several authors feel that the depth to which the dispersed clay is carried is a function of the depth of penetration of moisture fronts (Dijkerman, et al., 1967; Khalifa and Buol, 1968; Runge, 1973; and Scrivner et al., 1973). Scrivner et al. (1973) investigated well drained Missouri loessal soils and proposed that the A horizon and upper Bt horizon characteristics were associated with the penetration of summer rains. The thickness of the Bt horizon was thought to be determined by the annual depth of drying. The B2 horizon lower boundary was suggested as possibly coinciding with that depth which undergoes one annual cycle of wetting and drying. Runge (1973) presented a model of soil development in which gravity is considered the energy source that is available when water either runs off the soil or percolates through the soil profile. In a Mollic Albaqualf with a seasonably high water table, percolating waters are believed to encounter a zone of zero potential gradient immediately above the zone of saturation. This is the zone where clay is found to be deposited. In a well drained Typic Argiudoll the flow of water throughout the solum was believed to be unrestricted and unidirectional. The zone of clay accumulation was more broad and evenly distributed in this soil. The movement of moisture fronts are controlled by the amount and frequency of rainfall and the equilibrium conditions of moisture movement fronts. Ritchie et al. (1974) reported that fragipans are similar to other kinds of moisture restricting zones which perch water and favor illuviation at that contact. Downward flow may be halted at a lithologic discontinuity because of pore constriction (decreased permeability) or pore discontinuity (Brady, 1974).

The clay films in a B22t horizon of a Typic Hapludult may form more rapidly than those in the C horizon because rainfalls moving a wetting front into the B22t horizon are more numerous than those moving wetting fronts into the C horizon (Khalifa and Buol, 1968). Work in Wisconsin suggest that most of the percolating water ceases to move through the larger interstices in the soil upon reaching the C horizon (Buol and Hole, 1961). Work in Ohio and Michigan indicated evidence of translocated clay well into horizons commonly designated as C (Smith and Wilding, 1972). Similar findings were reported for surface and buried soils in Illinois (Follmer et al., 1979) in till-derived well drained Udolls in eastern Iowa (Arnold, 1965), and in the Miami soil of Indiana (Thorp et al., 1959).

Penetration of moisture fronts from rains occurring after a period of dryness may be a dominant mechanism for the mobilization of clay particles with subsequent translocation to deeper portions of the profile. Pawluk (1971) investigated the development of eluvial A horizons and illuvial B horizons in Fera Eluviated Gleysol in northwestern Alberta. The results suggested that the soil sola were subjected to a "leaching" environment for some period of time during their development. The relatively dry autumns and late summer rains of low intensity and short duration result in periodic drying of the soils. It was thought that this environment was conducive to eluviation-

illuviation upon rewetting. Snowmelt and frequent rains in the spring months are known to maintain the soil in a saturated state; an environment not conducive to eluviation-illuviation.

c. Deposition or accumulation

The deposition of clay in the illuvial zone as oriented clay films results from one or more complex physiochemical processes. Factors involved may include; surface tension effects upon drying (Cline, 1949; McCaleb, 1953; Brewer, 1956; Dijkerman et al., 1967; McKeague and St. Arnaud, 1969; and Brewer, 1973), the effect of flocculating agents (Jenny and Smith, 1935; McCaleb and Cline, 1950; Brewer and Haldane, 1957; McKeague and St. Arnaud, 1969; Brewer, 1973; Arora and Coleman, 1979; and Oster et al., 1980), and other minor mechanisms such as sieving (Jenny and Smith, 1935; and Dijkerman, 1967).

Thin section evidence of oriented clay along walls was used as an indicator of eluviation-illuviation (McCaleb, 1953). The data was interpreted as suggesting that the forces of surface tension, developed upon drying, were instrumental in causing the orientation observed, as the oriented bodies had lamellae that resembled a miniscus. Brewer (1956) indicated that the direction of orientation of clay grains, with their C-axes perpendicular to the surface of deposition, was due to surface tension forces during deposition from a sol. Results from experiments in sand columns suggested that the location and morphology of clay bridges between sand grains may be related to the retraction

of water menisci upon drying (Dijkerman et al., 1967). Drying forces may be able to reorient clay particles to a face to face structure. Oriented clay coatings were rapidly prepared by adding clay suspensions to columns of sand, and by passing them through columns of soil material with periodic drying (McKeague and St. Arnaud, 1969). Clay films were thought to form on the surfaces of grains and peds where the downward movement of water was arrested. The observed zone of clay accumulation, above that of lime accumulation, was suggested as resulting from the fact that there was little movement of gravitational water below that depth, or that porosity decreased at that depth. The flocculating effect of calcium was not thought to influence the zone of clay accumulation. Brewer (1973) described argillans with strong continuous extinction patterns, occurring on void surfaces, as forming by the simple process of drying. Argillans with less well oriented extinction patterns were thought to result from flocculation and then drying.

Electrochemical flocculation of the suspended clay particles occurs only beyond a certain minimum electrolyte concentration termed the critical salt concentration (CSC) or flocculation value (Arora and Coleman, 1979). The salt concentration corresponding to 50% dispersion was chosen as the CSC. The CSC of a given clay mineral depends strongly upon the valency of introduced cations. Surface coatings and other impurities, the extent of hydroxy Al and/or Fe-polymerization, and the mutual flocculation of positive-edge faces and negative surfaces also influence the CSC. Small changes in electrolyte concentration have an effect on flocculation as evidenced from dispersion experiments. Oster et al. (1980) determined the CSC of Na- and Ca-montmorillonite (homoionic) systems. It was found that the more that Na occupied the exchange sites, the higher the CSC value became. This is consistent with results reported by Arora and Coleman (1979) in which mixed ion systems showed that an increase in the SAR value resulted in a corresponding increase in the CSC value.

Illite was found to have a much higher CSC value than those observed for smectite and kaolinite (Arora and Coleman, 1979). The protective action of smectite to kaolinite suspensions was observed. The observed increase in CSC values with pH for soil clays was thought to indicate that the iron oxides and organic matter may contribute by providing more negative charge at high pH values, similar to smectite edge hydroxyls. Jenny and Smith (1935) suggest that colloidal humus exerts a protective action on suspensoids increasing sol stability.

It has been suggested that cations also play a role in gross aggregate formation, in addition to neutralizing the charge surrounding the particles (Jenny and Smith, 1935). With the introduction of dehydration agents the hydration shells around primary particles are removed and the particles are brought into contact forming more stable aggregates. Cline (1949) concluded that a prerequisite for the formation of a gray brown podzolic soil (Alfisol) in New

York was a parent material with a relatively high base status and divalent cations. McCaleb and Cline (1950) thought that the depth of clay accumulation in a gray brown podzolic soil was a function of the depth to free calcium carbonate.

Experiments designed to give information into the development of clay orientation in soils indicated that Na and K saturated clays gave sharp clay film boundaries in the zone of accumulation, whereas Ca and Mg saturated clays gave more diffuse boundaries (Brewer and Haldane, 1957). The saturating cation had a greater effect on macroscopic phenomena such as the type and magnitude of the zone of accumulation. Rapid flocculations produced a deposit in which the clay content was very high.

d. Minor processes

Mechanical sieving by the soil skeleton has been described by some authors as a possible mode of accumulation of clay from a suspension (Jenny and Smith, 1935; Dijkerman et al., 1967; and McKeague and St. Arnaud, 1969). A soil skeleton can sieve or filter particles of colloidal dimensions only if the pores themselves are of ultramicroscopic dimensions (Jenny and Smith, 1935). Claypans thought to form by the mechanical sieving of colloids are restricted to very fine-textured soil skeletons. Dijkerman et al. (1967) reached a similar conclusion during investigations of the formation of textural subsoil lamellae in coarse textured material; for dispersed systems sieving is important only for very small pores.

Sieving becomes more important as the migrating dispersed system begins to flocculate. McKeague and St. Arnaud (1969) rapidly added clay suspensions to columns of sand and columns of soil material. Sieving action resulted in the development of oriented clay cutans only if the clay was flocculated. Similar experiments by Dijkerman et al. (1967) suggested a similar conclusion. It was observed, after the column experiments, that the sands showed the smallest pores contained clay while the larger pores did not. Jenny and Smith (1935) proposed that electrolyte concentrations near or above the flocculation value favor the formation of relatively large secondary aggregates capable of being retained by the soil skeleton from mechanical sieve action. This process was thought to be reversible. As the particle size of the soil skeleton decreased the coarser clays were caught effectively reducing the area cross section of the pores. The claypan formation this process was thought to occur until the soil pores reach colloidal dimensions and almost stop the passage of the sol. Thus, a claypan may be self perpetuating. Dijkerman et al. (1967) added to this idea by suggesting that parent material textural stratification may initiate clay accumulation in the formation of textural lamellae. Once the accumulation is present, it should enhance its own growth.

Smith and Wilding (1972) reported difficulty in identifying clay illuviation as being a major factor in the genesis of argillic horizons in fine textured Ochraqualfs.

Work in the Soviet Union suggested that perhaps substances moving in soils change from the colloidal state into a true solution or vice versa (Gorbunov, 1961). The various indicies used to determine movement of clay and colloids, with or without decomposition, were felt to be unreliable. Lysimetric solutions were suggested as possibly offering some insight into whether the clay minerals migrate with or without decomposition. Oertel (1968) made the observations that trace element concentrations did not vary with depth, and Al/Fe ratios remained constant across textural boundaries, and concluded that illuviation in such soils was negligible. Brewer (1968) used micromorphological data to conclude that illuviation constituted an insignificant proportion of the clay in the Bt horizon of the soils investigated. Clay eluviation, inferred by the illuvial clay content, was insignificant in others in causing the small amount of clay in the A horizon. As clay eluviation, the deficiency of clay in the A horizon necessary for the illuvial clay observed, could not account for all of the particle size differentiation in the profiles examined, different mechanisms were suggested as being involved.

e. Neogenesis

Another mechanism by which B horizon clay maxima are thought to occur is the downward translocation of the soluble weathering products of precursor minerals with subsequent precipitation of clay minerals in the B horizon (Birkeland, 1974). Decomposition of the entire original mineral followed by crystallization of specific weathering products into aluminosilicate clays, has been termed neogenesis (Caillere and Henin, 1965; Jenny, 1980). The process of recrystallization from soluble weathering products is complex and involves a complete structural change from the original minerals (Brady, 1974). The mineral species that forms from a soil solution largely depends on the solution content of silica, the type and concentration of cations present, the soil solution pH, and the extent of prior leaching (Birkeland, 1974).

Buol and Hole (1959) suggested that perhaps clay-organic complexes may move in a soluble form to be later synthesized into clay films. Smith and Wilding (1972) suggested that the subtle total clay gains observed in the argillic horizons of Ochraqualfs in Ohio are due to the fine clay maxima, perhaps resulting from the in situ synthesis of clay, from among other processes. Similar conclusions were reached by Smeck and Wilding (1980). Whether the authors thought that the constituents for the clay synthesis were translocated weathering products was not clear. Although ped and void argillans are usually associated with illuviation, some have been attributed to neogenesis (Brewer and Sleeman, 1969). In the same study it was felt that gibbsite crystals were possibly crystallized from solution as they were observed to be perpendicular to the walls of voids. This is in contrast to argillans with their crystal platelets parallel to the surfaces of deposition. In an earlier study, Brewer (1960) described the necessity of distinguishing between depositions of illuviated plasma and depositions of material from solution. Those cutanic materials that form solutions are described as oxides and hydroxides of iron, secondary silica, and soluble salts; but not clay minerals.

Workers in the Soviet Union described in the process of podzolization as removal of clay minerals with destruction from the upper horizons (Fridland, 1958; Gorbunov, 1961; Antipov-Karatayev and Tsyurupa, 1961). In the process of podzolization, the composition of clay along the profile was found to vary (Fridland, 1958). The increased B horizon clay content was found to be associated with a clearly pronounced increase in the aluminum content. Often a decomposed portion of the clay and colloids is a small fraction of the nondecomposed portion. Therefore, a change in chemical composition cannot always be detected. Gorbunov (1961) suggested, however, that the nondecomposed portion may move at the same speed as the decomposition products. The total chemical composition of the clay and colloidal fraction would not change down the profile, or the change would be negligible. Substances moving in soils may possibly change from the colloidal state into a true solution or vice versa. Targul'yan (1964) reported the transformation and decomposition of primary minerals in the podzolic (eluvial) horizons of soils developing on massive crystalline rocks. The transformation and decomposition resulted in the formation of new clay minerals, and the mobilization and removal of Fe_2O_3 and Al_2O_3. Antipov-

Karatayev and Tsyrupa (1961) suggested that at soil solution pH values lower than 4.8 the decomposition products of the clay mineral fractions are brought into the illuvial horizons. Minashina (1958) described incrustational forms of clay in podzolic soils where leaching has been quite extensive, and then quoted several authors who felt that the incrustational characteristics were indicative of synthesis from solution of the decomposition products of minerals from the upper horizons. Minashina (1958) rejected such proposals.

Work by Grobunov (1961) suggested that division of minerals into groups based on their stability cannot be based solely on whether they were primary or secondary minerals, or whether they belonged to coarsely or finely sized fractions. The decomposition of primary and secondary minerals was thought to be a function of several factors; a seemingly resistant mineral in one environment may have been unstable in another environment. The large amounts of sesquioxides and silica found in lysimetric solution were interpreted as indicative of aluminosilicate decomposition.

Work on acid soils in Canada revealed that the major portion of extractable aluminum appeared to be either organically combined or in exchangeable form. The tendency for aluminum hydrolysis and polymerization was thought to be retarded in the low pH environment. The formation and position of textural B horizons in gray-brown podzolic soils of New York was thought to be associated with, among other factors, the rate of synthesis of clay from the alteration of primary minerals (McCaleb, 1953). The rate of alteration was accelerated to a considerable extent in the acid horizons. In coarser parent materials, however, acceleration of weathering by increasing acidity would affect the rate of silicate clay destruction more than the rate of clay formation for those clays stable in neutral environments (McCaleb and Cline, 1950).

Jackson (1965) proposed a mechanism of nucleation followed by silication of hydroxy sesquioxide layers on mineral surfaces to form new montmorillonite. The analogy was drawn between the described mechanism and the DNA process of biologic replication. The influx of soluble silica was thought to foster the formation of montmorillonite by silication of alluviated and illuvaited clays that have been aluminated. Birkeland (1974) stated that clay formation by precipitation from solution was enhanced by the increased surface area in finer-textured soils, as surfaces promote retention of clay-forming constituents.

Some authors felt that neogenesis did not contribute significantly to the maximum clay content occurring in the B horizon. Jenny and Smith (1935) concluded that clay particles migrated in whole form rather than in the form of colloidal SiO_2, Al_2O_3, and Fe_2O_3 with subsequent recombination. It was felt that synthesis of clays in the Bt horizon from solution products leached from above was unlikely to be a major factor in the genesis of argillic horizons of youthful soils (McKeague and St. Arnaud, 1969). Evidence for this conclusion came from the observation that

illuvial clay in the B horizons was generally mineralogically similar to fine clay in the A horizon. Drainage waters from the soils contained virtually all of the mineral forming elements, thus a net loss of most elements occurs in all but the most arid soils. During investigations of loessal soils in Missouri, Scrivner et al. (1973) found that kaolinite was the stable clay mineral phase, according to dilute solution chemistry studies and composite stability diagrams, and montmorillonite was the unstable phase. The soils investigated were found to be in the montmorillonitic mineralogy family. It was felt that silica in solution was too low for the formation of montmorillonite. This work has been interpreted as indicating that most clay particle formation must take place under nonequilibrium conditions, or that it is not controlled by dilute solution chemistry (Goddard et al., 1973). As soils are open systems, it may be that the rate of water movement and the time required for equilibrium of that water with soil minerals possibly plays major roles in stability consideration (Scrivner et al., 1973). Gorbunov (1961) suggested that oriented clay bodies were most likely polymineral formations consisting of highly disperse minerals and an admixture of amorphous substances including humus. It was thought that neogenesis might result in a monomineral formation. Brewer and Sleeman (1969) suggested that occasionally monomineral argillans occurred in soils with mixed clay in the matrix. Arnold (1965) pointed out that formation and destruction of silicate clays in an

environment was often suggested but seldom proved. Destruction of silicate clays assumed a complete breakdown of a highly organized mineral lattice, often requiring more severe and drastic chemical environments than was generally supported by supplemental chemical data. Much of the chemical data supplied to support either formation or destruction of clays are suggested as possibly resulting from the translocation of inherited clays. Jackson et al. (1948) suggested that clays, especially fine clay were the stable end-products which were more resistant to weathering than their parent materials.

Several investigators have undertaken studies of low temperature clay mineral formation from solution. Such attempts have been hindered by such factors as: very slow reaction rates at soil system conditions, difficult duplication of natural conditions in the laboratory, and present minerals in the system possibly being formed in the past under different conditions, thus not being part of the current mineral-solution equilibrium system (Kittrick, 1971; Birkeland, 1974). The first problem might be overcome by hydrothermal synthesis. Although this seemed only to increase the rate of reaction, there was some speculation that hydrothermal synthesis skipped or passed by various metastable precursors to the final product (Marshall, 1977). Consequently, results from such experiments cannot be safely extrapolated to naturally occurring conditions.

The third factor brings up the question as to whether or not minerals present in the solid phase are in equilibrium with the present soil mineral-soil solution system. If they are not, then they should be altering in some way so as to fit the present conditions. The assumption that equilibrium conditions exist between the solid phase minerals and the present solution has been used to explain kaolinite formation (Kittrick, 1969; Kittrick, 1971; Marshall, 1977). Basically, this idea suggested that, in spite of very low solubility with slow rates of dissolution and precipitation, the reactions of the common soil minerals with the soil solution can be described by elementary thermodynamics of the equilibrium conditions (Kittrick, 1971). The assumption is that the precipitation and dissolution of soil clay minerals can be explained by an equilibrium reaction between the constituents in the soil solution and the soil mineral (solid) matrix. Stability of the solid minerals in this equilibrium can then be explained by applying thermodynamic concepts. Scrivner et al. (1973) pointed out that in order to compare soil solution data with composite stability diagrams the standard free energies of formation of minerals and their ion species must be known.

Kaolinite formation in soil systems was thought to be impossible without aluminum being complexed with organic compounds (DeKimpe et al., 1961; Linares and Huertas, 1971; Hem and Lind, 1974; Costanzo et al., 1980). In order for kaolinite to form aluminum has to be in sixfold coordination so it can form the octahedral hydroxide sheet. Organic acids were thought to be particularly effective in placing aluminum in a position favorable to the precipitation of sixfold coordinated aluminum hydroxide (Hem and Lind, 1974). A great deal of success has been achieved in synthesizing gibbsite by complexing aluminum with fulvic acid (Linares and Huertas, 1971). This gibbsite structural layer is necessary to the formation of kaolinite because it unites with a tetrahedral layer of silica. Buol and Hole (1959) suggested the possibility of clay-organic complexes in soluble form being translocated and later synthesized into clay films. Antipov-Karatayev and Tsyurupa (1961) felt that the decomposition of rocks and minerals was caused primarily by chelation. They cited the abundance of microbes and plant products having the ability to chelate, the stability of organo-metallic chelates, and the wide pH range in which the formation of chelates is possible.

Silica needs to exist in the tetrahedral form in order to form phyllosilicate minerals (Callere and Henin, 1965). One of the essential conditions to achieve the proper coordination is to operate in very dilute systems. Apparently, in these conditions, silica exists in the form of $Si(OH)_4$.

Kittrick (1970) succeeded in precipitating kaolinite on a montmorillonite surface. Kaolinite was found on montmorillonite surfaces after the solutions were supersaturated with kaolinite. Undersaturation of the solution with kaolinite yielded no kaolinite precipitation. Linares and Huertas (1971) synthesized gibbsite in solutions having a pH range of 2 to 9 and SiO_2/Al_2O_3 ratios from 1 to 10. The aluminum was complexed with fulvic acid.

There are problems associated with the assumed equilibrium conditions concept. Evidence for this may come from clay mineral suites found in the argillic horizons of some Alfisols and Ultisols (Scrivner et al., 1973; Weaver and Bloom, 1977). Evidently these clay mineral suites were not consistent with stability fields predicted by dilute solution chemistry studies. Weaver and Bloom (1977) suggested that solute activities were in equilibrium with the mineral surface phase rather than the bulk mineral.

f. Diagenesis

The genesis of aluminosilicate clay minerals by comparatively slight physical and chemical alteration, in which the elementary crystal lattice remains intact and certain soluble constituents are removed and exchanged for others within the lattice, has been termed diagenesis (Callere and Henin, 1965) and alteration (Brady, 1974). In situ diagenesis, or alteration, has been suggested as a possible mechanism in the formation of clay rich B horizons (Brewer, 1968; Oretel, 1968; Birkeland, 1974; Smeck et al., 1981). If the weathering primary (parent) mineral is a phyllosilicate from the original igneous rock, or from a soil or sediment, then diagenesis occurs basically in the solid state (Birkeland, 1974). During investigations of gray-brown podzolic soils in New York, McCaleb (1953) reported that secondary minerals were formed in situ throughout the profile and in the parent material. The amount of secondary minerals formed was observed to decrease with depth. Work by Targul'yan (1964) described accumulations of brown clayey material in the form of crusts of coats on the upper sides of blocks and rock debris in the lower most rocky and blocky horizons. The author suggested the possible formation of a surface weathering crust on the rock fragments.

Oertel (1968) used the evidence of a minimum bulk density occurring in the B horizon to indicate that in situ weathering was dominant. Brewer (1968) reported the observation that the proportion of clay formed in situ always decreased progressively from the top of the Bt to the deeper horizons, implying an increasing production of clay from in situ weathering from the deeper horizons upwards to the upper Bt horizon. In situ formed clay was defined as the total clay minus the illuvial clay (determined by point counts in thin section analysis). The proportion of illuvial clay to total clay in the Bt horizons was actually small, thus it was thought that most of the clay in the Bt horizon was inherited from parent material and formed in situ. The net gain in total clay, resulting from a greater gain in fine clay than loss in coarse clay, has been interpreted as suggesting fine clay being formed in situ from coarse clay (Smith and Wilding, 1972). This was thought to occur in addition to translocation. Clay rich horizons in which the total clay gain can be attributed to gains in fine clay at the expense of coarse clay were considered nonargillic if argillan evidence was lacking (Ritchie et al., 1974). The clay gain in the above case was thought to be the result of in situ shale weathering. In situ clay formation from the weathering of shale lithorelics was thought to account for the B horizon clay increase in some soils, based on their lack of illuviation evidence.

A similar conclusion, given by McKeague et al. (1981), suggests that estimation of illuvial clay be micromorphologic methods might be impossible in materials with inherited bodies of oriented clay derived from the in situ weathering of clayey limestone. Argillans that have weathered in place have been proposed to explain the occurrence of weakly oriented apparently silty argillans.

In situ weathering that results in the formation of specific clay minerals may be limited to the coarse clay fraction (Jackson et al., 1948). The fine clays occur in a more advanced stage of mineral weathering while coarse clays usually contain minerals in earlier stages of weathering than fine clays. Fine clays have a much greater surface area, however. Increased specific surface along with increased acidity accelerates weathering (McCaleb and Cline, 1950).

Work in the Soviet Union suggested that, where illuvial processes are hindered, there was no other way to form optically oriented clays except by intrazonal weathering and clay formation in situ under the influence of the soil forming factors (Minashina, 1958). The occurrence of mutually isolated films on the surfaces of weathering minerals along with the random-fiber habit of optically oriented clays were considered to be evidence of in situ formation.

Heil and Buntley (1965) used the evidence of greater amounts of extractable calcium on the face of peds, than in ped interiors to indicate increased weathering of the ped face materials, particularly Cabearing minerals. This phenomena was observed on ped faces of B21t horizon peds which were stripped of their surface clays by eluviation. It was felt that the differential distribution of extractable Ca, Mg, and Na between ped faces and interiors was primarily the result of differential eluviation-illuviation and/or differential in situ weathering resulting from microclimate differences. Compared to the macroclimate of the pedon, ped faces were thought to be more humid and ped interiors more arid. Goddard et al. (1973) suggested that clay particle formation was primarily a function of wet-dry phenomena.

Dudal (1973) described the concept of ferrolysis, a cation exchange reaction involving iron in respective reduction-oxidation cycles, resulting from conditions of alternating wetness and dryness. Ferrolysis involves acid attack on Fe^{+2} displaced octahedral clay mineral layer edges. Every moisture cycle leaches cations and destroys part of the crystal lattice. Brewer (1973) described various mica forms in thin section. Generally, micas tended to retain their form during weathering. Exfoliated grains represented an early stage in weathering, during which some interlayer clay minerals might be formed. Pale bleached grains probably resulted from the removal of iron. Dark reddish grains are thought to have resulted from oxidation of iron, and might infer some alteration to secondary minerals. Weathered borders on mica grains might indicate expansion of interlayers with the subsequent formation of clay minerals. Pseudomorphs were considered to be an advanced stage of weathering. Chlorite structures were more susceptible than micas to acidic weathering (Kodama, 1979). The susceptibility varied with the mineral species. Iron rich minerals were most easily weathered, while aluminum rich species might be more durable.

g. Parent material stratification

Examinations into the genesis of textural subsoil lamellae indicated that in situ clay formation was of minor extent, in contrast to previously proposed hypotheses (Dijkerman et al., 1967). Field and micromorphological studies suggested the presence of sedimentary lamellae, along with lamellae resulting from illuviation influenced by parent material stratification. The sedimentary lamellae were found to be textural strata parallel to well defined bedding planes; and nonparallel to the boundary of $CaCO_3$ accumulation. The clay of the silt and clay lamellae was found to be very weakly oriented. Illuvial lamellae dependent on parent material stratification were found to be similar to the sedimentary lamellae except that clay bodies were strongly oriented. In soils derived from calcareous glacial outwash, the materials in which the sola formed were believed to be originally stratified as the C horizons of the soils were found to be stratified with respect to particle size distribution and $CaCO_3$ content (Smeck and

Wilding, 1980). Argillic horizon genesis in such soils was difficult to determine due to the presence of lithologic discontinuities. Brewer (1968) suggested sedimentary layering to explain Bt horizon clay contents in cases where the amount of illuviated clay (inferred from thin section analysis) cannot explain the particle size differentiation.

Parent material stratification is thus seen as one possible mechanism for the clay maximum occurring in the B horizon. Several other mechanisms of minor and/or local extent have been proposed by various authors. One of the most obvious, residual clay enrichment resulting from the dissolution of limestone, was addressed by Ballagh and Runge (1970). Two soils were investigated with the assumptions that; the residual clay would be similar mineralogically to the clay in the limestone; the clay in the clay rich horizon should be similar in size to residues in the limestone, and the organic carbon associated with the clay should be relatively old compared to the organic carbon in the upper horizons. After laboratory analysis in which the clay rich horizons failed to meet the above assumptions, it was concluded that the clay rich horizons were illuvial rather than residual.

Workers in Ohio have suggested a similar carbonate dissolution mechanism to explain clay rich horizons in various calcareous glacial sediments (Rostad et al., 1976, Smeck and Wilding, 1980). It was felt that, in such deposits, the particle size distribution generally changed upon carbonate leaching as the result of a non-uniform particle-size distribution of $CaCO_3$. The product was a horizon higher in clay and lower in silt, sand, and gravel. Clay enrichment resulting from carbonate leaching was thought to possibly mask changes due to clay translocation.

Physical weathering has been proposed by workers in Ohio, as another mechanism by which clay rich B horizons form (Rostad et al., 1976; Smeck et al., 1981). Fine-textured B horizons formed in coarse-textured calcareous outwash were thought to result from disintegration of shale, siltstone, and sandstone crystalline lithorelics in the sand and gravel particle size fractions. The matrix of the lower B2t and B3t horizons of investigated soils were composed primarily of lithorelics and associated argillans.

Oriented clay bodies were also thought to be formed by the influence of mechanical pressure (Minashina, 1958). Brewer (1964) described these as stress cutans. Grossman et al. (1964) suggested that oriented void peripheries might form in some cases by shear along planar surfaces during wetting. In Soil Taxonomy (Soil Survey Staff, 1975) slickensides were described as polished and grooved surfaces resulting from one mass sliding against another. Slickensides were felt to be common in swelling clays with the associated marked changes in moisture content. Buol and Hole (1959) suggested that laminated structure observed in clay films might be the result of the flow of clay skin material under pressure from expanding or shifting soil masses.

The gravity induced mechanical falling of particles through cavities, both in a dry situation in very stony and porous soils (Targul'yan, 1964) and in sandy soils with water filled pores (Dijkerman et al., 1967). has been proposed as a possible mechanism in which clay rich B horizons form. The latter situation differed very little from illuviation. It was suggested by Dijkerman et al. (1967) that perhaps clay moving in this manner exists in a flocculated state, with individual clay platelets perpendicular to one another, as opposed to a dispersed state necessary for illuviation. The forces of drying could then reorient clay particles to a face to face structure. Increased biological activity at the surface favored a small increase in translocation due to pedoturbations (Arnold, 1965).

Various authors have suggested that some clay rich horizons may be relics of a paleoclimate (Cline, 1949; Gile and Grossman, 1968; Brewer, 1973). Such conclusions were drawn as argillic horizons were not thought to form under the present environmental conditions in the areas studied.

D. Hydrosequences

The influence of topography on soil profile morphology has long been recognized. Drainage and the slope of the land surface were recognized as two of the environmental factors which governed the conditions under which profile development took place (Norton and Smith, 1930). It was proposed that the most important effect of slope on profile development of forested loessal soils in Illinois was the moisture condition. Generally, as slope increases the amount of runoff increases, and the amount of water entering the soil decreases. The concept of a sequence study of soils was developed most fully by Jenny (1941). The five soil forming factors were thought of as the independent variables that define the soil system. In order to study the role played by each factor all of the remaining factors needed to be held relatively constant. This is the concept of a sequence. A toposequence would reflect soil morphology changes as a function of changes in topography. Jenny (1980) defined the state factor topography as pertaining to the configurations of the landscape including the water table positions. The topographical influence on the hydrology of a soil system gave rise to soil catenas. Catena was defined by Brown and Thorp (1942) as including geographic groups of soils developed from one kind of parent rock but under different drainage conditions induced by differences in slope. Each well drained upland soil in the catena normally has moderately-well, somewhat-poorly (or imperfectly), poorly, and very-poorly drained associates. This usually occurs in a continuum, unless sharp topographic breaks are present, and may just involve two or three drainage classes.

In simplified view the well drained soil occurred on the high ground and can be the result of either rapid infiltration and percolation on highly permeable material, or runoff disposal on less permeable material (Cline, 1953). Such areas were the convex crests of knolls on gently undulating to rolling landscapes, or the upper parts of hills with greater local relief. Moderately-well drained soils occurred in similar landscapes, but commonly in positions where water was received from adjacent higher ground, both in the form of overland flow and lateral throughflow. The somewhat-poorly and poorly drained soils occurred in lowland positions commonly on concave slopes where water accumulated, sometimes excessively. They also occurred where slowly permeable material and lack of slope favor saturated conditions for a good part of the year.

Zones of saturation greatly influence the internal environment of the soil. In addition to supplying additional moisture for chemical weathering, water tables can also function as relatively impermeable barriers to percolating waters (Runge, 1973). Water tables that fluctuate greatly during the year subject the soil to alternating oxidation and reduction regimes. Soils with relatively high persistent water tables were greatly reduced and were characterized by gley colors and thin A2 horizons (Daniels et al., 1971). Well drained soils with very deep water tables were characterized by bright colors, deep zones of accumulation, and the leaching of soluble constituents.

McKeague (1965) investigated the well drained, imperfectly drained, and poorly drained members of the Uplands catena in Canada. The results indicated major differences between the properties of the poorly-drained member and those of the better drained members. The differences were thought to be associated more closely with

the redox conditions of the soils and less closely with the water tables. Oxidizing conditions commonly prevailed well below the water table, except when it was at the surface, for both a catena of sandy soils and a sequence of clayey soils.

Water table regimes of five soil series investigated in Oregon occurred to the same magnitude as predicted by soil morphology (Boersma et al., 1972). There was no consistent relationship found between Munsell values and water table regimes throughout the entire drainage sequence however. The degree of drainage achieved at a specific depth by three alluvial soils was three months lag for moderately-well drained soils versus well drained, and four months for somewhat-poorly drained versus well drained.

Water table levels in five soil catenas, each consisting of well drained, imperfectly drained, poorly drained, and very-poorly drained members, were monitored for five years in southern Ontario (Mackintosh and Hulst, 1978). The respective drainage classes were identified according to a combination of soil morphology and landscape position. Soil morphology along with water table measurements were used to establish the zone of free water saturation. The data indicated that the length of the period of saturation, at a specific depth, increased from the well drained to the very poorly drained conditions. The range of water table characteristics within a soil series was found to be as large as those between series. Water table fluctuations, described as a range between the mean highest water table and the mean lowest water table, were found to overlap in very-poorly drained, poorly drained, and imperfectly drained soils. The well drained class had no overlap to other classes.

Underlying zones of free water saturation are the feature associated with a water table that is important to soil genesis and morphology. Soil morphology is the product of the mean physical and chemical conditions over prolonged periods of time, whereas water table information is point source data collected over a short interval of time (Mackintosh and Hulst, 1978). Van Heesen (1970) suggested that in some landscapes soil development and gley phenomena no longer bore relation to the present soil drainage and might be fossil features. Small variations in drainage should be downgraded in mapping while the role of morphological data in soil classification and mapping should be reevaluated (Mackintosh and Hulst, 1978).

Van Heesen (1970) investigated the idea that seasonal water table fluctuations could be presented on soil maps utilizing soil profile characteristics. Differences in the depth of the gray and rusty colors that accompanying gleying were first used to derive data about fluctuations of the water table. It was found, however, that the expression of gley phenomena was not exclusively dependent on soil drainage. Soil texture and structure were also found to influence the occurrence of gley. The gley characteristics of different soils with similar drainage were found to sometimes be different.

Water table depths, periodically measured in an Oregon catena, were correlated with soil morphological features (Simonson and Boersma, 1972). Water tables were at or above the depths of faint mottling a nearly identical percentage of time in a given month for the five soils of the catena. The average depth below the surface to the midpoint of the uppermost mottled horizon decreased as the extent of drainage decreased. During January through April the average percent of time that water tables were at or above the depth with distinct mottling were nearly identical for the five soils. The depth of mottling was not found to be a consistent indicator of the degree of waterlogging at depths above the mottled horizon.

In soil systems without water tables, runon, or lateral seepage from adjacent areas, only runoff and losses to deep percolation need be quantified in order to complete the characterization of moisture regimes after rainfall and evapotranspiration data (Scrivner et al., 1973). In other soils the extent of recharge and discharge and water storage were important, in addition to precipitation and evapotranspiration, with respect to the depth and fluctuation of the groundwater (Van Heesen, 1970).

The distribution of mottling under various moisture regimes in a Glossoboralf-Haplaquoll hydrosequence in Wisconsin were studied (Richardson and Hole, 1979). Mottling distribution occurred as expected; from none in the well drained pedons, to considerable mottling in the somewhat-poorly drained pedons, to few in the very poorly drained pedons where gley characteristics predominated.

A Miami catena in a virgin beech-maple forest in eastern Indiana was investigated in order to determine the annual fluctuations of water levels (Thorp and Gamble, 1972). Water levels and relative moisture contents of the soils were found to be closely related to the period of transpiration of the forest; a phenomenon also observed in Wisconsin (Wilde et al., 1953). The three soils composing the Miami catena in eastern Indiana were the Miami (Typic Hapludalf), Bethel (Typic Ochraqualf), and Brookston (Typic Argiaquoll). The Bethel soil was completely saturated two weeks to two months before the Brookston soil approximately 80% of the time. During the summer months, however, the Bethel soil became much drier than the Brookston soil. Both soils remained saturated for periods of two to four months at a time, with the Bethel soil usually remaining saturated for somewhat longer periods of time than the Brookston soil. The Miami soil became saturated to within 25 to 30 cm of the surface two or three months after the Bethel soil, but only remained saturated for short periods of time immediately after heavy rains. The authors concluded that not only did increased transpiration in the Miami and Bethel soils account for the drying phenomena, but subsurface waterflow from the Miami and Bethel soils to the Brookston soils also occurred.

A similar study in Illinois revealed that water tables in all of the soils were relatively higher in the winter and spring with a subsequent drying in summer and autumn (Fehrenbacher et al., 1969). Poorly and somewhat-poorly drained soils were found to have high water tables in late winter, early spring, and in the autumn following heavy rains. Water tables were also observed in moderately-well drained soils, but for brief periods of time. Water tables above one meter depth were seldom found in well drained soils.

A Miami catena investigated in Ohio showed strong agreement between soil profile drainage class and the depth and duration of the water tables (Anonymous, 1962). All of the soils of the catena had water tables that rise in late winter. The Miami soil had the deepest water table while the Brookston soil had the shallowest. The water table drop in spring corresponded with the onset of forest transpiration similar to the observations of Thorp and Gamble (1972).

Water table studies in New york indicated that drainage classes, determined from soil profile characteristics, provided a good indication to the depth of the apparent water table (Fritton and Olson, 1972). All of the soils in the drainage sequence of soils formed in loamy glacial till showed the characteristic high water table in the spring, and the low water table in autumn. The poorly-very poorly drained Lyons soil showed a lag in the fall of the water table in the later summer, and in the magnitude of the range between the high and low depths of water table. Factors in the fluctuations of the water tables were thought to be:

monthly precipitation patterns, precipitation forms as snowmelt can add more to a water table depth than would be indicated by precipitation alone, the distribution of precipitation from site to site resulting from localized storm centers and drifting snow, the difference between precipitation and evapotranspiration, and the occurrence of surface and subsurface runoff. Van Heesen (1970) suggested that the point of time at which evapotranspiration begins to exceed precipitation approximately coincides with the springtime fall of water tables. Once precipitation exceeds evapotranspiration the water table started to rise again. The observed rate of water table rise in separate years appeared to be almost constant.

Water table levels were recorded in five soil catenas in southern Ontario (Mackintosh and Hulst, 1978). The data revealed a pattern of a yearly sigmoidal cycle with the superposition of shorter term variations reflecting precipitation events. The water tables were closest to the soil surface during March, April, and early May. With the onset of the growing season, the levels gradually dropped until they reached a low level during September and October.

McKeague (1965) investigated water table levels and Eh values in three soils characterized by differing drainage classes. At the well drained site the water table remained several feet below the surface throughout the year and oxidizing conditions prevailed. The imperfectly drained site was subject to the widest fluctuations in water table levels, in wetness and dryness, and in redox status. At the very-poorly drained site the water table remained at or near the soil surface, and below a depth of two feet, reducing conditions prevailed throughout the year.

E. Soil Genesis Studies Based On Drainage

Investigations into the genesis of the well drained Miami soil revealed a definite accumulation of clay in the B22t horizon, with clay films occurring from the B22t horizon down into the C1 horizon (Thorp et al., 1959). It was concluded that clay eluviated from the A horizon and illuviated into the B horizon. Although illite was the dominant clay mineral in the till parent material, montmorillonite was dominant in the horizons of clay accumulation. Brydon (1965) investigated three well drained soils on medium textured ground moraine till in eastern Canada. Minimum clay contents occurred in the Ae horizons while maximum total and fine clay contents occurred in the horizons immediately below the Ae horizon. None of the pedons had oriented clay films in the upper B horizon. It was thought that illuviated organic matter and sesquioxides may have prevented their formation. Illuviation was proposed as the mechanism of clay accumulation in the strongly acid sola of the three soils. Solum depth in some well drained soils from Missouri was found to be related to the depth that was characterized by a frequency of one completed moist-dry cycle per year (Scrivner et al., 1973). The upper boundary of the B horizon was thought to indicate the average depth of penetration of summer rains. Pawluk and Dudas (1978) studied well drained Acid Luvisolic soils in Alberta and reported that particle size distribution and argillan evidence in the B horizon indicated illuvial clay accumulation sufficient for a Bt horizon designation. Clay illuviation appeared to have extended well into the C horizon. Vermiculite contents showed a general decrease with depth while mica contents increased. This was suggested to reflect a significant degradation of mica to vermiculite, especially in the upper solum where the eluvial horizon contained a hydrous mica-chlorite intergrade.

Smith and Wilding (1972) investigated argillic horizon genesis in somewhat-poorly drained Ochraqualfs in northwest Ohio. Clay translocation and pedogenic weathering in lake plain soils were found to occur well into the upper portion of the calcareous zone. The morainal soil investigated showed more prominent evidence of clay translocation by illuviation. It was thought that these soils had undergone a higher frequency of wetting and drying cycles as they occurred on an older more dissected surface than the lake plain soils. Illite contents were found to increase with depth along with a decrease in vermiculite. Areas further to the south showed a close relationship between the expandable clay content and more poorly drained conditions.

Ritchie et al. (1974) investigated B horizons of fine textured Aeric Ochraqualfs in which a water table is at or near the surface during late winter through early summer. Late in the summer the Aqualfs may have been depleted of moisture in the upper meter. Particle-size analysis revealed clay enrichment in the B horizon; but a lack of argillan evidence in some kept those horizons from meeting the requirements for an argilic horizon. The clay gain in those cases was proposed as resulting from in situ shale weathering. The upper part of the B horizon had lower pH values and relative base saturation values, indicating a more intense weathering environment. A weathering sequence of clay minerals with vermiculite decreasing and mica increasing with depth was noted along with the slight accumulation of expanding 14A material in the B horizon. This mineral was thought to be pedogenic montmorillonite as it was not detected in the C horizon.

Medium and fine textured soils characterized by poor and very poor drainage were investigated in Ohio (Schafer and Holowaychuk, 1958). Horizons of maximum clay content and detectable clay films on ped surfaces occurred relatively near the surface of several profiles. Poorly drained Brookston soils in the Miami and Russell catenas all showed a slight but distinct maximum clay content at a depth of about 25 to 30cm. Parent material stratification obscured the evidence of a pedogenic textural B horizon in a number of profiles. The more poorly drained soils were generally less acid than the associated better drained soils. Illite was the main clay mineral found in the poorly drained Brookston soil although montmorillonite was also found.

Poorly drained soils in western Ohio were investigated in order to determine whether or not they contained sufficient evidence of illuvial clay in the B horizons to meet argillic horizon criteria (Smeck et al., 1981). Only two out of five of the soils investigated had sufficient clay increases to meet the criteria of an argillic horizon. Thin section evidence indicated that none of the soils had sufficient argillan development in order to qualify for argillic horizons. Stress cutans were noted during the micromophological study. Mica increased with depth and vermiculite decreased suggesting a weathering sequence in which mica was diagenetically altering to verimculite. The authors suggested a reclassification of the three soils that failed to meet the argillic horizon criteria.

Asady and Whiteside (1982) investigated eight Udollic Ochraqualfs and eight Typic Argiaquolls in order to test the homogeneity of the tentative map unit they studied. Laboratory determinations revealed some translocation of clay and fine clay from the surface horizons to the subsoil in all of the soils. More translocation appeared to have occurred in the somewhat-poorly drained soils than in the poorly drained soils. Laurin (1973) reported that poorly drained soils from eastern Michigan showed a fairly uniform distribution of clay throughout the profile, while the fine clay to total clay ratios in the same soils decreased with depth to a minimum in the C horizon. One somewhat poorly drained soil showed a sharp increase in the percentage of fine clay in the Bt horizon followed by a sharp drop. The same soil showed an abrupt increase in the fine clay to total clay ratio directly below the Ap horizon, followed by a decrease. This soil also had evidence of oriented, apparently illuvial clay in the B21t and B22t horizon thin sections, whereas those of the poorly drained soils did not. Asady and Whiteside found that the fine clay to total clay ratio criteria set forth in Soil Taxonomy (Soil Survey Staff, 1975) was too high for the soils they investigated. They suggested that in Michigan an increase of one tenth or more in the fine clay total clay ratio would be sufficient criteria by which to identify an argillic horizon.

In the Soviet Union soils in which leaching was greatly hindered or completely lacking were found to lack the uncrusted forms of secondary clay associated with translocation (Minashina, 1958). Pawluk (1971) interpreted eluvial A horizons and illuvial B horizons in poorly drained Fera Eluviated Gleysols of Alberta as indicative of a former leaching environment. Eluviated Gleysols, similar to Aqualfs, are characterized by excessive wetness, periodic reducing conditions, hydrophytic vegetation, and well developed horizons of clay eluviation and illuvation (McKeague, et al., 1973). Particle-size data and nearly continuous thin clay films on Bt horizon peds have been reported for many profiles of the Eluviated Gleysols. These soils were thought to develop in sites where appreciable net downward movement of water occurred. Few studies on the moisture regime of such soils have been done in Canada. McKeague et al. (1981) report that none of the three Gleysolic soils examined had even 0.5% illuvial clay occupying the area of the thin section from their field designated Bt horizons.

Stobbe (1952) investigated the transition from a Modal Gray-Brown Podzolic soil, the dominant well drained soil in southern Ontario, to the Dark Gray Gleisolic soils. The former soils were analogous to well drained Alfisols, the latter resulted form imperfect drainage and were analogous to Aquepts. Generally, the morphologic differences between the A2 and B2 horizons became less distinct as the drainage became poorer. Particularly, textural differences between the A2 and B2 horizons were much less pronounced as in the well drained soils. The more poorly drained soils were also characterized by thicker darker A1 horizons, and by mottling and gley colors in the B horizon.

McKeague (1965) investigated a drainage sequence of three clayey soils in the Ottawa Valley in order to determine relationships between soil properties and water table depth with the associated redox status. Analysis indicated that the greatest degree of horizon differentiation occurred in the imperfectly drained soil, followed by the well drained member. The very-poorly drained soil had very little horizon differentiation. Thin section data indicated only meager, very thin, oriented clay coatings in any horizon of the well drained soil, although the clay content increased with depth. In the imperfectly drained soil thin discontinuous oriented clay coatings were found on some surfaces, but not quite to the extent that the horizon was designated Bt, although there was an increase in total clay and fine clay below the Aeg horizon. The imperfectly drained soil was subject to the widest fluctuations in water table levels and in redox conditions.

Daniels et al. (1968) determined that well drained Ultisol profiles had thicker more prominent A2 horizons and stronger contrasts between the A2 and B horizons than their associated more poorly drained soils. Water table data was interpreted as indicating little or no translocation of clay during the winter months in poorly drained and moderately well drained soils. Downward translocation was thought to be limited to low water table periods of wetness in summer and fall. The well drained soil had the potential for leaching and translocating all year round. The clay maximum occurred much deeper in the somewhat-poorly drained and poorly drained soils than in moderately-well drained soils.

Areas of maximum soil morphology change were found to closely correspond with areas of maximum water table level change (Daniels et al., 1971). It was thought that high water tables had an inhibiting effect on developing a thick solum, and that only small amounts of clay can be translocated as particulate matter below a water table.

A catena of soils developed in compact, reddish brown, sandstone derived till was studied by McKeague et al. (1973). All of the soils had the Bt horizon by current criteria, although some were borderline. The degree of Bt horizon development, as determined in the field, appeared to be greater in the more poorly drained soils. Micromorphology data agreed with this, although the other data did not. The general mineral weathering trend seemed to be the alteration of mica, the dominant mineral in the BC and C horizons, to expansible minerals, and then further alteration to montmorillonite. Montmorillonite only occurred in the Ae horizons of all four soils. It appeared that montmorillonite was not translocated, even in small amounts, to the B horizon. This was interpreted as indicating that clay translocation had been occurring since deglaciation whereas mica alteration to montmorillonite was a recent phenomena.

Runge (1973) proposed a model of soil formation in which organic matter production was a renewing vector and the water available for leaching was a developing vector. In the model the amount of water passing through any part of the soil profile must be considered in the developing vector, especially in poorly drained soils with a high water table. Two developmental sequences were studied in Illinois. In the first sequence, one soil was found to be more developed than associated soils, because more than twice the amount of water had percolated through it than the associated soils. Production of less organic matter may have left mineral grain surfaces exposed to weathering. In the second sequence, one soil was found to be less developed than the associated soils, because less than the normal amount of water had percolated through the upper horizons of it because of a persistently high water table. Cisne, a Mollic Albaqualf, was compared to Tama, a Typic Argiudoll. The narrow vertical zone of clay accumulation in the Cisne zone was found to coincide with the depth of a shallow persistent water table. Moisture fronts were believed to reach a potential gradient of zero repeatedly in the zone directly above the water table. Water movement became static in that zone; the zone where the clay accumulation was found. In the well drained Tama soil the broad zone of clay accumulation was thought to reflect unidirectional flow of water throughout the solum, controlled by the frequency or precipitation.

a. Clay mineralogy in a catena

Clay mineral variability in the soils of a catena has been studied by various workers (Biswas and Das, 1960; Iniguez and Scoppa, 1973; Schouten, 1974). Montmorillonite became the dominant clay mineral replacing illite in descending from the highest point of a slope down to the depressional area (Biswas and Das, 1960). Kaolinite was lacking in the depressional area, and was more abundant than montmorillonite in the higher slope position. Cation exchange values also increased downslope supporting the apparent montmorillonite dominance. Jackson (1965) suggested that drainage restriction, as controlled by topography, texture, and evapotranspiration, was associated with the accumulation of silica and other constituents essential to form montmorillonite.

Iniguez and Scoppa (1973) investigated Typic Argiudolls and associated poorly drained soils along with Vertic Argiudolls. The dominant clay mineral was illite with only a very slight differentiation of the clay minerals. The composition of the poorly drained soil was in a general way similar to that of the parent materials of this soil and the well drained soils of the region. It was suggested that clay evolution is inhibited by poor drainage, probably because of reducincing conditions and less intense biological activity.

A toposequence showing the influence of the profile drainage factor was investigated in order to study the application of a micro densitometer to clay mineralogy studies (Schouten, 1974). Well drained red soils were compared to associated poorly drained pseudogley soils. Smectite was present in the poorly drained soils but was absent in the well drained soils. Leaching and desilification on the well drained sites was proposed as supplying cations to the poorly drained site, favoring the formation of smectite minerals. The differences in the mineral suite between the well drained site and the poorly drained site were less obvious in soils developed from basic rocks as compared to those developed from acid rocks. The influence of the profile drainage factor seemed to increase with time.

Chapter 3. MATERIALS AND METHODS

A. Field Methodology

Four hydrosequences were located and sampled for this study. Suitable sequences were located using modern soil surveys. The sequences had to meet the following criteria, determined beforehand:

1. The three soils in each hydrosequence should occur in a repeating mappable pattern over a significant portion of the county. Such a pattern could occur as an association or a catena.
2. The hydrosequences should occur as true sequences as defined by Jenny (1941, 1980). All of the other soil forming factors should be kept relatively constant.
3. The hydrosequence should occur on nondisturbed land. Disturbance here would include cultivation, artificial drainage or extensive erosion.

Two of the hydrosequences were located in Clinton County near the town of Maple Rapids. The third hydrosequence was located in Ionia County near the town of Palo. Three additional pedons, comprising the fourth hydrosequence were sampled, one of each drainage class, in western Ionia County northwest of the town of Saranac. The location of the two counties, the surface geology, and hydrosequence locations are shown in Figure 1. Hydrosequence 1 was located in the N1/2 SW1/4 of section 10, T.8N., R.3W. in Clinton County. Hydrosequence 2 was located in the N1/2 NE1/4 NW1/4 of section 15, T.8N., R.3W. in Clinton County. Hydrosequence 3 was located in the N1/2 NE1/4 NW1/4 of section 3, T.8N., R.6W. in Ionia County. Pedon M4 was located in the SW1/4 SE1/4 of section 10, T.7N., R.8W. in Ionia County. Pdeon C4 was located in the NW1/4 NE1/4 of section 20, T.7N., R.8W. in Ionia County. Pedon B2 was located in the SE1/4 NE1/4 of section 20, T.7N., R.8W. in Ionia County.

The parent material in the area of each hydrosequence is loamy glacial till in the form of a series of north-south oriented moraines dividing till plains. Hydrosequence 1 and Hydrosequence 2 occur on the Flint moraine of the Lake Border morainic system (Bretz, 1951; Ward, 1979). In this area the moraine is bisected by the Maple River to the north, and various glacial drainageways to the south and west. Till plain topography occurs to the east. Hydrosequence 3 occurs on a till plain approximately one and a half miles north of the northern tip of the Ionia moraine of the Lake Border morainic system (Bretz, 1951; Martin, 1955). Pedons M4, C4, and B2 occur on the Charlotte moraine (Martin, 1955).

The dominant forest cover in southern Michigan is the central hardwood forest. Hydrosequence 1 occurs in a 120 acre woodlot consisting of: white oak (*Quercus alba*), shagbark hickory (*Carya ovata*), and northern red oak (*Quercus rubra*) in the well drained site; white oak, sugar maple (*Acer saccharum*), and shagbark hickory in the

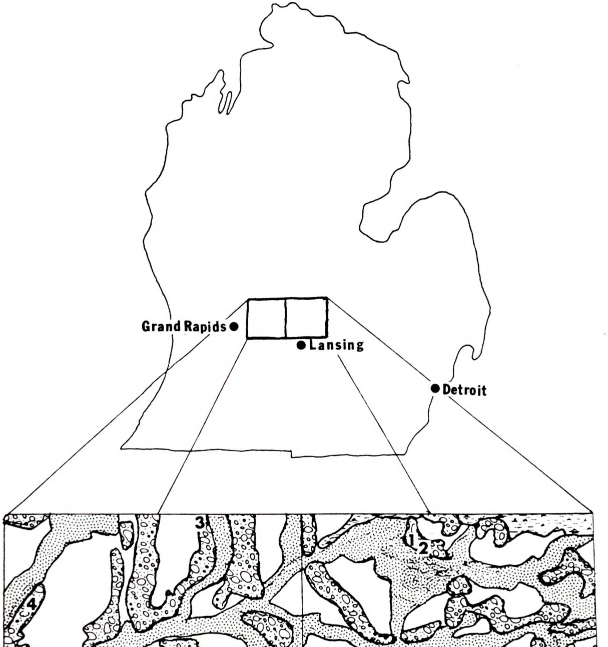


Figure 1. Surface geology and hydrosequence location in Ionia and Clinton Counties (After Martin, 1955).

somewhat-poorly drained site; and white oak, quaking aspen (Populas tremuliodes), and swamp white oak (Quercus bicolor) in the poorly drained site. The poorly drained site also contained a dense ground cover of yellow nutsedge (Cyperus esculentus). Hydrosequence 2 occurs in a 150 acre woodlot consisting of: sugar maple, American basswood (Tilia Americana), and northern red oak in the well drained site; red maple (Acer rubrum), sugar maple, northern red oak, and shagbark hickory in the somewhat-poorly drained site; and white ash (Fraxinus Americana), white oak, and swamp white oak in the poorly drained site. Yellow nutsedge occurred throughout the poorly drained site. Hydrosequence 3 occurs in an extensive wooded area consisting of white oak, shellbark hickory (Carya laciniosa), and pin oak (Quercus palustris) in the well drained site; bitternut hickory (Carya cordiformis), shagbark hickory, white oak, and quaking aspen in the somewhat-poorly drained site; and sugar maple, American basswood, and slippery elm (Ulmus rubra) in the poorly drained site. Pedon M4 occurred in a 35 acre woodlot consisting primarily of American beech (Fagus grandifolia), white ash, and bigtooth aspen (Populus grandidentata) in the well drained site. Pedons C4 and B2 occurred in an 80 acre woodlot consisting of bur oak (Quercus macrocarpa), white ash, and shagbark hickory in the somewhat-poorly drained site (C4) with sugar maple, and yellow nutsedge in the poorly drained site (B2).

The pedon sites were located by selectively sampling the soils with a bucket auger. The pedons had to possess

properties within the range of characteristics for the respective soil series of the mapping unit. Maturity of the vegetation stand, and size of the immediate polypedon area also influenced the pedon selection. Pedon locations are shown in Figure A1 and Figure A2 (Appendix A). Pedon locations are given in the pedon descriptions in Appendix B.

Once sizeable areas with the desired characteristics were located, sampling pits were dug. The pits were dug deep enough to expose relatively unaltered glacial till materials. The face of one side of the pits was prepared for description purposes and sample collection. This preparation included elimination of spade marks and soil debris from above or below the horizon being described and collected. The pedons were described according to the Soil Survey Manual (Soil Survey Staff, 1951).

Approximately 5 to 10 kg of bulk sample was collected from each horizon of each pedon for use in a majority of the chemical and physical analysis. The horizon to be collected was isolated by chipping away overlying and underlying materials. The isolated horizon was then cut free and placed on a small cotton trap. The sample was "homogenized" by taking adjacent corners of the tarp in each hand and gently mixing. After mixing, the larger aggregates were placed in a plastic bag as the sample. The debris left on the tarp was discarded.

As the bulk samples were being taken from the pit, large well shaped aggregates were selected and set aside for use in making thin sections and determining bulk density.

The aggregates were carefully cleaned of any debris and sampling marks in order to obtain as natural a sample as possible. The aggregates were then wrapped in paper towels and stored in pint sized cardboard containers. In preparation for shipment to the petrographer the aggregates were carefully wrapped in aluminum foil and labeled, noting the orientation of the aggregate with respect to the soil surface.

Before the bulk samples were air dried, peds from all of the Bt horizons were selected for clay film analysis. The remaining bulk samples were crushed and ground using a wooden rolling pin. This was used in order to avoid the breaking down of any coarse fragments. A 2mm sieve was used to sieve the samples and remove all coarse fragments, roots, etc. The samples were then stored in quart size cardboard containers for use in the analysis.

Neutron moisture probe access tubes were installed near each of the sampled pedons. The neutron moisture probe was used to monitor the fluctuations in the depth and duration of the zone of saturation. The access tubes consisted of aluminum tubing with an inside diameter of 51mm cut to a length of 3.0 meters. One end of each tube was sealed with a #11 rubber stopper and silicon sealer. The site was prepared by augering a hole near the sample pedons using a bucket auger with a 63.5 mm diameter bucket. Most of the sites were augered to a 3 meter depth, although rocks, dense till, and water prevented augering to that depth in some of the sites. The tubes were lowered down the holes and soil

material from the augering process was sprinkled down the sides to hold the tube firmly in place, and to cut down on capillary rise. A #11 rubber stopper was hammered in the access end of each tube to keep moisture out. Weights were placed on the tubes to prevent the soil water pressure from pushing them out of the soil.

In order to take a moisture measurement the neutron probe was set on top of the access tube, and the source was lowered down the tube. A standard count was taken at each hydrosequence as the probe was turned off between sequences. Moisture measurements were taken in 0.3 meter increments. Two measurements were taken at each depth and recorded.

B. Laboratory Analysis

Mechanical Analysis - The texture of each sample was determined by the pipette method of particle size analysis (Soil Survey Staff, 1972). Minor modifications were made in the removal of cementing agents, the pipette used for sampling, and the collection of the fine clay fraction. Removal of the cementing agents required three steps: 1) removal of free calcium carbonates by dissolution in 1<u>N</u> sodium acetate pH5, 2) removal of organic matter by oxidation in 30% hydrogen peroxide, and 3) removal of free iron oxides by reduction in a dithionite-citrate-bicarbonate extraction (Jackson, 1956). The samples were dispersed with 10% sodium hexametaphosphate. The fine clay fraction was sampled by pouring approximately 75ml of the sample suspension into a 100 ml centrifuge tube, and centrifuging

at 2500 rpm for 34.9 minutes. The pipette was lowered 5cm into the tube.

Bulk density determinations were made using the Saran-coated clod method (Brasher et al., 1966; Soil Survey Staff, 1972). Clods, or aggregates of about 50 to 200cc were held by a thread and immersed briefly in Saran. Two additional coatings were made in order to waterproof the aggregates. The aggregates were then weighed in air and in water.

Chemical Analysis - The cation exchange capacity (CEC) and exchangeable bases of each sample were determined using ammonium acetate at pH7 (Soil Survey Staff, 1972) as modified by Warnke et al. (1980). The supernatents from the three initial extracts (1N ammonium acetate pH7) were used in the base saturation determination. The samples were washed with n-propyl alcohol to remove excess ammonium ions. Magnesium content was determined colorimetrically. Calcium, potassium, and sodium contents were determined by flame photometry.

The pH of each sample was determined using a 1:1 soil-solution ratio. Both water pH and salt pH (0.1N KC1) were measured.

The inorganic carbon content was determined using the titrimetric method (Bundy and Bremner, 1972). The samples were analyzed for organic carbon using the heat of dilution method (NCR-13 Staff, 1980). This procedure is an acid dichromate digestion using $NaCr_2O_7$ and concentrated H_2SO_4. The results were determined colorimetrically and compared to soil standards.

The iron and aluminum contents were determined using a dithionite-citrate-bicarbonate extraction (Soil Survey Staff, 1972). The iron and aluminum content of the extracts were determined using integrated plasma coupling.

Fabric Analysis - The thin section slides used in the micromorphology study were prepared by Cal-Brea, P.O. Box 254, Brea, California 92621. The slides were observed and described according to the procedures outlined by Brewer (1964) and Cady (1965).

Clay Mineral Analysis - The clay mineralogy of each sample was examined by X-ray diffraction. Clay fractions were collected from particle-size fractionation procedures. Both the coarse clay and the fine clay fractions were analyzed. The X-ray patterns were used to qualitatively and semi-quantitatively study the mineralogy of the clay fraction.

The clay film minerals used in this study were collected from the ped surfaces of the aggregates from the argillic horizons. A small penknife was used to remove the clay films from the peds while viewed with a stereo microscope. The fine clay fraction of the clay film materials was isolated using particle size fractionation by centrifugation. This was based on the assumption that the majority of the translocated clay was of the fine clay fraction. Pretreatments to the centrifugation fractionation included removal of the cementing agents similar to the procedures of the particle size analysis, and dispersion using 0.1N $NaHCO_3$ at pH9 (Jackson, 1956).

The clay suspensions were applied to the tiles, under vacuum, using a 1-ml pipette. Three to five 1-m1 aliqouts were applied to the tiles in order to achieve an even coating of clay. The clays were leached with three to five increments of 0.1N $MgCl_2$ - glycerol (10% by volume) in order to achieve a magnesium saturated - glycerol solvated sample. A solution of water and 10% glycerol was also leached through the samples to get rid of excess $MgCl_2$. The samples were allowed to dry overnight in a dessicator. An X-ray diffractogram was made of each sample using a North American Phillips X-ray diffractometer utilizing Cu K α radiation, a nickel filter, a scanning rate of $2^{o}2\theta$ per minute, and a rate 4 scale 16 setting.

After X-raying the magnesium saturated-glycerol solvated sample, the exchangeable magnesium was displaced with potassium. Approximately 0.5ml of 1N KC1 was added to the films under vacuum. After four or five such increments, the clay film and the tile were rinsed with a small amount of distilled water. The sample was air dried and then heated to 300°C for two hours. After X-raying, the sample was heated to 550°C for 2 hours and another X-ray diffractogram was made. The relative peak areas were determined by multiplying peak height times the peak width at one-half peak height. This area value was then divided by the sum of peak areas of all of the 1st order peaks on the diffractogram.

Chapter 4. RESULTS AND DISCUSSION

A. Introduction

The results of this study will be given and discussed in light of the three objectives stated in the Introduction. Horizon designations described in the field were retained for use in identifying the samples during the various analyses. Where the evidence indicates a discrepancy it will be appropriately pointed out and discussed. The classification of the pedons will be discussed and compared to those originally intended in locating the pedons.

B. Parent Material Uniformity

Before the development of any horizon can be evaluated the uniformity of the parent material needs to be assessed. Horizons in a soil of nonuniform parent material may not be the result of pedogenesis. Table 1 gives the silt/sand ratios calculated for all horizons. Particle-size data for all horizons are given in Table C1, Appendix C. Asady and Whiteside (1982) proposed a value of ± 0.37, calculated by dividing the silt/sand ratio of the A horizon by the silt/sand ratio of the B horizon and subtracting one from the quotient, to indicate the point where lithologic discontinuities were recognized in the field. Values between ± 0.37 indicated uniform parent material. Based on this calculation pedons M1, C1, and B1 were found to be developed

in uniform parent material. Pedon M2 is borderline with a value of -0.37 between the A and B horizon and the B21t horizon. All of the other pedons have one or more lithologic discontinuities occurring within their solum.

Ritchie et al. (1974) used both sand/silt ratios and Ti/Zr ratios to investigate parent material uniformity. Deviations of greater than 0.08 and 30%, respectively, for the above ratios were used to indicate a lithologic discontinuity between adjacent horizons. Smeck et al. (1981) reported that the Ti/Zr ratio of the sand fraction provided an apparently stronger indicator of lithologic discontinuities than sand/silt ratios, and Ti/Zr ratios of the silt and combined sand and silt fractions.

Another calculation was made by adding the very fine sand fraction to the silt and dividing by the total sand content. The quotient between adjacent horizons was calculated and compared to the values from the method used by Asady and Whiteside (1982). According to their critical value of ± 0.37, pedon M2 would be considered as developed in uniform parent material. The previously determined lithologic discontinuity between the A1 and B and A horizons of Pedon C4 is not supported by the new calculation.

Both the calculation made by adding the very fine sand fraction to the silt fraction and the calculation used by Asady and Whiteside (1982) suffer from a lack of consistency when comparing more than two horizons. The lack of consistency results if the quotient is always determined with the overlying horizon as the numerator and the

Table 1. Particle - size distribution ratios of nonclay fractions.

Horizon	$\frac{Si}{S}$	$\frac{Si/S(1)}{Si/S(2)}$* -1	$\frac{Si+vfs}{S}$	$\frac{\frac{Si+vfs}{S}(1)}{\frac{Si+vfs}{S}(2)}-1$
Pedon M1				
A1	1.32	.031	1.58	.025
A2	1.28	.008	1.54	.020
B1	1.27	-.105	1.51	-.111
B21t	1.42	-.349	1.70	-.320
B22t	2.18	-.031	2.50	-.016
B3t	2.25	.184	2.54	.171
C1	1.90	-.128	2.17	-.125
C2	2.18		2.48	
Pedon C1				
A1	1.41	.052	1.68	.050
B1g	1.34	-.135	1.60	-.126
B21tg	1.55	-.139	1.83	-.120
B22tg	1.8	-.297	2.08	-.300
C	2.56		2.87	
Pedon P1				
A1	5.73	-.076	5.91	-.077
B1g	6.20	.051	6.40	.049
B21g	5.90	-.586	6.10	-.597**
B22g	14.25	4.70	14.50	4.370**
B23g	2.5	.042	2.70	.022
C	2.4		2.71	
Pedon M2				
A1	2.31	-.154	2.62	-.152
A+B	2.73	-.367	3.09	-.341
B21t	4.31	.197	4.69	.193
B22t	3.60	.074	3.93	.059
B3t	3.35	-.137	3.71	-.011
C1	3.88	-.060	4.19	-.062
C2	4.13		4.47	
Pedon C2				
A1	.928	.519	1.17	.345
B+A	.611	-.092	.87	-.073
B21t	.673	-.103	.939	-.097
B22t	.750	.473	1.04	.411
B3t	.509	-.731	.737	-.667**
IIC	1.890		2.21	
Pedon P2				
A1	3.17	1.66	3.44	1.47**
B21g	1.19	.102	1.39	.078
B22g	1.09	.139	1.29	.122
C	.948		1.15	

Horizon	$\frac{Si}{S}$	$\frac{Si/S(1)}{Si/S(2)}-1$	$\frac{Si+vfs}{S}$	$\frac{\frac{Si+vfs}{S}(1)}{\frac{Si+vfs}{S}(2)}-1$
Pedon M3				
A1	.80	-.024	.96	-.040
B+A	.82	-.024	1.0	-.020
B21r	.84	-.300	1.02	-.255
B22t	1.20	-.333	1.37	-.325
B3t	1.80	.487	2.03	.430
C	1.21		1.42	
Pedon C3				
A1	.492	-.472	.651	-.414
B+A	.933	.178	1.111	.135
B21t	.792	.154	.979	.110
B22t	.656	-.025	.382	-.028
B3t	.704	-.124	.907	-.093
C	.804		1.00	
Pedon B1				
A1	.492	-.016	.623	-.057
B1g	.500	-.194	.661	-.152
B21tg	.620	-.117	.780	-.106
B22tg	.702	.267	.872	.253
B3tg	.554	-.329	.696	-.272
C	.826		.956	
Pedon M4				
A1	1.30	.161	1.53	.147
A+B	1.12	.908	1.33	.654**
B21t	.587	1.39	.804	.791**
B22t	.246	1.05	.449	.554
IIB3	.120	-.804	.289	-.653**
IIIC	.611		.833	
Pedon C4				
A1	1.05	.464	1.24	.326
B+A	.717	.098	.935	.065
B21tg	.653	-.174	.878	-.139
B22tg	.791	-.145	1.02	-.132
B23tg	.925	5.8	1.175	3.3**
IIC1	.136	.782	.271	.672**
IIIC2	.623		.830	
Pedon B2				
A1	.953	.669	1.093	.447
B21tg	.571	-.134	.755	-.090
B22tg	.660	-.072	.820	-.089
B23tg	.711	-.092	.911	-.048
C	.783		.957	

* - (1) overlying horizon, (2) underlying horizon.

** - indicates lithologic discontinuity.

underlying horizon as the denominator. For example, in Pedon M3 the silt/sand ratios of the B22t, B3t, and C horizons are 1.2, 1.8, and 1.2 respectively. Neither method detects a lithologic discontinuity between the B22t and B3t horizons, yet both methods detect one between the B3t and C

If a value of ±0.60 is arbitrarily chosen as the critical value for the very fine sand plus silt to total sand ratio to determine whether a lithologic discontinuity exists between adjacent horizons, then pedons M1, C1, M2, M3, C3, B1, and B2 appear to have been formed in uniform parent material. This value seems to be the cutoff between questionable values and exceptionally large values. Pedons P1, C2, P2, M4, and C4 appear to have definite lithologic discontinuities within their profiles.

Subtle lithologic discontinuities are difficult to detect or define in a material as heterogenous as till. Till is possibly the most variable sediment of any kind known by a single name (Flint, 1971). Evidence interpreted as a lithologic break may be the result of pedogenesis if a stable constituent is not used to determine the change (Smeck et al., 1981). In Pedon P1 the B22g horizon is much finer, on a silt and sand basis, than the overlying and underlying horizons (Table 1). This suggests a material of different origin than the rest of the pedon. Bretz (1951) described the history of Early Lake Saginaw in the area just east of Maple Rapids. Evidently the Owosso maraine dammed glacial drainage waters, which were draining to the east in response to the slope of the land. Thus, for a brief period

of time the area between the Flint and Owosso moraines, near the town of Maple Rapids, was under the waters of Early Lake Saginaw. Ward (1979) cites the documented existence of beach deposits on the west side of the Owosso moraine as evidence for this. The B22g horizon of Pedon P1 may be a sedimentary feature deposited over a brief period of time, onto an otherwise uniform material. The relatively similar silt/sand ratios for the C horizons of the soils of Hydrosequence 1 indicate that the Flint moraine materials are fairly uniform in this area.

In Hydrosequence 2 Pedon C2 gets progressively coarser in going from the B22t horizon to the B3t horizon, and finer from the B3t horizon to the IIC horizon. The silt loam texture of the IIC horizon may reflect a lacustrine deposit of minor extent overlain by the B3t horizon possibly an alluvial sand deposit. In Pedon P2 a finer textured A1 horizon overlies a more loamy B21g horizon. This finer textured A horizon could result from deposition of fine textured erosion products of the nearby upland soils, by weathering of the coarser material resulting in an enrichment of the finer silts, or it may be a lacustrine deposit. The area of Hydrosequence 2 appears to be a little more varied than that of Hydrosequence 1, according to the silt/sand ratios in the subsolum horizons. Being on the western edge of the Flint moraine, this area may have had more influence from the melting process as the glacier retreated. Ice contact slightly stratified drift, including flowtill phenomena, has been described by Flint (1971).

Hydrosequence 3 appears to have been developed in rather uniform material of somewhat coarser texture than Hydrosequences 1 and 2. The lower part of Pedon M3 may have been developed in a somewhat finer material than pedons C3 and B1, based on the C horizon silt/sand ratios.

Pedon M4 of Hydrosequence 4 is so stratified that it appears to be alluvial, possibly of a deltaic origin. The IIC1 horizon of Pedon C4 is a coarse sand lens, probably of outwash origin, laid down during minor ice front fluctuations. Despite the occurrence of sand lenses and other minor outwash features, Pedons C4 and B2 appear to have been formed in relatively uniform material as evidenced by similar silt/sand ratios for the respective C horizons.

C. Argillic horizon criteria:

All of the clay ratios given in Table 2 were calculated using the weighted average clay content of the entire Bt horizon, or the particle-size control section for pedons without field described Bt horizons. Clay contents of the eluvial zones were determined for the A1 horizon in most pedons, and the A2 (E) horizon in Pedon M1. Transitional horizons such as the A&B and B&A (B/E, E/B) horizons were not used in the calculations. In pedons where the clay ratios were calculated between the B and C horizons the C2 horizon, where present, was chosen to represent the parent material. In pedons without a C2 horizon the C horizon represented the parent material. Transitional horizons like the B3t horizon were avoided in the calculations.

Table 2. Clay ratios and oriented clay criteria for argillic horizons.

Pedon	Total Clay		Coarse Clay		Fine Clay		Fine Clay/ Total Clay		% Argillans in Thin Section
	B/A	B/C	B/A	B/C	B/A	B/C	B/A	B/C	
M1	2.3	1.8	1.8	2.0	4.4	1.5	1.6	.9	1-5
C1	1.6	1.6	1.3	1.4	2.5	2.1	1.4	1.2	2-5
P1	1.2	-*	1.3	-	1.1	-	1.0	-	<0.5
M2	2.2**	1.4	1.7	1.1	3.9	2.0	1.6	1.4	2-3
C2	.9	-	.9	-	.8	-	1.0	-	3-5
P2	-	.9	-	.9	-	.9	-	1.0	<0.5
M3	2.2	1.4	2.0	1.3	2.5	1.4	1.1	1.0	2-5
C3	2.3	1.8	2.1	1.7	2.7	1.8	1.5	.9	2-5
B1	2.2	1.2	1.7	1.0	2.8	1.6	1.3	1.3	0.5-1
M4	-	-	-	-	-	-	-	-	1-2
C4	1.0	-	1.1	-	1.0	-	1.0	-	2-5
B2	1.4	1.3	1.1	1.0	1.7	1.5	1.2	1.2	0.5-1

* - indicates definite lithologic discontinuity.

** underscore indicates possible lithologic discontinuity.

Total clay ratio: The results of the complete particle size analysis are given in Table C1 of Appendix C. Pedons M1, C1, and P1 of Hydrosequence 1 are all characterized by an increase in clay with depth, the maximum occurring in the B horizon. All three of the pedons meet the minimum requirement ratio of 1.2 for total clay in the argillic horizon to that in the overlying eluvial horizon (Table 2) as set forth in Soil Taxonomy (Soil Survey Staff, 1975).

In Hydrosequence 2 Pedon M2 has a similar clay distribution, exceeding the minimum clay ratio. Pedon C2 fails to meet the minimum requirement. Pedon P2 fails to meet the minimum ratio, calculated between the B horizon and C horizon because of a possible lithologic discontinuity between the A and B horizons. In both pedons C2 and P2 a value of approximately one for the total clay ratio indicates a lack of clay accumulation in the B horizon compared to adjacent horizons.

All three pedons of Hydrosequence 3 show an increase in clay content with depth, the maximum occurring in the B horizon. All of the pedons exceed the minimum ratio to a similar extent.

Pedons M4 of Hydrosequence 4 was found to be stratified to a great extent (Table 1) using the criteria suggested by Asady and Whiteside (1982). Thus, argillic horizon expression could not be properly interpreted. Pedon C4 was characterized by a nearly uniform distribution of total, coarse, and fine clay with depth and consequently did not meet the minimum ratio criteria. Pedon B2 did have an

increase in clay content with depth and did meet the minimum clay ratio requirement.

Fine clay/total clay ratio: The fine clay to total clay ratio should be about one third or more in an argillic horizon as compared to an eluvial horizon (Soil Survey Staff, 1975). Pedons M1 and C1 of Hydrosequence 1 both have substantial increases in the ratio occurring in the B horizon, while Pedon P1 has a nearly uniform ratio from the A horizon to the B21g horizon (Table 2). The increase in the ratio in the B22g horizon of Pedon P1 is probably due to a lithologic discontinuity (Table 1).

In Hydrosequence 2 pedon M2 shows an increase in the ratio from the A to the Bt horizon, exceeding the minimum requirement. There is the possibility of a slight lithologic discontinuity between the A+B horizon and the B21t horizon (Table 2). Pedon C2 has a nearly uniform distribution of the ratio with depth, as does Pedon P2.

Pedon M3 does not meet the minimum requirement for the increase in the ratio between the eluvial horizon and the argillic horizon. The Bt/A ratios of total clay, coarse clay, and fine clay all point to a distinct enrichment in the Bt horizon however. Pedons C3 and B1 both meet the minimum requirement for the increase in the ratio in the Bt horizon.

Pedon C4 has a distribution of the ratio with depth that shows a slight decrease in the upper Bt horizon. The Bt/A horizon fine clay to total clay ratio, averaged over the entire Bt horizon, is 1.0 indicating no relative

enrichment or depletion of fine clay to total clay in the B horizon. The Bt/A ratios of total clay and of fine clay are like wise 1.0 in Pedon C4.

Pedon B2 shows a slight increase in the fine clay to total clay ratio occurring in the Bt horizon. The ratio does not meet the minimum criteria suggested by Soil Taxonomy (Soil Survey Staff, 1975). A possible lithologic discontinuity between the A and B21tg horizons may exist (Table 1), however, the ratio remains the same when calculated between the Bt and C horizons. The B/A and B/C coarse clay ratios are both approximately 1.0 for Pedon B2 indicating lack of movement of coarse clay into the B horizon. The B/A and B/C fine clay ratios, however, do indicate a translocation and subsequent accumulation of fine clay in the B horizon.

Clay films and argillans: All of the pedons except P1 and P2 were described in the field as having clay films on B horizon peds. Micromorphologic examination of thin sections substantiated this evidence (Table 2). Table C4 of Appendix C gives the description of argillans found to occur in B horizon and C horizon thin section samples. Pedons M1 and C1 both contained more than one percent oriented clay in cross section, the minimum requirement for an argillic horizon suggested in Soil Taxonomy (Soil Survey Staff, 1975). Pedon P1 did not meet the minimum requirement as it had less than 0.5 percent oriented clay.

In Hydrosequence 2 pedons M2 and C2 both contained adequate amounts of oriented clay to meet the criteria.

Pedon P2 contained approximately 0.5 percent oriented clay, less than the minimum requirement.

Pedons M3 and C3 both contain adequate amounts of oriented clay in cross section in order to meet the minimum requirement. Pedon B1 of Hydrosequence 3 contained 0.5 to 1 percent oriented clay in thin section which does not quite make the minimum requirement. The pedon did, however, have clay films coating Bt horizon peds.

Pedon M4 had 1 - 2 percent oriented clay in the Bt horizon and field described clay films on ped surfaces. Thus it met the minimum requirement. Pedon C4 had less than 0.5 percent oriented clay in all samples of the B and C horizons. Pedon B2 had 0.5 to 1 percent oriented clay in thin section, not quite enough for the minimum requirement. This pedon, like Pedon B1, did have clay films coating Bt horizon peds as described in the field.

Pedons M1, C1, M2, and C3 definitely have an argillic horizon, according to the data in Table 2 and the criteria proposed in Soil Taxonomy (Soil Survey Staff, 1975). Pedons P1, P2, and C4 clearly do not have an argillic horizon, any sign of clay eluviation-illuviation. Pedons M3, M4, C2, B1, and B2 were questionable, each with some of the data not meeting the proposed criteria. Pedon M3 and C2 did not have the increase in the fine clay to total clay ratio of one third or more but did have sufficient oriented clay and clay films. Pedon M4 was formed in stratified material (Table 2). It may be nearly impossible to tell if the profile characteristics are the result of pedogenesis or of parent

material stratification. Pedon M4 did have field described clay films and 1-2% oriented clay in thin section however. Pedon B1 meets all of the particle size requirements for having an argillic horizon and was described in the field as having clay films on B horizon ped surfaces. It does not have the one percent or more of oriented clay in cross section. Pedon B2 does not meet the fine clay to total clay ratio increase requirement, and in addition does not have the necessary amount of oriented clay in cross section.

Cf/Ct ratio criteria: An increase in the fine clay to total clay ratio of one third or more has been used to indicate a preferential movement of fine clay over coarse clay in the genesis of an argillic horizon (Soil Survey Staff, 1975). An examination of the data in Table 2 shows that coarse clay migrates also. Values of >1.0 for the B/A coarse clay ratio indicate an enrichment of coarse clay in the illuvial B horizon. Examination of the data in Table C1 shows that horizons of maximum coarse clay and maximum fine clay often coincide, although the maximum fine clay content tends to extend somewhat deeper in some pedons. Asady and White side (1982) concluded that the ratio of B horizon fine clay/total clay to A horizon fine clay/total clay of $\geq$1.3 was set too high. In pedons where clay films were described in the field this ratio was not greater than 1.3 or more. The authors suggested that a fine clay B2/A ratio seems to be more suitable, and is more consistent with the total clay ratio used in the definition of an argillic horizon. They

also suggest a value of ≥ 1.1 would be more suitable for defining argillic horizons in Michigan.

If one examines the factors involved in the calculation of these ratios, hereafter referred to as I/E indices, the inherited weakness in the assumption of the translocated clay being mainly of the fine clay fraction becomes clear.

Basically, the I/E index is:

$$\frac{\dfrac{\text{Fine clay in B}}{\text{Total clay in B}}}{\dfrac{\text{Fine clay in A}}{\text{Total clay in A}}} = \frac{\dfrac{F \cdot B}{T \cdot B}}{\dfrac{F \cdot A}{T \cdot A}} \qquad (1)$$

which upon rearranging becomes

$$\frac{F \cdot B}{F \cdot A} \times \frac{T \cdot A}{T \cdot B} \quad \text{or} \quad \frac{F \cdot B}{F \cdot A} \times \frac{1}{\dfrac{T \cdot B}{T \cdot A}} \qquad (2)$$

If we let $F = \frac{F \cdot B}{F \cdot A}$ and $T = \frac{T \cdot B}{T \cdot A}$ then equation 2 becomes $\frac{F}{T}$ the I/E index.

Where T = 1.0 an increase in fine clay of one third or more ($F \geq 1.3$) would make F/T = 1.3. However, in an argillic horizon T must be ≥ 1.2 (Soil Survey Staff, 1975) and is often considerably larger. If T = 1.2 then F must be ≥ 1.6 in order to achieve the minimum requirement of F/T = 1.3. Where T > 2.0 as in pedons M1, M2, M3, C3, and B1, F must be >2.6 which is the case in pedons M1, M2, C3, and B1. Pedon M3 has an F value of 2.5 and thus does not make the F/T (I/E index) minimum value of 1.3. All of the other clay ratios indicate quite a substantial enrichment of total, coarse, and fine clay in the B horizon however. If coarse clay and fine clay were to translocate in equal proportions (F = T) then F/T would equal 1.0 indicating that the horizon was not

an argillic horizon. This seems to be awkward as a soil could have T and F values equal to say 3.0 and still not be considered as having an argillic horizon. The F/T $\geq$1.3 criteria should be reexamined in view of the assumption that fine clay is translocated preferentially to coarse clay. In extremely uniform parent materials, such as loess, this assumption may be feasible. In heterogeneous material such as till the assumption would be difficult to prove.

Micromorphology criteria: Table C4 of Appendix C gives the description of thin section observations. The well drained M pedons all contain sufficient amounts of optically oriented clay to meet the criteria of $\geq$1.0%. Most of the argillans described in these pedons are ped and channel argillans with moderate to strong continuous orientation, indicative of illuviation (Brewer, 1964). In pedons C1, C2, and C3 the argillans mainly have moderate discontinuous orientation, with a few samples having strong continuous, moderate continuous, weak continuous, and weakly striated orientation. These argillans are still indicative of illuviation, however, they are not quite as well expressed as those in the well drained M pedons. The poorly drained P1, P2, B1, B2, and C4 pedons have few argillans in their cross sections. Those that are present are weakly expressed with common weakly straited orientation. Some of the pedons have moderate discontinuous orientation, although the amounts of these argillans are very small. Smeck et al. (1981) described weakly striated organo-argillans in the B2 horizon of a Brookston soil. Micromorphology failed to

indicate illuviation having occurred in three out of the five soils they examined, although particle size data, and field observations indicated otherwise. The evidence did indicate the existence of numerous stress cutans. Stress cutans are very difficult to distinguish from clay films in the field, particularly under poorly drained conditions. McKeague et al. (1981) suggest that, until uniform standards can be developed, micromorphological estimates of illuvial clay should serve as guidelines only, not be applied too strictly. Where particle size evidence and field observations of clay films indicate an argillic horizon, an amount of apparently illuvial clay in thin section of <1.0% but >0.5% should not keep the horizon from being a Bt horizon.

Summary of Argillic Horizon Expression: In light of the foregoing discussion it is concluded that pedons M1, C1, M2, M3, C3, B1, and B2 are characterized by the existence of an argillic horizon. Pedons P1, P2, C2, and C4 do not have an argillic horizon. Three groupings of the soils are possible from this based on the moisture regimes of the pedons: Soils characterized by a udic moisture regime and the occurrence of an argillic horizon (U-W), soils characterized by an aquic moisture regime and the occurrence of an argillic horizon (A-W), and soils characterized by an aquic moisture regime without the occurrence of an argillic horizon (A-W/O). The mean values of the total clay B/A ratio, fine clay B/A ratio, the I/E index of these groups are given in Table 3, along with the standard deviation.

Analysis of variance was determined for the values utilizing a random block design for missing data (pedons P2, and M4). The least significant difference test (LSD) was applied to the values at the .95 confidence level (Steele and Torrie 1978).

The mean value of the total clay B/A ratios for the U-W group was greater than that for the A-W group indicating a greater degree of argillic horizon development in the U-W group, although the difference between the two groups was not found to be significantly different at the .95 confidence level. Similarly, the mean value of the total clay B/A ratios for the A-W group was greater than that for the A-W/O group. This difference was found to be significantly different at the .95 confidence level. The mean value for the A-W/O group is approximately 1.0 which is to be expected in a soil without an argillic horizon. For the fine clay B/A ratios the mean value for the U-W group was larger than the value for the A-W group which, in turn, was larger than the mean value for the A-W/O group. The difference between the U-W and A-W groups was not found to be significantly different at .95 confidence level, while the difference between the A-W and A-W/O groups is borderline-right at the LSD value. For the I/E index the mean value for the U-W group was slightly more than that for the A-W group, but not significantly different at the .95 confidence level. The value for the A-W group was greater than that for the A-W/O group, although the two were not significantly different at the .95 confidence level. For the I/E index only the U-W and A-W/O groups were found to be significantly different. The I/E index mean value for the A-W/O group is to be expected.

The total clay B/A and fine clay B/A ratios indicate a stronger degree of argillic horizon expression towards the well drained unic moisture regime pedons. This expression decreases for the more poorly drained pedons characterized by an aquic moisture regime.

Table 3. Mean values of clay ratios

Group	Total B/A	Fine B/A	I/E Index
U-W	2.23±.06	3.60±.98	1.43±.29
A-W	1.88±.44	2.42±.50	1.35±.13
A-W/O	1.03±.15	0.97±.15	1.0
$LSD_{.05}$	.77	1.45	.40

D. Clay Mineralogy

Table 4 gives the relative abundance of various clay minerals in the pedons, as determined by X-ray diffraction. The relative distribution of interstratified clay minerals was not determined. Some amounts undoubtedly occur. X-ray diffraction peaks between 11-12.5 Å upon Mg saturation-glycerol solvation were observed in some pedons, although the peaks were diffuse and not very distinct.

Vermiculite formation by the in situ weathering of illite is one process influencing the clay mineral distribution in all of the pedons except P2, C4 and B1. The

Table 4. Relative abundance* of clay minerals in pedons.

** ZONE	*** FRAC	HYDROSEQUENCE 1	2	3	4
		M IV V I K Q†	M IV V I K Q	M IV V I K Q	M IV V I K Q
		Pedon M1	Pedon M2	Pedon M3	Pedon M4
A	1	0 1 4 4 5 2			
	2	0 1 5 4 3 1	0 0 3 3 2 2	0 1 4 3 3 1	2 1 3 2 2 1
	1	0 1 3 4 5 2			
	2	0 1 3 5 3 1	0 0 2 4 3 1	0 1 3 4 3 0	1 1 1 5 2 0
	3	0 1 3 5 3 0	0 0 0 5 2 0	0 1 2 4 3 1	0 1 1 4 3 0
B	1	0 1 2 4 5 2			
	2	0 1 2 5 3 0	0 0 2 5 2 0	0 0 2 4 3 0	1 1 2 4 2 0
	3	0 1 3 5 3 0	0 0 1 5 2 0	0 1 1 5 2 0	
C	1	0 1 3 4 4 1			
	2	0 1 2 5 4 2	0 1 1 4 3 1	0 1 2 4 3 1	0 0 0 5 3 0
		Pedon C1	Pedon C2	Pedon C3	Pedon C4
A	1	0 1 3 3 4 2			
	2	0 1 3 3 3 1	0 1 4 3 3 0	0 1 3 1 3 1	3 0 0 5 2 0
	1	0 1 2 3 3 1			
	2	0 1 4 3 2 0	0 1 2 4 2 0	1 1 2 4 3 0	4 1 0 3 2 0
	3				4 1 0 4 1 0
	1	0 1 3 3 3 1			
B	2	0 0 3 4 2 1	0 1 2 4 2 0	0 1 2 4 3 0	3 1 0 5 2 0
	3	0 0 0 5 2 1		0 1 1 5 2 0	5 1 0 3 1 0
	1				4 1 0 4 1 0
	2				
	3				
C	1	0 1 1 4 3 1			
	2	0 1 2 4 2 0	0 0 2 5 2 0	1 1 2 4 3 1	3 1 1 4 2 0
		Pedon P1	Pedon P2	Pedon B1	Pedon B2
A	1	0 0 3 4 2 1			
	2	0 1 4 4 1 1	0 0 2 4 3 1	1 1 1 5 2 0	5 1 5 5 2 0
	1	0 1 2 4 2 1			
	2	0 1 2 5 2 1	0 1 2 4 2 0	2 1 1 4 2 0	5 1 1 5 1 0
	3			4 1 1 3 2 0	3 0 0 4 3 1
	1	0 0 3 4 2 1			
B	2	0 0 3 5 2 0	0 1 2 4 3 0	3 1 1 4 2 0	5 1 5 5 2 0
	3			4 1 1 3 2 1	5 1 0 3 2 0
	1	0 0 3 3 3 1			5 1 5 5 2 0
	2	0 0 3 4 2 0			3 1 2 3 2 0
	3				
C	1	0 0 3 4 2 1			
	2	0 1 3 5 1 1	0 1 2 5 2 1	1 1 1 4 3 0	3 1 1 5 2 0

** - A - A horizon, B - B horizons with subdivisions, C - C horizon.
*** - 1 - coarse clay, 2 - matrix fine clay, 3 - clay film fine clay.
† - M - montmorillonite, IV - interstratified vermiculite, V - vermiculite, I - illite, K - kaolinite, Q - quartz.
* - 0 - nonexistant, 1 - trace, 2 - minor, 3 - moderate, 4 - abundant, 5 - extremely abundant.

weathering process seems to occur to a greater extent in the well drained pedons M1 and M3. Both of these pedons formed from till material relatively rich in illite with relatively abundant kaolinite, as evidenced by the C horizon clay mineral suites. Vermiculite occurs only in relatively minor amounts in these horizons, along with trace quantities of quartz and hydroxy interlayer vermiculite. The relatively large amounts of vermiculite in the A horizon as compared to the C horizon, along with a relative depletion of illite in the A horizon suggest that some of the illite has weathered in situ to form vermiculite. Vermiculite abundance decreases with depth which indicates that the weathering process is most intense in the A horizon. A similar distribution was reported by Klages and White (1957) and Kodama (1979).

Moderately-well drained Pedon M2 displays a similar vermiculite distribution, relatively rich in the A horizon decreasing to a minimum in the C horizon. Its parent material contains relatively less vermiculite than the parent materials of pedons M1 and M3. The relative enrichment of vermiculite in the A horizon of Pedon M2 along with the relative depletion of illite in the same horizon indicate that vermiculite is forming by the in situ weathering of illite. Pedon M2 displays evidence of somewhat less illite weathering to form vermiculite, as the two occur in relatively equal proportions in the A horizon. This contrasts with the A horizons of pedons M1 and M3 which have clay mineral suites dominated by vermiculite. Well

drained Pedon M4 is stratified to an extent as to make interpretation of the clay mineral distribution difficult at best (Table 1). The occurrence of montmorillonite in this pedon suggests that perhaps some of the illite has weathered beyond the vermiculite stage and formed montmorillonite (Ross, 1965).

The somewhat-poorly drained pedons C1 and C3 also show a somewhat milder extent of vermiculite formation. Both pedons display only a slight enrichment of vermiculite in the A horizon as compared to the C horizon, and illite depletion in the A horizon is only of minor extent. The parent materials for these two pedons are mineralogically similar to each other and to those of pedons M1 and M3. Pedon C3 has trace amounts of montmorillonite and Pedon C1 lacks abundant amounts of kaolinite.

The vermiculite distribution in Pedon C2 suggests relatively extensive vermiculite formation in the A horizon as compared to the B horizon. The distribution of illite indicates that it is weathering in the A horizon. A lithologic discontinuity between the B and IIC horizon prevents making a comparison between the latter and the A horizon.

Vermiculite is entirely absent in Pedon C4, while montmorillonite shares the relative dominance with illite. Perhaps this montmorillonite may have formed by the alteration of vermiculite that was weathered from illite, or the montmorillonite could have formed directly from illite without going through the vermiculite stage.

Pedons P1 and P2, both poorly drained, show slight evidence of vermiculite formation by in situ weathering of illite. Pedon P1, formed in somewhat stratified material (Table 1), shows a slight relative enrichment of vermiculite in the A horizon as compared to the B21g horizon none the less. This along with a slight relative depletion of illite in the A horizon compared to the B21g horizon suggests that some of the illite is weathering to form vermiculite. Previous data (Table 2) suggests that translocation of clay was not an active process in Pedon P1. In Pedon P2 vermiculite formation does not appear to have occurred at all. The relative abundance of vermiculite throughout the solum remains the same as in the C horizon, as does illite to a certain extent. The parent material for Pedon P2 is mineralogically similar to that for Pedon C1. This relative distribution of clay minerals remains nearly constant with depth in Pedon P2 while it changes towards the surface of Pedon C1 favoring vermiculite enrichment at the expense of the illite abundance. A lithologic discontinuity between the A horizon and B horizon in Pedon P2 makes this interpretation somewhat difficult.

In poorly drained Pedon B1 vermiculite formation does not appear to have occurred at all. Evidence for this lies in the occurrence of vermiculite in tract amounts distributed uniformly from the parent material to the A horizon. Montmorillonite occurs in relative abundance in the B horizon of Pedon B1, but only occurs in trace amounts in the A and C horizons. This means that the

montmorillonite is either being formed in the B horizon, or it is being formed in the A horizon and is quickly translocated or both. The relative distribution of illite suggests that it is not being weathered at all in the A horizon, as it clearly dominates the A horizon mineral suite.

Vermiculite is rather abundant in poorly drained Pedon B2 and is relatively rich in the A horizon as compared to the C horizon. Montmorillonite is also abundant in Pedon B2, being most abundant in the solum and least abundant in the C horizon.

The translocation of various clay mineral assemblages is another process affecting the clay mineral distribution in all of the pedons except P1, C2, P2, and C4. In the well drained pedons M1 and M3 vermiculite, illite, and kaolinite all translocate in significant proportions as evidenced by the mineral suites of the clay films. Illite dominates the clay mineral suites of the clay films whereas vermiculite dominates that of the A horizon. This indicates that illite is preferentially translocated to a slight extent. Vermiculite and kaolinite are still translocated to a significant extent as evidenced by their relatively moderate abundance in the clay films. Moderately-well drained Pedon M2 shows a more preferential translocation of illite as evidenced by clay films consisting of nearly all illite with relatively minor amounts of kaolinite and essentially no vermiculite. This is in contrast to the A horizon where vermiculite and illite are in relatively equal proportions.

Well drained Pedon M4 is stratified to an extent where interpretation of translocation is nearly impossible.

In the somewhat-poorly drained pedons C1 and C3 illite is preferentially translocated relative to vermiculite and kaolinite. Evidence for this is the relative dominance of illite in the clay film clay mineral suite. Kaolinite is translocated only in relatively minor amounts while vermiculite is translocated in trace amounts, or not at all. The A horizons of these pedons consist of a relatively uniform distribution of vermiculite, illite, and kaolinite. The C horizons are dominated by illite with relatively moderate amounts of kaolinite and minor amounts of vermiculite. Clay films were not collected from peds in Pedon C2, although they were described in the field. Particle-size data indicated that fine clay had not been translocated in Pedon C2 (Table 2).

In pedon C4 both montmorillonite and illite dominate the clay mineralogy of the clay films, with montmorillonite being translocated preferentially a little deeper than illite. Particle-size analysis and thin section observations (Table 2) indicate that Pedon C4 did not have an argillic horizon although clay films were described in the field.

Neither Pedon P1 or Pedon P2, both poorly drained, had a particle-size distribution that indicated translocation of clay, although the lithologic discontinuity in Pedon P1 made this interpretation difficult. Pedons B1 and B2, both poorly drained, did show evidence of translocation however.

Both pedons contain large amounts of montmorillonite, which appears to be easily translocated as evidenced by its relative dominance of the clay film-clay mineral suites. This is especially true for Pedon B1 which shows a depletion of montmorillonite in the A horizon while the clay films are rich in montmorillonite. At the same time illite is enriched in the A horizon while it is least abundant in the clay films, indicating that it is translocated only to a very minor extent. In Pedon B2 the clay films are generally dominated by montmorillonite and illite while vermiculite occurs in the clay films only in minor amounts. Kaolinite is also translocated to some extent. The abundant amounts of montmorillonite, vermiculite, and illite in the A horizon indicates that this is a horizon of mineral formation and not of mineral depletion.

In summary, pedons M1, M3, and C3 are all formed in similar parent material as evidenced by the C horizon clay mineral suites. The same is true for pedons C1, P1, and P2, and for pedons M2, and B1. Pedons C2, M4, and C4 are hard to evaluate due to lithologic discontinuities and Pedon B2 was formed in material unique to it and Pedon C4.

The general trend of illite weathering in situ to form vermiculite is most strongly expressed in the well drained pedons, followed by the moderately-well drained and somewhat-poorly drained pedons; and is least expressed in the poorly drained pedons. An exception to this would be the somewhat-poorly drained pedon C2 where the formation of vermiculite resembles that in the well drained pedons. In

two of the poorly drained pedons B1 and B2 the physiochemical conditions are right for the formation of montmorillonite in the sola.

The general trend of clay translocation involved mixed mineral assembleges with a slight preference towards illite, being translocated in the well drained pedons. In the moderately-well drained and somewhat-poorly drained pedons illite is preferentially translocated relative to kaolinite and especially to vermiculite. In the poorly drained pedons where translocation has occurred montmorillonite seems to be preferentially translocated relative to illite and kaolinite and especially to vermiculite.

E. Argillic Horizon Genesis and Soil Classification

All of the pedons except P2 were formed in loamy-textured calcareous parent material. Pedon P2 was formed in apparently non-calcareous loamy parent material. The dispersibility of soil clays depends, to a large extent, on the magnitude of the zeta potential. A high zeta potential favors ready dispersibility (Marshall, 1977). The leaching of soluble constituents, especially calcium carbonate, is therefore a major pedogenic process that has occurred in these pedons. Figure 2 shows the change in percent base saturation and pH, with depth, for the twelve pedons.

The well-drained and moderately-well drained M pedons are the most extensively leached as indicated by the low base saturation and low pH in the upper horizons. Evidently the flux of moisture through these pedons was sufficient to remove not only calcium but Mg and K also (Table C2,

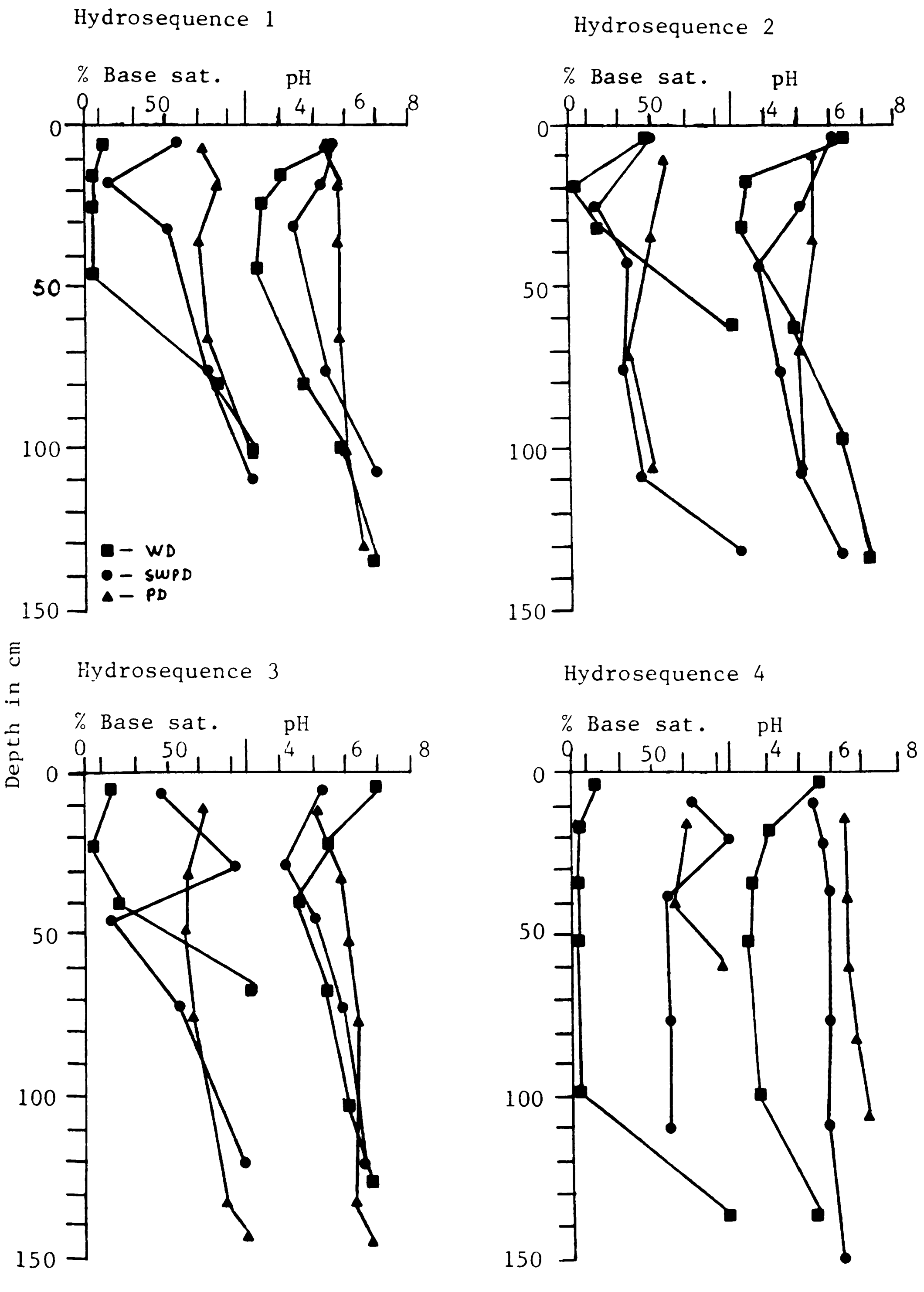


Figure 2. Change in % base saturation and pH (0.1N KCl) with depth.

Appendix C). This depletion in bases from the upper horizons also resulted in the relatively acidic conditions existing in these horizons. Organic matter enrichment in the A1 horizons accounts for the higher base saturation and pH relative to the immediate underlying horizons.

The somewhat-poorly drained pedons C1, C2, and C3 are characterized by an overall relatively higher percent base saturation than the M pedons. The general trend is the same, with a minimum value in the eluvial zone and B21t horizons and increasing percent base saturation towards the C horizon. Maximum values occur at the base of the solum while the C horizons all contain free calcium carbonate. Organic matter enrichment in the A1 horizons results in the relatively higher values occurring there. The distribution of pH values in the pedons is similar to that in the well-drained M pedons, but the values are somewhat higher than those in the M pedons.

Pedons P1, B1, B2, and C4, all poorly drained, show a relative distribution of base saturation and pH values that indicates leaching was not very extensive. The percent base saturation in these pedons reach a slight minimum in the B2 horizons but, except for Pedon C4, never go below 60 meq/100 g. The pH values are relatively higher than for the C and M pedons.

Pedon P2 was formed in noncalcareous material as evidenced by the relatively low percent base saturation and lack of free calcium carbonate in the C horizon. The pedon does show a lack of extensive leaching in that both the

percent base saturation and the pH values are relatively uniform with depth.

The leaching of exchangeable bases and carbonates favors the dispersibility of the soil clays, by raising the relative zeta potential. Zeta potential is related to the electrolyte concentrations in the soil solution. Dispersion is also favored by the wetting of an originally dry soil (Thorp et al., 1959; Arnold, 1965; and Daniels et al., 1967). Hydration of the clay particles during wetting leaves them in a relatively dispersed state.

Once clays are in a dispersed state, in the form of a relatively stable sol, they are capable of being translocated. The energy for this translocation is gravity in the form of downward moving moisture fronts (Runge, 1973). This translocation of dispersed particles out of a zone is defined as eluviation. If there are no restrictions or impedence to this impedence to this flow then the moisture front is free to carry suspended particles to a depth where the suspension is either flocculated, or the moisture is depleted, or both. Scrivner et al. (1973) determined that the upper boundary of the Bt horizon in some Missouri soils was a function of the depth of penetration of summer rains, while the lower boundary coincided with the depth which underwent one annual cycle of wetting and drying.

Figure 3 shows the estimated depth to the zone of saturation in the 12 pedons during the period from September

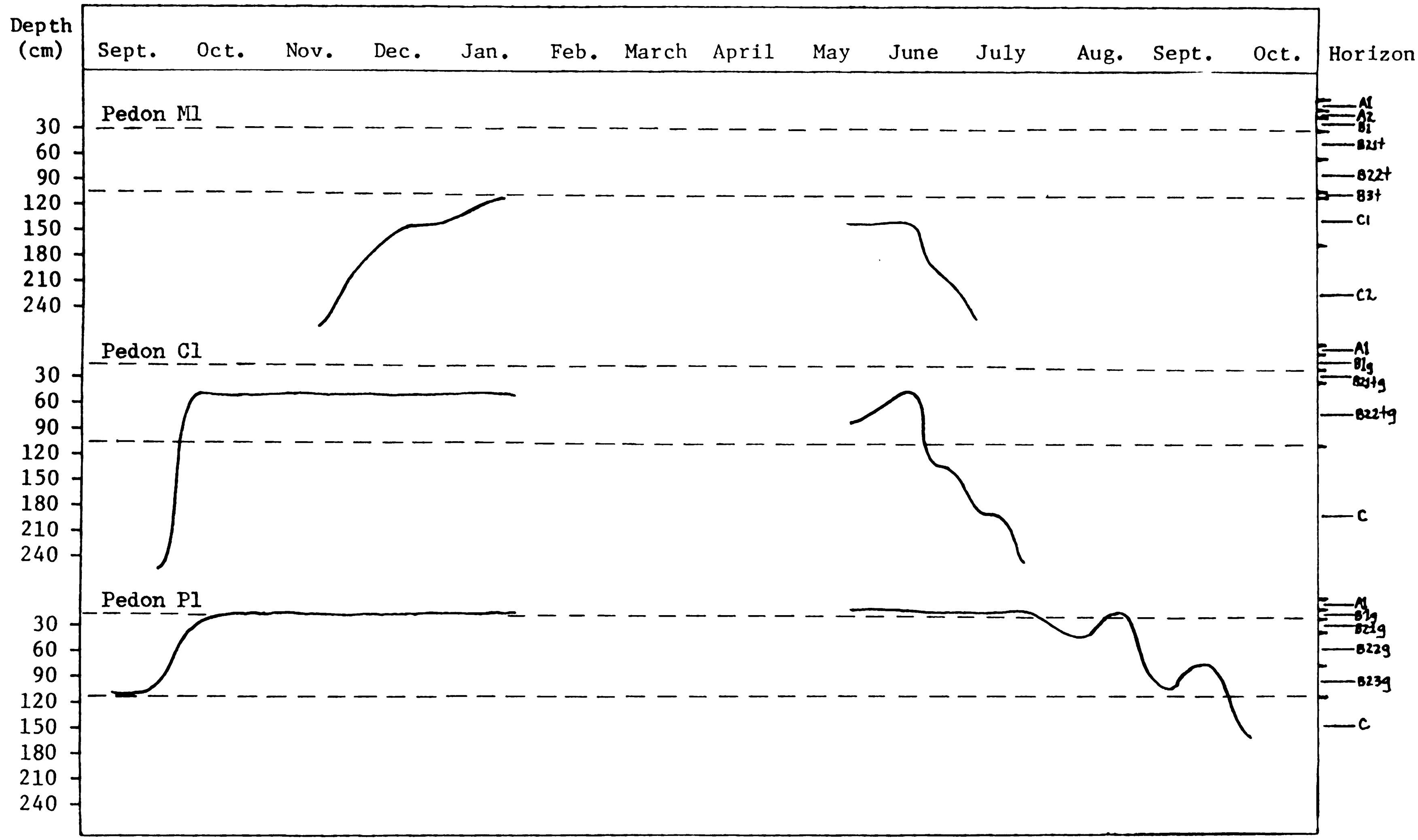
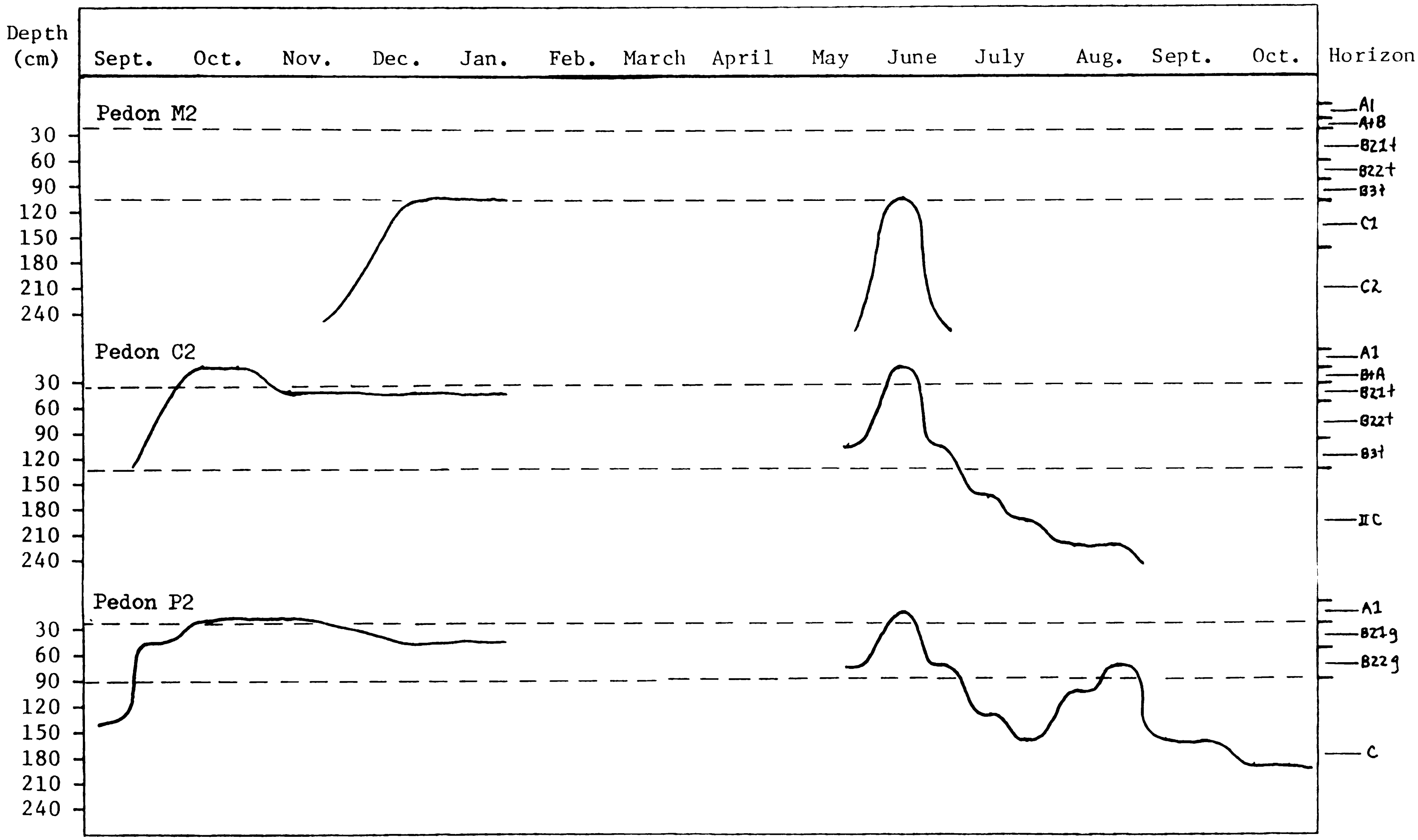
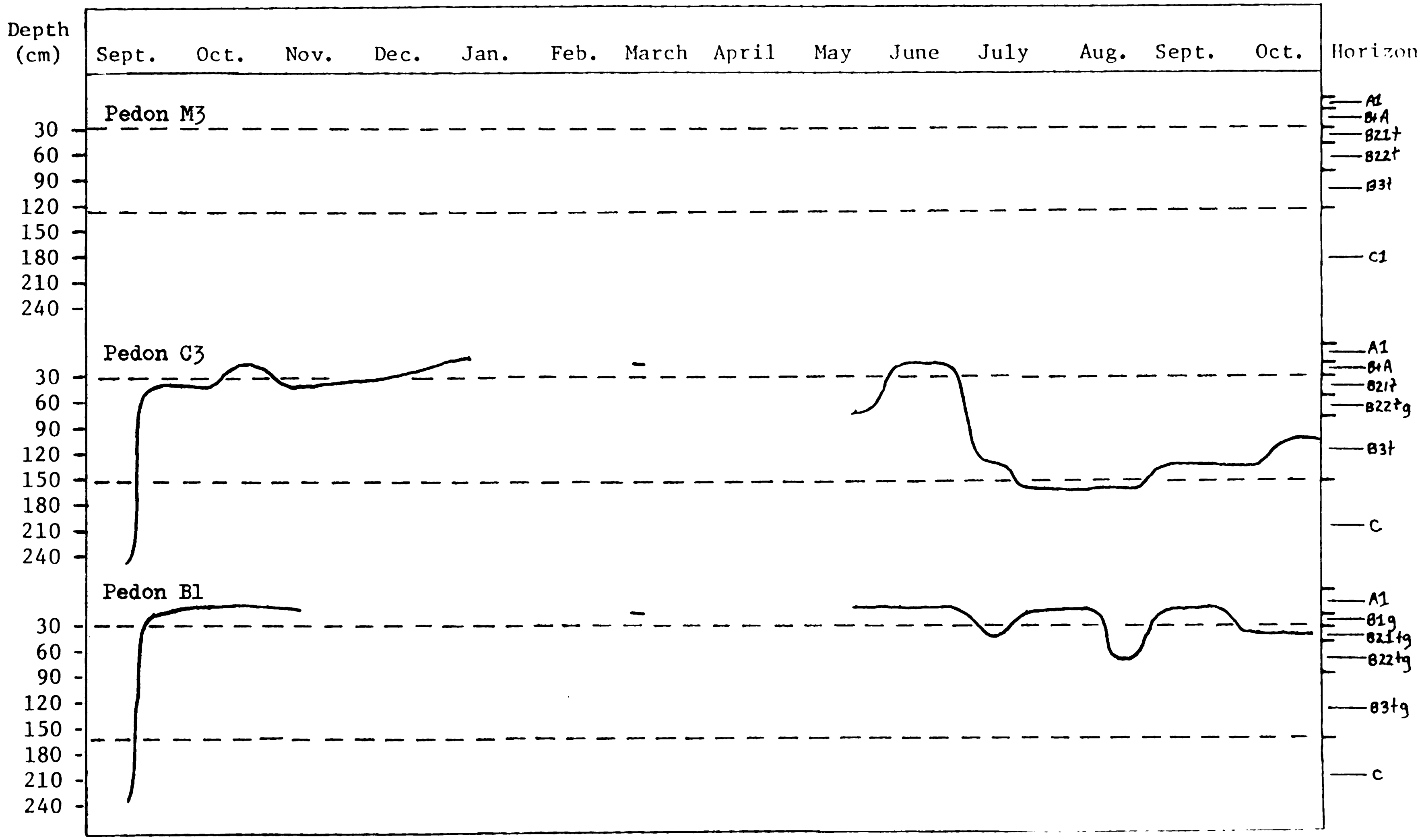


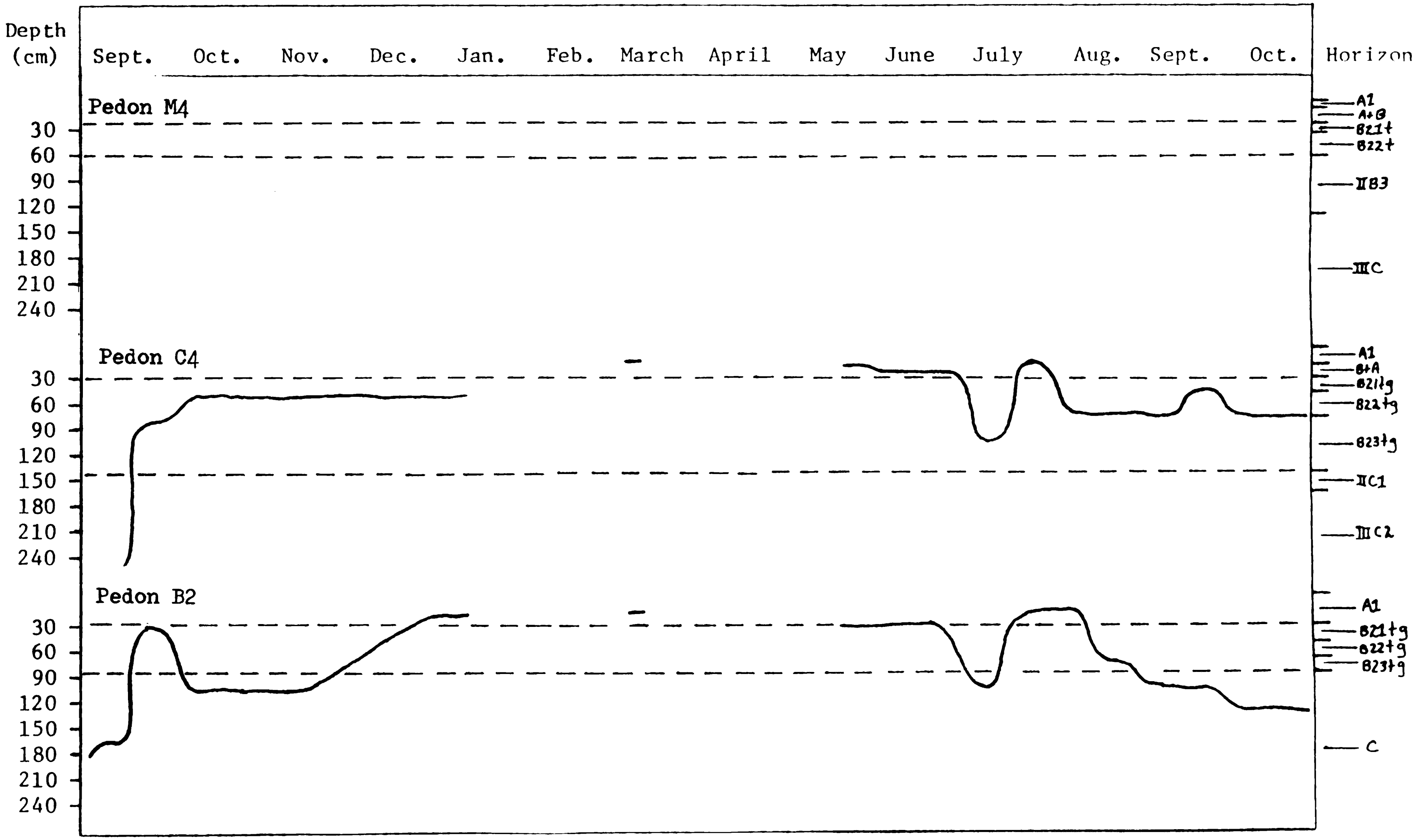
Figure 3. Estimated depth to zone of saturation from Sept. 1981 through Oct. 1982.



(Figure 3 Cont'd.).



(Figure 3 Cont'd.).



(Figure 3 Cont'd.).

1981 through October 1982. The well-drained and moderately-well drained M pedons were characterized by a deep subsolum zone of saturation throughout the year. Pedons M1 and M2 do show a zone of saturation that approaches the base of the solum during the late winter and early spring, whereas pedons M3 and M4 do not have a zone of saturation appearing within 2.4 meters of the surface for the same period. All of the M pedons have a profile free of water saturation in the period from midsummer through autumn. This period is when the soil is relatively dry, a condition that favors dispersion upon wetting (Thorp et al., 1959; Arnold, 1965; and Daniels et al., 1967). Thus, the moisture fronts that do result from any rain are capable of moving freely through the solum carrying suspended particles, without the water table acting as a physical barrier. Occasionally rains are heavy enough to where the moisture fronts are capable of carrying suspended particles further into the C horizon along joints and fractures. Evidence for this comes from the occurrence of cutans, including argillans, in the larger channels of the C horizon (Buol and Hole, 1961; Smith and Wilding, 1972).

The somewhat-poorly drained pedons C1, C2, and C3, were all characterized by a more persistent zone of saturation than the M pedons. This zone of saturation during the period from October 1981 to June 1982 occupied the zone of part or all of the B horizon. In some cases the zone of saturation persisted to the surface. Thus, the depth of the zone of saturation in these profiles was shallow for a longer

portion of the year than for the M pedons. The depth to the zone of saturation does decrease in the late summer, but rises earlier in the autumn. Moisture fronts, carrying suspended particles, would be retarded in their downward flow during those portions of the year when the zone of saturation was shallow.

The poorly-drained pedons P1, P2, B1, and B2 and Pedon C4 were all characterized by a relatively shallow and persistent zone of saturation throughout most of the year. Except for a very brief periods in the autumn the zone of saturation was well within the B horizon and even at the surface in some cases. Thus except for those brief periods when the zone of saturation was below the solum moisture fronts were not able to percolate into the B horizon.

The depth and duration of the zone of saturation was consistent with the soil drainage classes of the pedons, as determined by profile morphology, although the data was only for a 13-month period. The seasonal pattern of depth and duration of the zone of saturation was similar to that observed by other workers on similar soils formed in glacial till materials (Wilde et al., 1953; Fehrenbacher et al., 1969; Fritton and Olson, 1972; Thorp and Gamble, 1972; and Mackintosh and Hulst, 1978). The general pattern seems to be a relatively high water table in the spring with the drop coinciding with the onset of forest transpiration. The driest periods occur from the midsummer through midautumn. The rise of the water table in late autumn persists until the late spring.

In the well-drained and moderately-well drained M pedons moisture fronts are free nearly year round to move through the solum, leaching soluble constituents, and eluviating the clay particles that disperse as a result of the leaching. The eluviation and subsequent illuviation process results from the throughflow of moisture fronts and the profile distribution of soluble bases. Illuviation occurs as a result of the lowering of the zeta potential due to the increased concentration of electrolytes in the horizons at the base of the solum. This distribution of electrolytes is in itself a function of the extent of leaching and the penetration of moisture fronts. Illuviation also occurs as a result of the relative depletion of the water in the moisture front, a function of the precipitation and evapotranspiration patterns.

Enough energy moves through pedons M1 and M3 to eluviate-illuviate a variety of clay minerals, as evidenced by clay film mineral suites (Table 4). In Pedon M1 the eluviation and leaching process is extensive enough to form an A2 (E) horizon underlain by a well developed argillic horizon (Table 2). Thus, Pedon M1 is classified as a Typic Hapludalf. In Pedon M3 the eluvial zone encroached on the argillic horizon to give a transitional B&A (B/E) horizon, and is classified as Glossoboric Hapludalf. In the moderately-well drained pedon M2 the eluviation-illuviation process selectively moves illite as evidenced by its dominance of the clay mineral suite (Table 4). This pedon is classified as a Glossoboric Hapludalf as it has the characteristic A&B (E/B) transitional horizon. Pedon M4 was stratified to the point where evaluation of eluviation-illuviation was difficult. The pedon was classified as a Glossoboric Hapludalf although its relative base saturation was similar to that of a more extensively weathered Ultisol. The depth to free $CaCO_3$ kept it from being classified as an Ultisol. Table 4 gives the family and subgroup classification of the pedons.

The somewhat-poorly drained pedons C1, C2, and C3 have a somewhat more restrictive moisture regime as far as the throughflow of moisture fronts goes. This is shown by the lack of extensive leaching, as in the M pedons, and by less extensively developed argillic horizons. The mean I/E index of pedons C1, C2, and C3 is less than that for pedons M1 and M2 indicating less development of argillic horizons in the somewhat-poorly drained pedons. The zone of saturation is persistent for long enough periods of time that the energy for eluviation-illuviation is only active for a period of time in the late summer and early autumn. Illite is selectively translocated in pedons C1 and C3 as indicated by the clay film mineral suite (Table 4). This is in contrast to the well drained pedons M1 and M3 where vermiculite, illite, and kaolinite are all translocated. Pedon C1 is classified as a Udollic Ochraqualf as the A1 horizon is too dark to be classified as an Aeric Ochraqualf. Pedon C3 is also classified as a Udollic Ochraqualf for the same reason. Particle-size analysis indicated a lack of an argillic horizon in Pedon C2, although clay films were described in the field oriented clay was observed in thin section, and the pedon was sampled as an Alfisol. For this reason Pedon C2 is classified as an Aeric Haplaquept.

Table 5 Classification of the Pedons

Pedon	family	subgroup
M1	fine-loamy, mixed, mesic	Typic Hapludalf
C1	fine-loamy, mixed, mesic	Udollic Ochraqualf
P1	fine-silty, mixed, mesic	Mollic Haplaquept
M2	file-silty, mixed, mesic	Glossoboric Hapludalf
C2	coarse-loamy, mixed, mesic	Aeric Haplaquept
P2	fine-loamy, mixed, mesic	Humic Haplaquept
M3	fine-loamy, mixed, mesic	Glossoboric Hapludalf
C3	coarse-loamy, mixed, mesic	Udollic Ochraqualf
B1	fine-loamy, mixed, mesic	Typic Argiaquoll
M4	coarse-loamy, mixed, mesic	Glossoboric Hapludalf
C4	fine-loamy, mixed, mesic	Mollic Haplaquept
B2	fine-loamy, mixed, mesic	Typic Argiaquoll

In the poorly-drained pedons P1, P2, B1, B2, and C4 the throughflow of moisture fronts are restricted nearly year round except for brief periods in the early autumn. This means that the energy required to leach and eluviate-illuviate clay cannot penetrate into the B horizon zones. Base saturation data and pH values indicate that these are relatively unleached pedons. Particle-size data (Table 2) and thin section evidence indicated Pedons P1 and P2 did not have argillic horizons, although lithologic discontinuities make this interpretation difficult. The I/E indices for these pedons in near unity indicating lack of argillic horizon development. The increased organic matter content of the A1 horizon and lack of an argillic horizon resulted in Pedon P1 being classified as a Mollic Haplaquept. Pedon

P2 was similar, but because of its relatively low overall base saturation was classified as a Humic Haplaquept. Pedon C4 was classified as a Mollic Haplaquept even though an argillic horizon was described in the field. Particle-size analysis and thin section observations failed to substantiate the field description.

Pedons B1 and B2 were both classified as Typic Argiaquolls because of their organic matter distribution and the occurrence of an argillic horizon in each one. The I/E indices of these pedons were similar to those of pedons C1 and C3 but less than pedons M1 and M2 indicating moderate development of the argillic horizon. These pedons did not differ from pedons P1, P2, and C4 as to extent of leaching (Figure 1), and thus reflect the lack of throughflowing moisture fronts throughout most of the year. Pedons B1, B2, and C4 do differ from pedons P1 and P2 in that montmorillonite is present in the former and lacking in the latter. Montmorillonite is easily translocated as evidenced by its relative abundance in the clay film clay mineral suites of pedons B1 and B2 (Table 4). Thus whatever energy is able to move through the sola of pedons B1 and B2 is enough to result in the dispersion and eluviation of montmorillonite and some illite also. Possibly, the high hydration condition of montmorillonite in natural settings, allows for its relatively easy dispersion, and that which is dispersed moves with the drop in the zone of saturation occurring in the autumn.

Chapter 5 SUMMARY AND CONCLUSION

Argillic horizons are most strongly expressed in pedons M1 and M3, both well drained, and in Pedon M2 which is moderately well drained. Evidence for this comes from B to A horizon ratios of total clay and fine clay/total clay plus thin section observations. Pedon M3 failed to meet the criteria of having a B to A fine clay/total clay ratio, the I/E index, of 1.3 or more as suggested in Soil Taxonomy (Soil Survey Staff, 1975). As all of the other criteria are more than adequately met by Pedon M3 it is suggested that the I/E index criteria of 1.3 or more be reevaluated. Pedon M4 was stratified to an extent where argillic horizon evaluation was considered to be difficult at best.

Argillic horizons are moderately expressed in pedons C1 and C3, both somewhat-poorly drained, and in pedons B1 and B2, both poorly drained. Evidence for this comes from the B to A total clay ratio, the I/E index, and from thin section observations, although the latter were not conclusive for pedons B1 and B2. The mean values of the total clay B/A ratios and the I/E indices for these pedons were less than for pedons M1, M2, and M3, but were not significantly different at the .95 confidence level. Pedon B2 appeared to be borderline between having and not having an argillic horizon as the I/E index was 1.2 slightly less than the

criteria suggested in Soil Taxonomy (Soil Survey Staff, 1975).

Argillic horizons were lacking altogether in pedons P1, P2, and C4, all poorly drained, and in Pedon C2 which is somewhat-poorly drained. Evidence for this comes from values of near unity for the B to A total clay ratios and the I/E index, plus a lack of argillan development in all of the pedons except Pedon C2. The mean values of these two ratios were determined to be significantly different from those values for pedons M1, M2, and M3. The mean value of the total clay B/A ratios of pedons P1, P2, C4, and C2 differed significantly from that for values of pedons C1, C3, B1, and B2, while the mean value of the I/E index did not differ significantly in this comparison. Pedon C2 had the necessary argillan development for the argillic horizon criteria, but lacked the total clay B/A ratio and I/E index values necessary to define an argillic horizon. These ratios calculated across the transitional B/A (B/E) horizon B2 horizon boundary make the possible definition of an argillic horizon marginal.

Poorly-drained pedons P1, P2, and C4 were characterized by a lack of argillic horizon development while poorly-drained pedons B1 and B2 both had an argillic horizon as defined in Soil Taxonomy (Soil Survey Staff, 1975).
The profile drainage class of these four pedons, determined from morphologic properties, and the depth and duration to the zone of saturation from September 1981 until October 1982 were fairly similar. Thus, the potential for the

penetration and throughflow of energy in the form of moisture fronts should be similar in all of the poorly-drained pedons.

Pedons B1, B2, and C4 all have montmorillonite in their mineral suites, to the point where it is dominant with illite, while pedons P1 and P2 lack montmorillonite, and are dominated by illite and vermiculite. In pedons B1 and B2 the clay film mineral suites contain both montmorillonite, indicating that montmorillonite is eluviated to a significant extent. The eluvial zone in Pedon B2 was dominated by montmorillonite, vermiculite, and illite, indicating that montmorillonite and illite are eluviated to a significant extent while vermiculite is not. In Pedon C4 montmorillonite and illite occurred in the clay film mineral suite, similar to the B horizon matrix and the eluvial horizon.

In the somewhat-poorly drained pedons C1 and C3 illite clearly dominates the clay film mineral suite in contrast to the B horizon matrix which also contains significant amounts of vermiculite and kaolinite. The eluvial horizon also contains significant vermiculite and kaolinite along with illite, which indicates that illite is preferentially eluviated out of the A horizon and illuviated into the B horizon.

Moderately-well drained Pedon M2 had a clay film mineral suite clearly dominated by illite. A similar conclusion for pedons C1 and C3 can be drawn in that illite

is preferentially translocated. In contrast the well-drained pedons M1 and M3 have clay film mineral suites containing significant amounts of vermiculite and kaolinite along with an abundance of illite. This indicates that eluviation-illuviation processes involve all three minerals rather than preferentially translocating any one mineral.

The ability of energy, in the form of downward moving moisture fronts, to move through the solum determines the particle size distribution of these pedons. Where this energy is not restricted in any form, as in the well-drained pedons, the leaching of soluble constituents and the eluviation-illuviation of clay occurs to an extent that forms a well defined argillic horizon. The leaching of soluble bases from the eluvial zone results in the easy translocated with moving moisture fronts. The zone of maximum deposition of clay is dependent on the penetration of the moisture fronts, otherwise clay films would be distributed evenly throughout the profile. The distribution of the flocculating bases has a similar relationship to the penetration of moisture fronts. In the well-drained pedons the depth of penetration of the critical summer and autumn rains determines the depth of the zone of maximum deposition of clay.

In the somewhat-poorly and poorly drained pedons the zone of saturation functions as a physical barrier to the downward flow of moisture fronts. If the zone of saturation is deep during a part of the summer-autumn period then moisture fronts are able to leach the pedon and carry

suspended clay particles. In this case the depth of penetration of the moisture front would be a function of the magnitude of the rains as is the case with the well drained pedons. If the zone of saturation is shallow during most of this time period, as in the poorly-drained pedons, then the moisture front is impeded in its downward flow, and is not effective in leaching and eluviation-illuviation. Nonleached soils have enough bases in their eluvial zone, or A horizon, to prevent good dispersion of the clay fraction. Thus, even if the moisture fronts were able to move through the pedon the clay particles would not be in a form that allows for easy eluviation. In addition, if the zone of saturation is fairly shallow the A horizon will not be very dry, a condition that does not favor dispersion. Poorly-drained conditions do not allow the soil to dry enough, between precipitation events, to create the surface tension forces required to form good distinct argillans. Thin section observations of poorly-drained pedons indicate poorly oriented often striated argillans as compared to the strongly oriented argillans occurring in pedons with better drainage.

In order for argillic horizons to form under poorly-drained conditions a different mechanism than the potential for throughflow of moisture fronts is required. Differential dispersion based on the clay mineral type may be one possible explanation. If montmorillonite, in its usual state of high hydration, is relatively easily dispersed and does not require the extensive leaching for

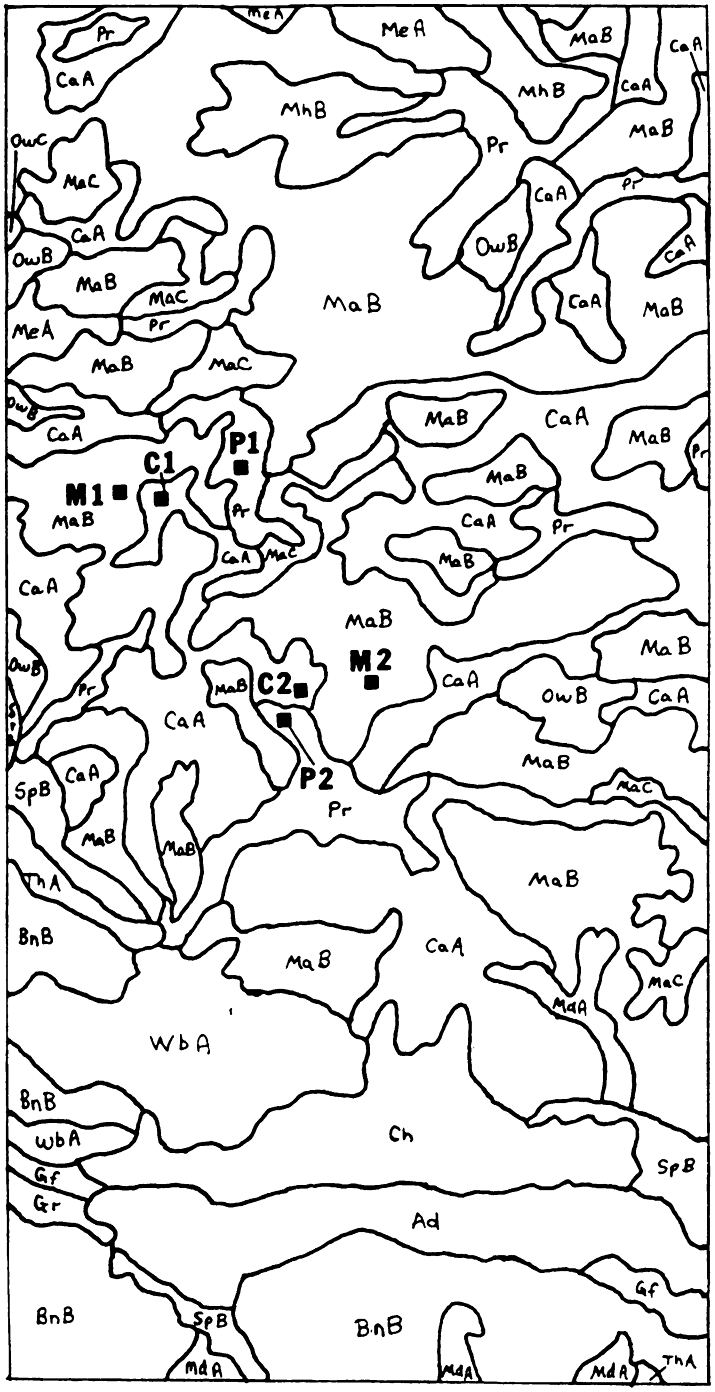
dispersion; then perhaps it can be eluviated during the very brief periods in autumn when the zone of saturation drops.

It may even be translocated with the zone of saturation during the autumn when the soils dry somewhat.

Further study is needed into actually monitoring the cyclic throughflow of the moisture fronts in relation to the depth and duration of the zone of saturation. Such a study would require determination of the actual moisture content of the horizons of the studied pedons at various degrees of wetness. Using this information along with soil profile moisture determinations made on a regular basis with the neutron moisture meter, one should be able to monitor the flux of various precipitation events through the soil.

APPENDICES

APPENDIX A



<u>Legend</u>

Ad	Adrian muck
BnB	Boyer sandy loam, 0-6% slopes
CaA	Capac loam, 0-4% slopes
Ch	Cohoctah loam
Gf	Gilford sandy loam
Gr	Granby loamy sand
MaB	Marlette loam, 2-6% slopes
MaC	Marlette loam, 6-12% slopes
MdA	Matherton loam, 0-3% slopes
MeA	Metamora-Capac sandy loams, 0-4% slopes
MhB	Metea loamy sand, 2-6% slopes
OwB	Owosso-Marlette sandy loams, 2-6% slopes
OwC	Owosso-Marlette sandy loams, 6-12% slopes
Pr	Parkhill loam
SpB	Spinks loamy sand, 0-6% slopes
ThA	Thetford loamy sand, 0-3% slopes
WbA	Wasepi sandy loam, 0-3% slopes

Figure A1 - Soil map and pedon location in sec. 10 and sec. 15 T. 8 N. R. 3 W., Clinton County (After Pregitzer, 1978).

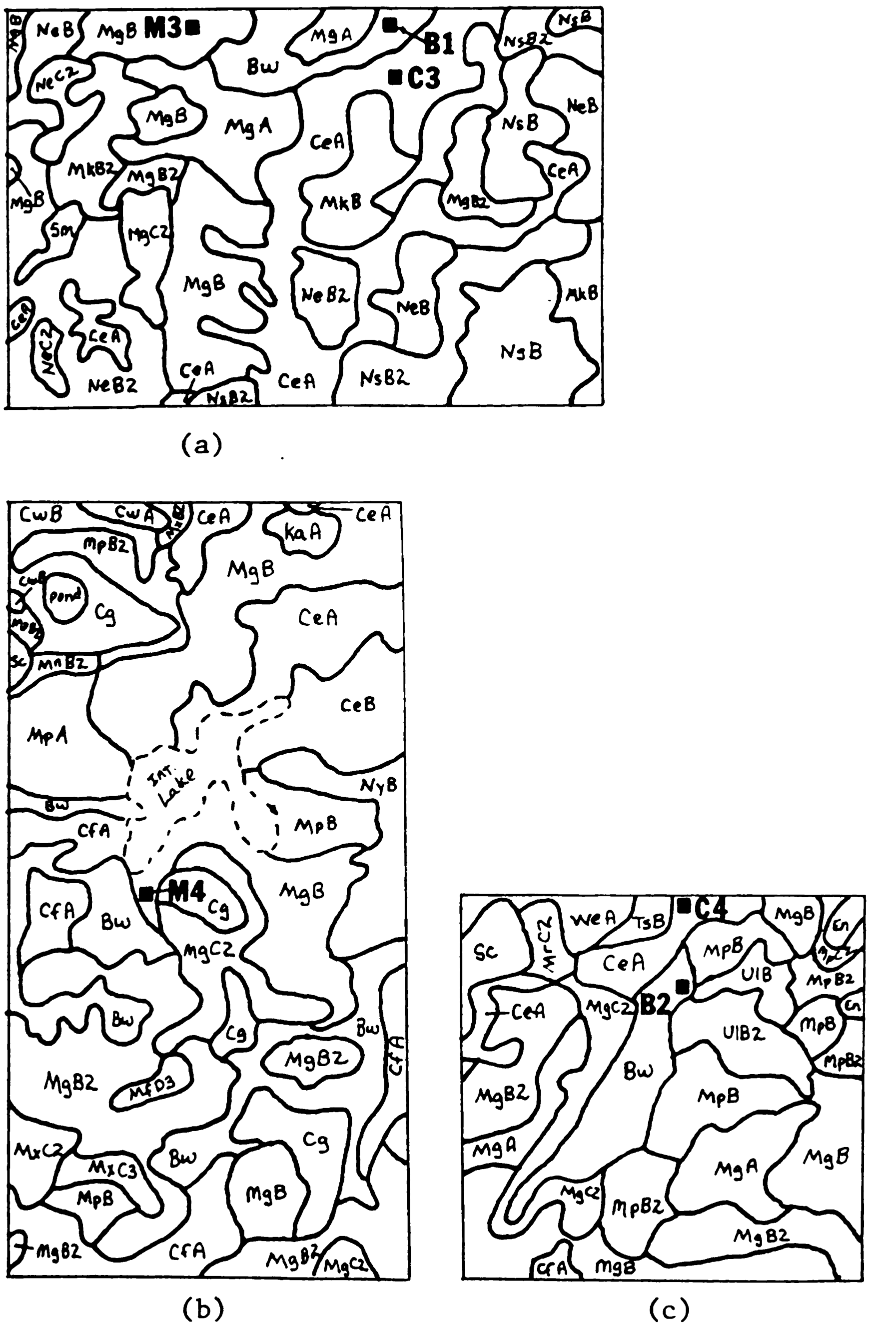


Figure A2 - Soil map and pedon locations in a) NW¼ and W½ NE¼ sec. 3 T. 8 N., R. 6 W., b) SE¼ sec. 10 and NE¼ sec. 15 T. 7 N., R. 8 W., and c) NE¼ sec. 20 T. 7 N., R. 8 W.,Ionia County.(After Frelkeld and Alfred,1967).

Legend for Figure A2

BW	Brookston loam
CeA	Capac loam, 0-2% slopes
CeB	Capac loam, 2-6% slopes
CfA	Capac sandy loam, 0-2% slopes
Cg	Carlisle muck
CwA	Coral sandy loam, 0-2% slopes
CwB	Coral sandy loam, 2-6% slopes
En	Ensley loam
KaA	Kawkawlin loam, 0-2% slopes
MfD3	Marlette clay loam, 12-18% slopes, severely eroded
MgA	Marlette loam, 0-2% slopes
MgB	Marlette loam, 2-6% slopes
MgB2	Marlette loam, 2-6% slopes, moderately eroded
MgC2	Marlette loam, 6-12% slopes, moderately eroded
MkB	Marlette sandy loam, 2-6% slopes
MkB2	Marlette sandy loam, 2-6% slopes, moderately eroded
MnB2	McBride loamy sand, 2-6% slopes, moderately eroded
MpA	McBride sandy loam, 0-2% slopes
MpB	McBride sandy loam, 2-6% slopes
MpB2	McBride sandy loam, 2-6% slopes, moderately eroded
MpC2	McBride sandy loam, 6-12% slopes, moderately eroded
MrC2	Menominee loamy sand, 6-12% slopes, moderately eroded
MxB2	Montcalm loamy sand, 2-6% slopes, moderately eroded
MxC3	Montcalm loamy sand, 6-12% slopes, severely eroded
NeB	Nester loam, 2-6% slopes
NeB2	Nester loam, 2-6% slopes, moderately eroded
NeC2	Nester loam, 6-12% slopes, moderately eroded
NsB	Nester sandy loam, 2-6% slopes
NsB2	Nester sandy loam, 2-6% slopes, moderately eroded
NyB	Newaygo sandy loam, 2-6% slopes
Sc	Saranac silt loam
Sm	Sims clay loam
TsB	Tuscola soils, 2-6% slopes
WeA	Wasepi sandy loam, 0-2% slopes

APPENDIX B

Pedon M1

Sampled as: Marlette, Glossoboric Hapludalf, fine-loamy, mixed, mesic.
Classification: Typic Hapludalf, fine-loamy, mixed, mesic.
Location: Essex Township, Clinton County, NE¼SW¼SE¼NW¼SW¼ sec. 10 about 30 m north of edge of cultivated field, T. 8 N., R. 3 W.
Geomorphic position: Summit position on moraine system, gently sloping.
Drainage: Well drained.
Vegetation: <u>Quercus alba</u>, <u>Carya ovata</u>, and <u>Quercus rubra</u>.
Parent material: Calcareous glacial till.
Sampled by: D. Cremeens and O. Doumbia. June 12, 1981.
Remarks: C2 horizon collected with bucket auger. Approximately 5-8% coarse fragments throughout pedon.

A1 (A)	0-10 cm. Dark grayish brown (10YR 4/2) silt loam (38% sand, 12% clay); moderate fine granular structure; friable; common fine roots; clear wavy boundary.
A2 (E)	10-19 cm. Pale brown (10YR 6/3) silt loam (39% sand, 11% clay); weak fine platy structure; very friable; few fine roots; gradual wavy boundary.
B1 (BE)	19-28 cm. Yellowish brown (10YR 5/4) loam (37% sand, 16% clay); moderate medium subangular blocky structure; friable; few medium roots; clear smooth boundary.
B21t (Bt1)	28-64 cm. Dark yellowish brown (10YR 4/4) loam (33% sand, 20% clay); moderate medium subangular blocky structure; firm; thin discontinuous dark grayish brown (10YR 4/2) clay films; few medium roots; gradual smooth boundary.
B22t (Bt2)	64-97 cm. Dark brown (10YR 4/3) clay loam (22% sand, 30% clay); moderate medium subangular blocky structure; firm; thick continuous dark grayish brown (10YR 4/2) clay films; few fine roots; gradual smooth boundary.
B3t (BC)	97-104 cm. Dark brown (10YR 4/3) silt loam (24% sand, 22% clay); moderate coarse subangular blocky structure; firm; few fine faint mottles; thin patchy very dark gray brown (10Y 3/2) clay films; thin lime coats; slightly effervescent; gradual smooth boundary.
C1 (C1)	104-165 cm. Brown (10YR 5/3) silt loam (30% sand, 13% clay); weak coarse platy structure; firm; few fine faint mottles; thick lime coats; moderately effervescent.
C2 (C2)	165 + cm. Dark brown (10YR 4/3) silt loam (27% sand, 14% clay); firm; many coarse faint mottles; thick lime coats; strongly effervescent.

Pedon Cl

Sampled as: Capac, Aeric Ochraqualf, fine-loamy, mixed, mesic.
Classification: Udollic Ochraqualf, fine-loamy, mixed, mesic.
Location: Essex Township, Clinton County, NW¼SW¼SE¼NW¼SW¼ sec. 10 about 38 m north of edge of cultivated field, T. 8 N., R. 3 W.
Geomorphic position: Foot slope in moraine system, gently sloping.
Drainage: Somewhat poorly drained.
Vegetation: *Quercus alba*, *Acer saccharum*, and *Carya ovata*.
Parent material: Calcareous glacial till.
Sampled by: D. Cremeens and O. Doumbia. June 23, 1981.
Remarks: C horizon collected with bucket auger. Approximately 5% coarse fragments throughout pedon. BA and Btgl horizons have 50/50 mix of matrix colors and mottles.

Al (A) — 0-12 cm. Very dark grayish brown (10YR 3/2, 10YR 5/2 dry) loam (34% sand, 18% clay); moderate fine granular structure; friable; clear wavy boundary.

Blg (BA) — 12-25 cm. Light brownish gray (2.5Y 6/2) loam (35% sand, 18% clay); moderate medium subangular blocky structure; friable; many medium prominent strong brown (7.5YR 5/6) mottles; clear wavy boundary.

B21tg (Btgl) — 25-40 cm. Light olive gray (5Y 6/2) loam (29% sand, 26% clay); moderate medium subangular blocky structure; firm; many coarse prominent strong brown (7.5YR 5/8) mottles; clear wavy boundary.

B22tg (Btg2) — 40-110 cm. Gray (5Y 5/1) clay loam (25% sand, 30% clay); moderate medium subangular blocky structure; firm; common coarse distinct strong brown (10YR 4/6) mottles; common medium continuous dark grayish brown (10YR 4/2) clay films; gradual wavy boundary.

C (C) — 110 + cm. Brown (10YR 5/3) silt loam (23% sand, 18% clay); augered structure appears medium blocky; firm; moderately effervescent.

Pedon P1

Sampled as: Parkhill, Mollic Haplaquept, fine-loamy, mixed, mesic.
Classification: Mollic Haplaquept, fine-silty, mixed, mesic.
Location: Essex Township, Clinton County, SW¼SE¼SW¼NE¼SW¼ sec. 10 about 26 m north of edge of woods and lowest spot in field, T. 8 N., R. 3 W.
Geomorphic position: Toe slope position on moraine system, nearly level.
Drainage: Poorly drained.
Vegetation: Quercus alba, Populas tremuloides, and Quercus bicolor with ground cover of Cyperus esculentus.
Parent material: Calcareous glacial till.
Sampled by: D. Cremeens and O. Doumbia. July 7, 1981.
Remarks: Some parts of A horizon appeared to have faint mottles. BA horizon delineated by observed increase in mottles, gley colors, and tendency of structure toward blocky type. Less than 5% coarse fragments throughout pedon.

A1 (A)	0-16 cm. Very dark gray (10YR 3/1) to very dark grayish brown (10YR 3/2) (10YR 5/1 dry) silt loam (11% sand, 26% clay); moderate medium granular structure; friable; abrupt wavy boundary.
B1g (BA)	16-25 cm. Dark grayish brown (2.5Y 4/2) silty clay loam (10% sand, 28% clay); moderate fine subangular blocky structure; friable; few medium gray (10YR 5/1) and few fine strong brown (7.5YR 5/6) distinct mottles; clear wavy boundary.
B21g (Bg1)	25-46 cm. Dark gray (5Y 4/1) silty clay loam (10% sand, 31% clay); strong medium angular blocky structure parting to moderate fine angular blocky; firm; common medium prominent strong brown (7.5YR 4/6) and common fine distinct dark yellowish brown (10YR 4/4) mottles; clear wavy boundary.
B22g (Bg2)	46-85 cm. Gray (N 5/0) silty clay loam (5% sand, 39% clay); strong medium angular blocky structure parting to strong fine angular blocky; firm, many coarse prominent strong brown (7.5YR 4/6) and common fine distinct dark yellowish brown (10YR 4/4) mottles; gradual wavy boundary.
B23g (Bg3)	85-119 cm. Gray (N 5/0) silty clay loam (20% sand, 30% clay); moderate medium angular blocky structure parting to moderate fine angular blocky; firm; many medium distinct dark yellowish brown (10YR 4/4 and 10YR 4/6) mottles; gradual wavy boundary.
C (C)	119 + cm. Brown (10YR 5/3) silt loam (24% sand, 18% clay); moderate medium angular blocky structure; very firm; many coarse distinct gray (N 5/0) and common medium distinct strong brown (7.5YR 4/4) mottles; moderately effervescent.

Pedon M2

Sampled as: Marlette, Glossoboric Hapludalf, fine-loamy, mixed, mesic.
Classification: Glossoboric Hapludalf, fine-silty, mixed, mesic.
Location: Essex Township, Clinton County, NE¼NW¼NW¼NW¼NE¼ sec. 15 about 23 m south of Island Road, T. 8 N., R. 3 W.
Geomorphic position: Summit position on moraine system, gently sloping.
Drainage: Moderately well drained.
Vegetation: Acer saccharum, Tilia americana, and Quercus rubra.
Parent material: Calcareous glacial till.
Sampled by: D. Cremeens and O. Doumbia. July 1, 1981.
Remarks: C2 sample collected with bucket auger. Thin lens (1 cm thick) of strong brown (7.5YR 4/6) loamy sand found at 85 cm depth. Less than 2% coarse fragments throughout pedon.

A1 (A) 0-12 cm. Dark grayish brown (10YR 4/2) silt loam (26% sand, 14% clay); moderate medium granular structure; friable; abrupt wavy boundary.

A+B (E/B) 12-26 cm. Yellowish brown (10YR 5/6) and brownish yellow (10YR 6/6) silt loam (22% sand, 18% clay); weak medium platy structure parting to moderate medium subangular blocky; friable; clear wavy boundary.

B21t (Bt1) 26-40 cm. Dark yellowish brown (10YR 4/4) silty clay loam (13% sand, 31% clay); moderate medium subangular blocky structure; firm; thin patchy dark grayish brown (10YR 4/2) clay films; gradual smooth boundary.

B22t (Bt2) 40-84 cm. Dark yellowish brown (10YR 4/4) silty clay loam (15% sand, 31% clay); moderate medium angular blocky structure; firm; few fine faint yellowish brown (10YR 5/4) mottles; thick continuous dark grayish brown (10YR 4/2) clay films; clear wavy boundary.

B3t (BC) 84-108 cm. Dark yellowish brown (10YR 4/4) silt loam (17% sand, 26% clay); strong coarse platy structure parting to moderate medium angular blocky; firm; few medium faint yellowish brown (10YR 5/4) mottles; thick continuous dark grayish brown (10YR 4/2) clay films; moderately effervescent; clear wavy boundary.

C1 (C1) 108-165 cm. Grayish brown (10YR 5/2) silt loam (16% sand, 22% clay); strong coarse platy structure parting to moderate medium subangular blocky; very firm; few medium faint yellowish brown (10YR 5/4) mottles; strongly effervescent.

C2 (C2) 165 + cm. Brown (10YR 5/3) silt loam (15% sand, 23% clay); very firm; common fine faint yellowish brown (10YR 5/4) mottles; strongly effervescent.

Pedon C2

Sampled as: Capac, Aeric Ochraqualf, fine-loamy, mixed, mesic.
Classification: Aeric Haplaquept, coarse-loamy, mixed, mesic.
Location: Essex Township, Clinton County, NW¼NW¼NE¼NE¼NW¼ sec. 15 about 30 m south of Island Road, T. 8 N., R. 3 W.
Geomorphic position: Foot slope position on moraine system, gently sloping.
Drainage: Somewhat poorly drained.
Vegetation: _Acer rubrum_, _Acer saccharum_, _Quercus rubra_, and _Carya ovata_.
Parent material: Calcareous glacial till.
Sampled by: D. Cremeens. July 2, 1981.
Remarks: A horizon could have been divided into A1 and A2 based on size of structural units. Augered to approximately 2.5 m no C2 horizon detected. Water table at 1.8 m. About 10% coarse fragments throughout pedon except BC which contained slightly more and 2C which contained approximately 5%.

A1 (A)	0–22 cm. Very dark gray (10YR 3/1, 10YR 5/2 dry) loam (42% sand, 19% clay); moderate medium granular structure; friable; clear wavy boundary.
B+A (B/E)	22–32 cm. Brown (10YR 5/3) and light yellowish brown (10YR 6/4) sandy loam (54% sand, 13% clay); weak fine subangular blocky structure; friable; few fine faint mottles; clear smooth boundary.
B21t (Bt1)	32–53 cm. Brown (10YR 5/3) loam (49% sand, 18% clay); moderate medium angular blocky structure; firm; moderate medium distinct strong brown (7.5YR 4/4) and few medium faint grayish brown (10YR 5/2) mottles; medium continuous dark brown (7.5YR 4/2) clay films; clear wavy boundary.
B22t (Bt2)	53–97 cm. Dark grayish brown (2.5Y 4/2) loam (48% sand, 16% clay); moderate medium subangular blocky structure; friable; common medium distinct strong brown (7.5YR 4/4) and few medium distinct brown (10YR 5/3) mottles; medium discontinuous grayish brown (10YR 5/2) clay films; gradual smooth boundary.
B3t (BC)	97–125 cm. Dark grayish brown (2.5Y 4/2) sandy loam (57% sand, 14% clay); weak medium subangular blocky structure; friable; many medium prominent strong brown (7.5YR 5/6) and common fine distinct gray (N 5/0) mottles; thin discontinuous grayish brown (10YR 5/2) lining root channels; gradual smooth boundary.
IIC (2C)	125 + cm. Olive brown (2.5Y 4/4) silt loam (28% sand, 19% clay); moderate coarse platy structure breaking to weak coarse angular blocky; firm; common coarse distinct gray (N 5/0) and many fine distinct dark yellowish brown (10YR 4/6) mottles; moderately effervescent.

Pedon C2

Sampled as: Capac, Aeric Ochraqualf, fine-loamy, mixed, mesic.
Classification: Aeric Haplaquept, coarse-loamy, mixed, mesic.
Location: Essex Township, Clinton County, NW¼NW¼NE¼NE¼NW¼ sec. 15 about 30 m south of Island Road, T. 8 N., R. 3 W.
Geomorphic position: Foot slope position on moraine system, gently sloping.
Drainage: Somewhat poorly drained.
Vegetation: Acer rubrum, Acer saccharum, Quercus rubra, and Carya ovata.
Parent material: Calcareous glacial till.
Sampled by: D. Cremeens. July 2, 1981.
Remarks: A horizon could have been divided into A1 and A2 based on size of structural units. Augered to approximately 2.5 m no C2 horizon detected. Water table at 1.8 m. About 10% coarse fragments throughout pedon except BC which contained slightly more and 2C which contained approximately 5%.

A1 (A)	0-22 cm. Very dark gray (10YR 3/1, 10YR 5/2 dry) loam (42% sand, 19% clay); moderate medium granular structure; friable; clear wavy boundary.
B+A (B/E)	22-32 cm. Brown (10YR 5/3) and light yellowish brown (10YR 6/4) sandy loam (54% sand, 13% clay); weak fine subangular blocky structure; friable; few fine faint mottles; clear smooth boundary.
B21t (Bt1)	32-53 cm. Brown (10YR 5/3) loam (49% sand, 18% clay); moderate medium angular blocky structure; firm; moderate medium distinct strong brown (7.5YR 4/4) and few medium faint grayish brown (10YR 5/2) mottles; medium continuous dark brown (7.5YR 4/2) clay films; clear wavy boundary.
B22t (Bt2)	53-97 cm. Dark grayish brown (2.5Y 4/2) loam (48% sand, 16% clay); moderate medium subangular blocky structure; friable; common medium distinct strong brown (7.5YR 4/4) and few medium distinct brown (10YR 5/3) mottles; medium discontinuous grayish brown (10YR 5/2) clay films; gradual smooth boundary.
B3t (BC)	97-125 cm. Dark grayish brown (2.5Y 4/2) sandy loam (57% sand, 14% clay); weak medium subangular blocky structure; friable; many medium prominent strong brown (7.5YR 5/6) and common fine distinct gray (N 5/0) mottles; thin discontinuous grayish brown (10YR 5/2) lining root channels; gradual smooth boundary.
IIC (2C)	125 + cm. Olive brown (2.5Y 4/4) silt loam (28% sand, 19% clay); moderate coarse platy structure breaking to weak coarse angular blocky; firm; common coarse distinct gray (N 5/0) and many fine distinct dark yellowish brown (10YR 4/6) mottles; moderately effervescent.

Pedon P2

Sampled as: Parkhill, Mollic Haplaquept, fine-loamy, mixed, mesic.
Classification: Humic Haplaquept, fine-loamy, mixed, mesic.
Location: Essex Township, Clinton County, NE¼NE¼NW¼NE¼NW¼ sec. 15 about 38 m south of Island Road, T. 8 N., R. 3 W.
Geomorphic position: Toe slope position on moraine system, nearly level.
Drainage: Poorly drained.
Vegetation: Fraxinus americana, Quercus alba, Quercus bicolor, and Cyperus esculentus.
Parent material: Noncalcareous glacial till.
Sampled by: D. Cremeens and G. Lemme. July 3, 1981.
Remarks: No carbonates detected down to 2.4 m. C horizon delineated due to structureless condition. Approximately 5-10% coarse fragments throughout pedon.

A1 (A)	0-23 cm. Very dark grayish brown (10YR 3/2, 10YR 5/1 dry) silt loam (19% sand, 25% clay); strong very fine subangular blocky structure; firm; clear smooth boundary.
B21g (Bg1)	23-53 cm. Dark gray (5Y 4/1) loam (36% sand, 21% clay); moderate fine subangular blocky structure; firm; few fine distinct brown (10YR 4/3) and few fine prominent yellowish red (5YR 4/6) mottles; clear wavy boundary.
B22g (Bg2)	53-91 cm. Gray (5Y 5/1) loam (38% sand, 21% clay); moderate medium subangular blocky structure parting to moderate fine subangular blocky; common fine prominent strong brown (7.5YR 5/6) mottles; gradual wavy boundary.
C (C)	91 + cm. Dark grayish brown (2.5Y 4/2) loam (39% sand, 24% clay); structureless, massive; firm; common medium distinct brown (10YR 5/3) and strong brown (7.5YR 5/6) mottles with gray (N 6/0) coatings along root channels.

Pedon M3

Sampled as: Marlette, Glossoboric Hapludalf, fine-loamy, mixed, mesic.
Classification: Glossoboric Hapludalf, fine-loamy, mixed, mesic.
Location: Ronald Township, Ionia County, N½NE¼NW¼NW¼ sec. 3 about 30 m south of Bricker Road, T. 8 N., R. 6 W.
Geomorphic position: Summit position on till plain, gently sloping.
Drainage: Well drained.
Vegetation: *Quercus alba*, *Carya laciniosa*, and *Quercus palustris*.
Parent material: Calcareous glacial till.
Sampled by: D. Cremeens, O. Doumbia, and L. Gloden. July 8, 1981.
Remarks: Rather mature forest, 10-12% coarse fragments throughout pedon.

A1 (A)	0-12 cm. Dark grayish brown (10YR 4/2) loam (50% sand, 10% clay); moderate medium granular structure; friable; clear wavy boundary.
B+A (B/E)	12-32 cm. Dark brown (7.5YR 4/4) and grayish brown (10YR 5/2) loam (49% sand, 11% clay); weak medium platy structure parting to moderate fine subangular blocky; friable; clear wavy boundary.
B21t (Bt1)	32-48 cm. Strong brown (7.5YR 4/6) loam (44% sand, 19% clay); strong fine subangular blocky structure; friable; thin discontinuous dark brown (10YR 4/3) clay films; clear wavy boundary.
B22t (Bt2)	48-86 cm. Brown (7.5YR 5/4) loam (35% sand, 23% clay); moderate medium subangular blocky structure; firm; thick continuous dark brown (7.5YR 4/2) clay films; clear wavy boundary.
B3t (BC)	86-127 cm. Brown (10YR 5/3) silt loam (31% sand, 13% clay); strong medium platy structure parting to moderate medium angular blocky; friable; thin patchy dark brown (7.5YR 3/4) clay films; mildly effervescent; clear wavy boundary.
C (C)	127 + cm. Dark brown (10YR 4/3) loam (38% sand, 16% clay); strong coarse platy structure parting to moderate coarse angular blocky; friable; few fine distinct yellowish red (5YR 5/6) mottles; moderately effervescent.

Pedon C3

Sampled as: Capac, Aeric Ochraqualf, fine-loamy, mixed, mesic.
Classification: Udollic Ochraqualf, coarse-loamy, mixed, mesic.
Location: Ronald Township, Ionia County, N½SE¼NE¼NE¼NW¼ sec. 3 about 75 m south of Bricker Road, T. 8 N., R. 6 W.
Geomorphic position: Foot slope position on till plain, nearly level.
Drainage: Somewhat poorly drained.
Vegetation: *Carya cordiformis*, *Carya ovata*, *Quercus alba*, and *Populas tremuloides*.
Parent material: Calcareous glacial till.
Sampled by: D. Cremeens and O. Doumbia. July 9, 1981.
Remarks: C horizon collected with bucket auger. Water table at 150 cm. Large granite and basalt boulders near site. 10-15% coarse fragments throughout pedon.

A1 (A)	0-17 cm. Very dark gray (10YR 3/1, 10YR 4/1 dry) sandy loam (63% sand, 6% clay); moderate fine granular structure; friable; abrupt wavy boundary.
B+A (B/E)	17-33 cm. Dark yellowish brown (10YR 4/4) and brown (10YR 5/3) loam (45% sand, 13% clay); moderate fine subangular blocky structure; friable; thin patchy dark grayish brown (10YR 4/2) clay films along channels in the bottom of the horizon; clear wavy boundary.
B21t (Bt)	33-58 cm. Dark yellowish brown (10YR 4/4) loam (48% sand, 14% clay); moderate fine subangular blocky structure; firm; common fine distinct grayish brown (2.5Y 5/2) and common medium distinct strong brown (7.5YR 4/6) mottles; thin discontinuous dark brown (10YR 4/3) clay films; clear wavy boundary.
B22tg (Btg)	58-85 cm. Grayish brown (2.5Y 5/2) loam (51% sand, 14% clay); moderate medium subangular blocky structure; firm; moderate medium distinct dark yellowish brown (10YR 4/4) and common fine distinct grayish brown (10YR 5/2) mottles; thick discontinuous dark grayish brown (10YR 4/2) clay films; clear wavy boundary.
B3t (BC)	85-160 cm. Yellowish brown (10YR 5/6) sandy loam (54% sand, 9% clay); moderate coarse platy structure parting to moderate fine platy; friable; many fine distinct gray (10YR 6/1) and common medium distinct reddish brown (5YR 5/4) mottles; thin patchy reddish brown (5YR 5/4) clay films; slightly effervescent; clear smooth boundary.
C (C)	160 + cm. Pale brown (10YR 6/3) loam (51% sand, 8% clay); friable; moderate medium faint gray (10YR 6/1) and few coarse distinct dark brown (7.5YR 4/4) mottles; moderately effervescent.

Pedon B1

Sampled as: Brookston, Typic Argiaquoll, fine-loamy, mixed, mesic.
Classification: Typic Argiaquoll, fine-loamy, mixed, mesic.
Location: Ronald Township, Ionia County, NW¼NE¼NW¼NE¼NW¼ sec. 3 about 25 m south of Bricker Road, T. 8 N., R. 6 W.
Geomorphic position: Large depressional area on till plain, nearly level.
Drainage: Poorly drained.
Vegetation: Acer saccharum, Tilia americana, and Ulmus rubra.
Parent material: Calcareous glacial till.
Sampled by: D. Cremeens. September 3, 1981.
Remarks: Bt horizon appears bluish. Several sandy and gravelly lenses running through the immediate pedon area. C horizon has very thin 2 cm lenses of sandy loam. Area ponded until early August. 10 to 15% coarse fragments throughout pedon.

A1 (A)	0-25 cm. Black (10YR 2/1, 10YR 4/1 dry) sandy loam (61% sand, 9% clay); moderate medium granular; friable; abrupt wavy boundary.
B1g (BA)	25-40 cm. Dark gray (5Y 4/1) sandy loam (56% sand, 16% clay); moderate fine subangular blocky structure; friable; few fine distinct dark grayish brown (10YR 4/2) mottles; clear smooth boundary.
B21tg (Btg1)	40-58 cm. Olive gray (5Y 5/2) loam (51% sand, 19% clay); weak medium subangular blocky structure parting to moderate fine subangular blocky; friable; common medium distinct yellowish brown (10YR 5/4) mottles; medium discontinuous gray (5Y 5/1) clay films; gradual wavy boundary.
B22tg (Btg2)	58-95 cm. Gray (5Y 5/1) loam (47% sand, 20% clay); weak coarse prismatic structure parting to moderate medium subangular blocky; friable; few fine distinct dark yellowish brown (10YR 4/4) mottles; medium discontinuous gray (N 5/0) clay films on ped faces; gradual wavy boundary.
B3tg (BC)	95-170 cm. Gray (5Y 5/1) sandy loam (56% sand, 13% clay); weak fine subangular blocky structure; friable; many fine prominent strong brown (7.5YR 5/6) mottles; thin patchy olive gray (5Y 5/2) clay films along ped faces; clear wavy boundary.
C (C)	170 + cm. Dark yellowish brown (10YR 4/4) loam (46% sand, 16% clay); structureless, massive; firm; common medium distinct gray (N 5/0) mottles; moderately effervescent.

Pedon M4

Sampled as: Marlette, Glossoboric Hapludalf, fine-loamy, mixed, mesic.
Classification: Glossoboric Hapludalf, coarse-loamy, mixed, mesic.
Location: Keene Township, Ionia County, S½SE¼SW¼SE¼ sec. 10 about 268 m east of corner of Higgins and Richmond Roads 15 m south of fence dividing property of Sparks and Higgins, T. 7 N., R. 8 W.
Geomorphic position: Summit position on till plain, gently sloping.
Drainage: Well drained.
Vegetation: Fagus grandifolia, Fraxinus americana, and Populus grandidentata.
Parent material: Calcareous coarse textured glacial till with some water reworking.
Sampled by: D. Cremeens. September 15, 1981.
Remarks: About 12-15% coarse fragments in 2BC and C horizons, 8-10% throughout the rest of the pedon. E/B horizon consists of 70% E and 30% B near the top of the horizon and grades into 30% E and 70% B in the bottom of the horizon.

A1 (A)	0-7 cm. Very dark grayish brown (10YR 3/2) silt loam (40% sand, 8% clay); moderate medium granular structure; friable; abrupt wavy boundary.
A+B (E/B)	7-27 cm. Pale brown (10YR 6/3) and brown (7.5YR 5/4) loam (42% sand, 11% clay); weak fine subangular blocky structure; friable (E) and firm (B); clear wavy boundary.
B21t (Bt1)	27-40 cm. Dark yellowish brown (10YR 4/4) sandy clay loam (46% sand, 27% clay); moderate medium subangular blocky structure; firm; thin discontinuous reddish brown (5YR 5/4) clay films; clear smooth boundary.
B22t (Bt2)	40-62 cm. Dark yellowish brown (10YR 4/4) sandy loam (69% sand, 14% clay); weak medium prismatic structure parting to moderate medium subangular blocky; firm; medium continuous reddish brown (5YR 5/4) clay films; gradual smooth boundary.
IIB3 (2BC)	62-132 cm. Yellowish brown (10YR 5/4) loamy sand (83% sand, 7% clay); weak coarse subangular blocky structure; firm; clear smooth boundary.
IIIC (3C)	132 + cm. Dark brown (10YR 4/3) sandy loam (54% sand, 13% clay); weak fine subangular blocky structure; firm; moderately effervescent.

Pedon C4

Sampled as: Capac, Aeric Ochraqualf, fine-loamy, mixed, mesic.
Classification: Mollic Haplaquept, fine-loamy, mixed, mesic.
Location: Keene Township, Ionia County, NW¼NW¼NW¼NE¼NE¼ sec. 20, approximately 12 meters south of Sparks Road, T. 7 N., R. 8 W.
Geomorphic position: Depressional area on till plain, nearly level.
Drainage: Somewhat poorly drained.
Vegetation: *Quercus macrocarpa*, *Fraxinus americana*, and *Carya ovata*.
Parent material: Calcareous glacial till with some water reworking.
Sampled by: D. Cremeens. July 10, 1981.
Remarks: Water table at 100 cm during sampling. Boundaries of Bt3 and 2C horizons could not be determined. Large root channel carried A material down into Bt2. 10-12% coarse fragments throughout pedon, more concentrated in 2C horizon. Micromorphologic examination does not give evidence of 1% or greater oriented illuvial clay in any subhorizon of B horizon.

A1 (A)	0-18 cm. Very dark gray (10YR 3/1, 10YR 4/1 dry) loam (38% sand, 22% clay); strong coarse granular structure parting to moderate fine granular; friable; clear wavy boundary.
B+A (B/E)	18-30 cm. Dark brown (10YR 4/3) and gray (10YR 5/1) loam (46% sand, 21% clay); moderate medium subangular blocky structure parting to moderate fine subangular blocky; friable; few fine faint dark brown (7.5YR 4/4) mottles; thin patchy dark gray (10YR 4/1) clay films along root channels and some ped faces; clear wavy boundary.
B21tg (Bt1)	30-46 cm. Grayish brown (2.5Y 5/2) loam (49% sand, 19% clay); moderate medium subangular blocky structure; firm; common fine distinct strong brown (7.5YR 5/6) mottles; medium discontinuous dark gray (10YR 4/1) clay films along ped faces; clear smooth boundary.
B22tg (Bt2)	46-75 cm. Grayish brown (10YR 5/2) loam (43% sand, 23% clay); moderate medium subangular blocky structure parting to moderate fine angular blocky; firm; common medium distinct strong brown (7.5YR 5/6) and few medium faint gray (10YR 5/1) mottles; medium discontinuous grayish brown (10YR 5/2) and dark gray (10YR 4/1) clay films along ped faces and in voids; gradual wavy boundary.
B23tg (Bt3)	75-145 cm. Light brownish gray (10YR 6/2) loam (40% sand, 23% clay); weak coarse subangular blocky structure parting to moderate fine subangular blocky; friable; common medium distinct brown (7.5YR 5/4) mottles; medium discontinuous gray (10YR 5/1) clay films on ped faces with dark gray (N 4/0) in root channels.

IIC1 (2C1)	145-165 cm. Dark brown (7.5YR 4/4) loamy sand (81% sand, 8% clay); structureless, massive; very friable; slightly effervescent.
IIIC2 (3C2)	165 + cm. Brown (7.5YR 5/4) loam (53% sand, 14% clay); moderate fine platy structure; firm; moderately effervescent.

Pedon B2

Sampled as: Brookston, Typic Argiaquoll, fine-loamy, mixed, mesic.
Classification: Typic Argiaquoll, fine-loamy, mixed, mesic.
Location: Keene Township, Ionia County, NW¼NW¼SW¼NE¼NE¼ sec. 20 about 18 m west from NW corner of cultivated field occupying E½SW¼NE¼NE¼ sec. 20, T. 7 N., R. 8 W.
Geomorphic position: Depressional position on till plain, nearly level.
Drainage: Poorly drained.
Vegetation: *Acer saccharum* and *Cyperus esculentus*.
Parent material: Calcareous glacial till with some water reworking.
Sampled by: D. Cremeens. September 11, 1981.
Remarks: C horizon extends up into Btg2 horizon in the form of pockets of calcareous gravel with C horizon material below the pockets. Main body of C horizon has small lime concretions. Approximately 12-15% coarse fragments throughout pedon except pockets of C horizon consisting of about 50% gravel and coarse sand.

A1 (A)	0-32 cm. Very dark grayish brown (10YR 3/2, 10YR 4/2 dry) loam (43% sand, 16% clay); strong fine subangular blocky structure; friable; clear wavy boundary.
B21tg (Btg1)	32-48 cm. Gray (5Y 5/1) sandy clay loam (49% sand, 23% clay); weak medium subangular blocky structure; firm; few fine prominent strong brown (7.5YR 5/6) mottles; medium continuous dark gray (10YR 4/1) clay films; clear smooth boundary.
B22tg (Btg2)	48-70 cm. Gray (5Y 5/1) loam (47% sand, 22% clay); moderate medium and fine subangular blocky structure; firm; moderate medium faint dark gray (5Y 4/1) and few medium prominent strong brown (7.5YR 5/6) mottles; medium discontinuous dark grayish brown (10YR 4/2) clay films on bottom and sides of peds; clear irregular boundary with C horizon extending up as pockets of calcareous gravel.
B23tg (Btg3)	70-90 cm. Grayish brown (2.5Y 5/2) loam (45% sand, 23% clay); moderate fine subangular blocky structure; firm; few coarse distinct strong brown (7.5YR 4/6) mottles; medium patchy very dark grayish brown (10YR 3/2) clay films on void walls and bottom side of peds; gradual wavy boundary.
C (C)	90 + cm. Pinkish gray (7.5YR 6/2) loam (46% sand, 18% clay); weak medium subangular blocky structure; firm; moderate medium faint gray (N 6/0) and few fine distinct strong brown (7.5YR 4/6) mottles; moderately effervescent.

APPENDIX C

Table C1. Selected physical properties.

		Particle Size Distribution (%)												
		Total			Sand					Silt		Clay		
Horizon	Depth (cm)	sand 2-.5	silt .5-.002	clay <.002	vcs 2-1	cs 1-.5	ms .5-.25	fs .25-.1	vfs .1-.05	csi .05-.02	fsi .02-.002	cc .002-.0002	fc <.0002	Bulk Density
		mm												g/cc
Pedon M1														
A1	0-10	38	50	12	1	2	8	16	10	21	29	9	3	1.45
A2	10-19	39	50	11	1	2	7	18	10	18	32	9	2	1.84
B1	19-28	37	47	16	1	2	7	17	9	18	29	11	5	1.84
B21t	28-64	33	47	20	1	2	6	15	9	25	22	14	6	1.85
B22t	64-97	22	48	30	0	1	2	12	7	29	19	18	12	1.91
B3t	97-104	24	54	22	1	1	2	12	7	33	21	13	9	1.79
C1	104-165	30	57	13	1	2	5	13	8	41	16	8	5	2.01
C2	>165	27	59	14	1	2	5	11	8	40	19	8	6	1.92
Pedon C1														
A1	0-12	34	48	18	1	2	6	14	9	27	21	13	5	1.68
B1g	12-25	35	47	18	2	3	6	14	9	20	27	15	3	1.77
B21tg	25-40	29	45	26	1	1	6	14	8	22	23	16	10	1.86
B22tg	40-110	25	45	30	1	1	4	11	7	31	14	17	13	1.87
C	>110	23	59	18	1	1	4	10	7	52	7	12	6	2.00
Pedon P1														
A1	0-16	11	63	26	0	1	3	4	2	35	28	15	11	1.65
B1g	16-25	10	62	28	0	1	2	4	2	35	27	16	12	1.69
B21g	25-46	10	59	31	1	1	2	4	2	29	30	19	12	1.79
B22g	46-85	4	57	39	0	0	1	2	1	25	32	22	17	1.83
B23g	85-119	20	50	30	1	1	5	9	4	10	40	17	13	1.80
C	>119	24	58	18	1	1	4	10	7	38	20	11	7	2.01

(Table C1 Cont'd.).

		Particle Size Distribution (%)												
		Total			Sand					Silt		Clay		
Horizon	Depth (cm)	sand 2-.5	silt .5-.002	clay <.002	vcs 2-1	cs 1-.5	ms .5-.25	fs .25-.1	vfs .1-.05	csi .05-.02	fsi .02-.002	cc .002-.0002	fc <.0002	Bulk Density
		mm												g/cc
Pedon M2														
A1	0-12	26	60	14	1	1	5	10	8	27	33	11	3	1.43
A+B	12-26	22	60	18	1	1	4	8	8	34	26	14	4	1.91
B21t	26-40	13	56	31	0	1	2	5	5	25	31	20	11	1.87
B22t	40-84	15	54	31	1	1	2	6	5	31	23	19	12	1.86
B3t	84-108	17	57	26	1	1	3	6	6	38	19	15	11	1.93
C1	108-165	16	62	22	1	2	2	6	5	42	20	14	8	2.04
C2	>165	15	62	23	1	1	2	6	5	41	21	17	6	2.01
Pedon C2														
A1	0-22	42	39	19	1	3	10	18	10	25	14	10	9	1.44
B+A	22-32	54	33	13	2	3	10	24	14	17	16	8	5	1.87
B21t	32-53	49	33	18	2	2	10	22	13	18	15	9	9	1.91
B22t	53-97	48	36	16	1	2	9	22	14	20	16	9	7	1.86
B3t	97-125	57	29	14	2	3	13	26	13	15	14	7	7	1.88
IIC	>125	28	53	19	1	2	5	11	9	48	5	11	8	2.10
Pedon P2														
A1	0-23	18	57	25	1	2	4	6	5	29	28	14	11	1.68
B21g	23-53	36	43	21	1	3	10	15	7	22	21	12	9	1.78
B22g	53-91	38	41	21	0	3	11	16	8	21	20	12	9	1.99
C	>91	39	37	24	1	2	12	16	8	17	20	14	10	1.92

(Table C1 Cont'd.).

		Particle Size Distribution (%)												
		Total			Sand					Silt		Clay		
Horizon	Depth (cm)	sand 2-.5	silt .5-.002	clay <.002	vcs 2-1	cs 1-.5	ms .5-.25	fs .25-.1	vfs .1-.05	csi .05-.02	fsi .02-.002	cc .002-.0002	fc <.0002	Bulk Density
		mm												g/cc
Pedon M3														
A1	0-12	50	40	10	0	4	14	21	8	17	23	6	4	1.50
B+A	12-32	49	40	11	1	3	13	21	9	16	24	8	3	1.90
B21t	32-48	44	37	19	1	3	12	19	8	19	18	11	8	1.96
B22t	48-86	35	42	23	1	2	10	15	6	22	20	12	11	1.90
B3t	86-127	31	56	13	1	2	8	13	7	46	10	7	6	1.97
C	>127	38	46	16	1	3	10	16	8	31	15	9	7	2.05
Pedon C3														
A1	0-17	63	31	6	2	5	19	27	10	17	14	4	2	1.49
B+A	17-33	45	42	13	2	4	12	18	8	21	21	9	4	2.05
B21t	33-58	48	38	14	1	4	13	20	9	22	16	8	6	1.91
B22tg	58-85	51	35	14	2	4	13	21	10	19	16	9	5	1.86
B3t	85-160	54	38	8	2	4	14	22	11	28	10	4	4	2.03
C	>160	51	41	8	1	3	13	22	10	29	12	5	3	2.09
Pedon B1														
A	0-25	61	30	9	5	5	19	23	8	16	14	5	4	1.46
B1g	25-40	56	28	16	2	4	17	24	9	12	16	6	10	1.92
B21tg	40-58	50	31	19	2	4	16	20	8	13	18	8	11	1.87
B22tg	58-95	47	33	20	1	4	15	19	8	15	18	9	11	1.82
B3tg	95-170	56	31	13	2	4	20	22	8	14	17	6	7	1.83
C	>170	46	38	16	2	4	15	20	6	33	5	9	7	2.00

(Table C1 Cont'd.).

		Particle Size Distribution (%)												
		Total			Sand					Silt		Clay		
Horizon	Depth (cm)	sand 2-.5	silt .5-.002	clay <.002	vcs 2-1	cs 1-.5	ms .5-.25	fs .25-.1	vfs .1-.05	csi .05-.02	fsi .02-.002	cc .002-.0002	fc <.0002	Bulk Density
		mm												g/cc
Pedon M4														
A1	0-7	40	52	8	0	2	10	17	9	28	24	5	3	1.43
A+B	7-27	42	47	11	1	2	11	18	9	23	24	7	4	1.67
B21t	27-40	46	27	27	1	3	11	20	10	11	16	10	17	1.85
B22t	40-62	69	17	14	1	3	16	34	14	8	9	6	8	1.87
IIB3	62-132	83	10	7	1	3	20	45	14	6	4	2	5	1.75
IIIC	>132	54	33	13	1	2	9	29	12	19	14	6	7	2.00
Pedon C4														
A1	0-18	38	40	22	1	3	11	14	7	27	13	9	13	1.57
B+A	18-30	46	33	21	1	3	11	19	10	16	17	9	12	1.89
B21tg	30-46	49	32	19	1	3	12	21	11	15	17	9	10	1.91
B22tg	46-75	43	34	23	1	2	10	18	10	15	19	11	12	1.92
B23tg	75-145	40	37	23	1	2	9	18	10	17	20	9	14	1.94
IIC1	145-165	81	11	8	2	4	22	42	11	7	4	2	6	1.96
IIIC2	>165	53	33	14	1	3	13	24	11	22	11	6	8	2.15
Pedon B2														
A1	0-32	43	41	16	2	4	13	17	6	22	19	8	8	1.28
B21tg	32-48	49	28	23	1	3	13	22	9	13	15	8	15	1.91
B22tg	48-70	47	31	22	2	3	13	20	8	13	18	8	14	1.84
B23tg	70-90	45	32	23	1	2	10	21	9	17	15	11	12	1.95
C	>90	46	36	18	1	3	12	21	8	21	15	9	9	2.15

Table C2. Selected chemical properties.

Horizon	Depth (cm)	pH		CEC	Base Saturation Status					Dithionite-Citrate Ext.		Carbon	
					Base Sat.	Exchangeable Bases						Inorganic as $CaCO_3$	Organic as O.M.
		H_2O	0.1N KCl			K	Ca	Mg	Sum	Fe	Al		
				meq/100g	%	meq/100g				%	%	%	%
Pedon M1													
A1	0-10	6.5	5.5	14.3	9.8	.18	1.2	-*	1.4	.29	.05	-	3.9
A2	10-19	5.6	4.0	7.8	1.7	.13	-	-	.13	.30	.04	-	1.0
B1	19-28	4.5	3.5	9.7	1.6	.16	-	-	.16	.44	.06	-	0.8
B21t	28-64	4.2	3.1	12.8	1.5	.19	-	-	.19	.57	.08	-	0.6
B22t	64-97	4.9	4.5	21.2	81.6	.31	10.7	6.3	17.3	.92	.10	0.3	0.6
B3t	97-104	6.0	5.6	15.5		.26	+	4.5	48.7	.72	.07	1.9	0.5
C1	104-165	6.8	6.5	9.6		.19	+†	2.9		.59	.03	3.3	0.4
C2	>165	7.3	6.9	9.1		.19	+	3.0		.57	.03	3.5	0.4
Pedon C1													
A1	0-12	6.4	5.7	23.8	57.4	.27	9.5	3.9	13.7	.48	.04	-	5.1
B1g	12-25	6.1	5.3	11.2	15.2	.18	-	1.5	1.7	.34	.03	-	1.2
B21tg	25-40	5.7	4.4	19.8	40.9	.32	2.8	5.0	8.1	.69	.06	-	0.7
B22tg	40-110	5.8	5.1	22.6	73.9	.35	8.1	8.3	16.7	.82	.06	.01	0.6
C	>110	6.8	6.6	9.8		.25	+	8.7		.50	.02	3.7	0.4
Pedon P1													
A1	0-16	5.9	5.4	39.1	77.2	.48	21.2	8.5	30.2	.38	.07	-	6.9
B1g	16-25	6.4	5.8	36.5	80.5	.45	19.6	9.4	29.4	.34	.07	-	4.8
B21g	25-46	6.3	5.8	31.7	68.5	.41	13.6	7.7	21.7	.31	.07	-	2.2
B22g	46-85	7.3	5.8	27.9	75.6	.37	12.6	8.1	21.1	.89	.15	-	0.7
B23g	85-119	7.3	5.9	20.6		.69	12.6	9.4	22.7	.55	.09	0.9	0.6
C	>119	7.0	6.5	22.2		.29	+	4.3		.42	.07	2.8	0.6

* - = negligible quantity
† + = free $CaCO_3$ present

Table C2 (cont'd.)

Horizon	Depth (cm)	pH H_2O	pH 0.1N KCl	CEC	Base Saturation Status: Base Sat.	Exchangeable Bases: K	Ca	Mg	Sum	Dithionite-Citrate Ext.: Fe	Al	Carbon: Inorganic as $CaCO_3$	Organic as O.M.
				meq/100g	%	meq/100g				%	%	%	%
Pedon M2													
A1	0-12	7.0	6.4	22.1	45.7	.31	7.9	1.9	10.1	.37	.06	-	5.8
A+B	12-26	4.8	3.5	12.0	1.5	.18	-*	-	.18	.42	.06	-	1.1
B21t	26-40	4.7	3.4	19.4	15.5	.28	.6	2.1	3.0	.81	.12	-	0.7
B22t	40-84	5.2	5.1	21.3		.35	16.1	6.2	22.7	.84	.10	0.5	0.7
B3t	84-108	6.8	6.4	15.8		.28	+†	4.4		.58	.06	2.2	0.6
C1	108-165	7.5	7.1	12.4		.25	+	3.7		.53	.04	2.1	0.5
C2	>165	7.7	7.5	10.9		.28	+	6.6		.53	.04	2.5	0.4
Pedon C2													
A1	0-22	6.6	6.0	38.1	49.6	.47	13.6	4.8	18.9	.62	.09	-	6.9
B+A	22-32	6.5	5.1	9.3	14.0	.25	-	1.0	1.3	.34	.03	-	0.6
B21t	32-53	5.4	3.9	14.1	38.3	.21	2.0	3.2	5.4	.63	.05	-	0.4
B22t	53-97	5.6	4.6	12.7	32.3	.24	.76	3.1	4.1	.68	.05	-	0.4
B3t	97-125	6.1	5.0	10.4	39.4	.21	1.4	2.5	4.1	.64	.05	.01	0.4
IIC	>125	6.6	6.2	11.0		.21	+	3.8		.66	.04	1.9	0.3
Pedon P2													
A1	0-23	6.1	5.6	30.0	59.0	.56	12.4	4.7	17.7	.63	.10	-	3.7
B21g	23-53	6.1	5.6	22.8	50.9	.41	7.3	3.9	11.6	.45	.07	-	2.6
B22g	53-91	6.3	5.2	16.8	38.1	.28	2.9	3.2	6.4	.89	.07	-	1.0
C	>91	6.2	5.0	15.8	48.1	.37	3.4	3.8	7.6	.63	.07	0.3	0.6

* - = negligible quantity

† + = free $CaCO_3$ present

Table C2 (cont'd.)

Horizon	Depth (cm)	pH H_2O	pH 0.1N KCl	CEC	Base Saturation Status: Base Sat.	Exchangeable Bases: K	Ca	Mg	Sum	Dithionite Citrate Ext.: Fe	Al	Carbon: Inorganic as $CaCO_3$	Organic as O.M.
				meq/100g	%	meq/100g				%	%	%	%
Pedon M3													
A1	0-12	7.1	6.9	12.6	13.5	.28	1.4	-*	1.7	.21	.04	-	3.8
B+A	12-32	6.7	5.4	6.4	3.6	.23	-	-	.23	.28	.04	-	0.8
B21t	32-48	5.6	4.6	13.4	21.6	.41	1.5	1.0	2.9	.61	.09	-	0.5
B22t	48-86	6.0	5.3	15.5	101	.45	8.5	6.6	15.6	.69	.09	0.6	0.5
B3t	86-127	6.5	6.1	7.9		.24	+†	2.3		.38	.04	2.2	0.4
C	>127	7.3	6.8	9.9		.24	+	2.7		.38	.04	2.3	0.3
Pedon C3													
A1	0-17	5.6	5.3	20.8	44.2	.21	7.6	1.4	9.2	.31	.05	-	4.0
B+A	17-33	6.0	4.3	12.5	92.0	.26	9.0	2.2	11.5	.44	.05	-	0.6
B21t	33-58	6.0	5.0	16.1	16.8	.21	.8	1.7	2.7	.50	.08	-	0.5
B22tg	58-85	6.6	5.7	14.0	55.7	.28	4.2	3.3	7.8	.45	.06	-	0.4
B3t	85-160	7.0	6.7	6.1		.28	4.8	3.4	8.5	.32	.03	3.8	0.2
C	>160	7.8	7.2	5.8		.19	+	2.4		.32	.03	2.2	0.2
Pedon B1													
A1	0-25	6.0	5.3	43.7	72.1	.32	26.1	5.1	31.5	.16	.05	-	8.3
B1g	25-40	6.5	6.0	18.8	64.4	.37	8.1	3.6	12.1	.21	.07	-	0.8
B21tg	40-58	7.2	6.2	17.2	63.9	.36	7.3	3.3	11.0	.24	.07	-	0.5
B22tg	58-95	7.4	6.5	18.7	64.7	.37	8.1	3.6	12.1	.29	.08	-	0.4
B3tg	95-170	7.3	6.4	16.9	88.8	.34	9.2	5.5	15.0	.55	.05	0.6	0.4
C	>170	7.4	6.9	8.3		.21	+	4.3		.34	.05	3.6	0.3

* - = negligible quantity
† + = free $CaCO_3$ present

Table C2 (cont'd.)

Horizon	Depth (cm)	pH H_2O	pH 0.1N KCl	CEC	Base Saturation Status: Base Sat.	Exchangeable Bases: K	Ca	Mg	Sum	Dithionite Citrate Ext.: Fe	Al	Carbon: Inorganic as $CaCO_3$	Organic as O.M.
				meq/100g	%	meq/100g				%	%	%	%
Pedon M4													
A1	0-7	6.7	5.8	17.7	16.4	.28	2.6	-*	2.9	.23	.04	-	4.5
A+B	7-27	5.4	4.2	6.9	4.0	.28	-	-	.28	.34	.03	-	0.4
B21t	27-40	5.0	3.6	12.6	2.9	.27	-	.10	.37	.51	.06	-	0.5
B22t	40-62	4.8	3.5	10.1	2.7	.24	-	.03	.27	.46	.05	-	0.3
IIB3	62-132	5.2	3.9	3.5	3.4	.12	-	-	.12	.23	.02	-	0.1
IIIC	>132	6.2	5.6	6.0		.18	+†	2.77		.26	.02	3.3	0.2
Pedon C4													
A1	0-18	5.7	5.5	51.2	75.0	.44	30.9	7.1	38.4	.25	.08	-	11.1
B+A	18-30	6.4	5.9	14.8	101.3	.40	10.4	4.2	15.0	.17	.06	-	1.7
B21tg	30-46	6.6	6.0	16.5	60.0	.33	6.4	3.2	9.9	.19	.05	-	0.8
B22tg	46-75	6.9	6.0	16.3	58.9	.35	6.0	3.2	9.6	.28	.04	-	0.4
B23tg	75-145	7.0	6.1	16.8	60.7	.37	6.4	3.4	10.2	.42	.04	-	0.4
IIC1	145-165	7.4	6.7	3.4		.12	14.8	2.0	16.9	.11	.03	2.3	0.1
IIIC2	>165	7.6	6.9	5.4		.18	+	1.6		.11	.03	4.0	0.2
Pedon B2													
A1	0-32	6.8	6.4	41.1	70.3	.31	22.8	5.8	28.9	.20	.09	-	8.0
B21tg	32-48	7.2	6.5	19.6	66.3	.25	8.2	4.5	13.0	.19	.08	-	0.8
B22tg	48-70	7.7	6.7	17.2		.25	28.5	6.4	35.2	.35	.07	-	0.6
B23tg	70-90	7.8	6.9	17.3		.26	27.8	7.9	36.0	.31	.06	2.1	0.6
C	>90	8.0	7.3	10.4		.24	+	4.6		.32	.05	3.3	0.3

* - = negligible quantity
† - + free $CaCO_3$ present

Table C3. Percent of combined peak areas from X-ray diffraction.

		Mg sat. - Gly solv.					K sat. @ 300°C				K sat. @ 550°C			
Horizon	Frac.*	18 Å	14.2 Å	10 Å	7.0 - 7.2 Å	4.2 Å	14.2 Å	10 Å	7.0 - 7.2 Å	4.2 Å	14.2 Å	10 Å	7.0 - 7.2 Å	4.2 Å
Pedon M1														
A1	1		26	19	37	18	I†	37	54	9	I	83		17
	2		32	20	39	9	I	53	40	7	I	88		12
A2	1		28	22	37	13		32	40	28	I	49		51
	2		43	30	27	t‡	I	84	16		I	100		t
B1	1		14	17	52	17		27	52	21	I	87		13
	2		12	28	60	t	I	45	55	t	I	100		t
B21t	1		17	29	45	9	3	48	45	4	I	84		16
	2		10	46	44	t	I	71	29	t		100		
	3		9	59	32		I	79	21			100		
B22t	1		10	34	48	8	I	49	45	6	I	90		10
	2		14	52	34		I	76	24		I	100		
	3		27	49	24		I	78	22		I	100		
B3t	1		8	37	48	7	5	47	42	6	I	88		12
	2		6	44	50		13	55	32		I	100		
C1	1		15	40	45	t	11	50	35	4	I	89		11
	2		7	50	43		14	60	26		I	100		
C2	1		9	34	53	4	11	51	35	3	I	98		2
	2		9	58	33	t	I	64	29	7	I	93		7

*Fraction investigated, 1 - coarse clay, 2 - fine clay, 3 - clay film, fine clay.

†I - interstratified, asymmetrical 10 Å peak on low angle side.

‡t - trace, too small to determine peak area.

(Table C3 Cont'd.).

Horizon	Frac.*	Mg sat. - Gly solv.					K sat. @ 300°C				K sat. @ 550°C			
		18 Å	14.2 Å	10 Å	7.0 - 7.2 Å	4.2 Å	14.2 Å	10 Å	7.0 - 7.2 Å	4.2 Å	14.2 Å	10 Å	7.0 - 7.2 Å	4.2 Å
Pedon C1														
A1	1		26	26	36	12	I†	42	41	18	I	70		30
	2		23	35	42	t‡	I	66	34	t	I	100		t
B21tg	1		19	20	30	1	36	29	34	1	I	74		26
	2		21	36	43		I	84	16		I	100		
B22tg	1		16	31	46	7	I	60	36	4	I	91		9
	2		12	53	35	t		80	20			100		
	3			70	30			84	16			100		
C	1		13	42	43	2	I	54	41	6	I	100		t
	2		9	51	40		I	73	27					
Pedon P1														
A1	1		13	43	35	9		63	29	8		87		13
	2		11	54	31	4	I	86	11	3	I	100		
B21g	1		11	50	36	3	I	68	29	3	I	93		7
	2		t	67	33		I	77	20	3	I	100		
B22g	1		17	40	41	2		71	25	4		94		6
	2		10	65	25			84	16			100		
B23g	1		14	38	38	10		58	36	6		91		9
	2		12	51	40			78	22			100		
C1	1		15	43	39	3		65	28	7		91		9
	2		7	60	30	3	I	83	14	3	I	100		

*Fraction investigated, 1 - coarse clay, 2 - fine clay, 3 - clay film, fine clay.

†I - interstratified, asymmetrical 10 Å peak on low angle side.

‡t - trace, too small to determine peak area.

(Table C3 Cont'd.).

Horizon	Frac.*	Mg sat. - Gly solv.					K sat. @ 300°C				K sat. @ 550°C			
		18 Å	14.2 Å	10 Å	7.0 - 7.2 Å	4.2 Å	14.2 Å	10 Å	7.0 - 7.2 Å	4.2 Å	14.2 Å	10 Å	7.0 - 7.2 Å	4.2 Å
Pedon M2														
A1	2		20	33	34	13		55	22	23		90		10
B21t	2		17	47	34	2		65	34	1		97		3
	3			74	26			83	17			100		
B22t	2		12	64	24			81	19			100		
	3		t‡	76	24			81	19			100		
C	2		5	53	41	1	6	60	33	1	I†	100		
Pedon C2														
A1	2		42	27	31		I	77	23			100		
B21t	2		14	50	36		I	78	22			100		
B22t	2		14	52	34		I	78	22			100		
IIC	2		10	62	28			77	23			100		
Pedon PII														
A	2		19	41	37	3		64	31	5		97		3
B21g	2		10	53	37		I	77	20	3	I	93		7
B22g	2		13	52	35		I	69	31		I	100		
C	2		14	61	21	4	I	80	17	3	I	94		6

*Fraction investigated, 1 - coarse clay, 2 - fine clay, 3 - clay film, fine clay.

†I - interstratified, asymmetrical 10 Å peak on low angle side.

‡t - trace, too small to determine peak area.

(Table C3 Cont'd.).

Horizon	Frac.*	Mg sat. - Gly solv. 18 Å	14.2 Å	10 Å	7.0 - 7.2 Å	4.2 Å	K sat. @ 300°C 14.2 Å	10 Å	7.0 - 7.2 Å	4.2 Å	K sat. @ 550°C 14.2 Å	10 Å	7.0 - 7.2 Å	4.2 Å
Pedon M3														
A1	2		43	25	32	t‡	I†	75	23	2	I	97		3
B21t	2		10	46	44		I	72	28			100		
	3		12	40	37	11	I	58	31	11	I	86		14
B22t	2		13	55	32			69	31			100		
	3		t	73	27		I	90	10		I	100		
C1	2		9	58	31	2	12	65	20	3	I	100		
Pedon C3														
A1	2		56	12	29	3	41	36	21	2	I	100		t
B21t	2	4	19	50	27		I	75	25		I	100		
B22tg	2		11	56	33		I	72	28		I	100		
	3		t	67	33		I	81	19		I	100		
C1	2	4	13	52	31	t	I	75	23	2	I	100		t
Pedon B1														
A1	2	t	7	73	30		I	82	18		I	100		
B21tg	2	16	9	50	25		I	77	23		I	100		
	3	57		34	9		I	85	15		I	100		
B22tg	2	24	8	46	22		I	80	20		I	100		
	3	52	9	30	9	t	I	80	15	5	I	100		t
B3tg	2	23	10	50	17		I	74	26		I	100		
C	2	4	12	56	28		5	74	21		I	100		

*Fraction investigated, 1 - coarse clay, 2 - fine clay, 3 - clay film, fine clay.

†I - interstratified, asymmetrical 10 Å peak on low angle side.

‡t - trace, too small to determine peak area.

(Table C3 Cont'd.).

Horizon	Frac.*	Mg sat. - Gly solv. 18 Å	14.2 Å	10 Å	7.0 - 7.2 Å	4.2 Å	K sat. @ 300°C 14.2 Å	10 Å	7.0 - 7.2 Å	4.2 Å	K sat. @ 550°C 14.2 Å	10 Å	7.0 - 7.2 Å	4.2 Å
Pedon M4														
A1	2	19	33	16	26	6	I[†]	72	17	11	I	90		10
B21t	2	t[‡]		64	36		I	85	15		I	100		
	3			45	55		I	74	26		I	100		
B22t	2	7	18	56	19		I	89	11		I	100		
IIIC	2			69	31			77	23			100		
Pedon CIV														
A1	2	22		65	13			84	16			100		
B21tg	2	56		35	9		I	79	21		I	100		
	3	53		42	5		I	100	t		I	100		
B22tg	2	29		59	12		I	87	13			100		
	3	63		31	6		I	100	t			100		
B23tg	2	50		43	7		I	89	11			100		
IIC1	2	38	t	47	15		I	84	16			100		
Pedon BII														
A1	2	vs[§]	vs	64	36		I	81	19		I	100		
B21tg	2	vs	7	68	25		I	100			I	100		
	3	25		43	27	5								
B22tg	2	vs	vs	85	15		I	88	12			100		
	3	59		30	11		I	82	18		I	100		
B23tg	2	vs	vs	73	27		I	85	15		I	100		
	3	21	17	25	37									
C	2	24	t	61	15		I	87	13		I	100		

*Fraction investigated, 1 - coarse clay, 2 - fine clay, 3 - clay film, fine clay.

[†]I - interstratified, asymmetrical 10 Å peak on low angle side.

[‡]t - trace, too small to determine peak area.

[§]vs - very large, peak too large to determine area.

Table C4. Micromorphological description of selected horizons

Horizon	Description
Pedon M1	
B21t	Few simple embedded grain argillans with moderate discontinuous orientation commonly 0.05 - 0.10mm thick, occupying about 1% of slide area.
B22t	Many primary ped argillans with strong continuous orientation, commonly 0.10 - 0.25mm thick; few channel argillans, vugh argillans, and embedded grain argillans with weak discontinuous orientation, about 0.5mm thick; total argillans occupy 3-5% of slide area.
B3t	Very few primary ped and channel argillans with moderate discontinuous orientation, commonly 0.10mm thick, occupying less than 0.5% of slide area.
C1	Very few channel argillans with weak discontinuous orientation, commonly 0.025 - 0.05mm thick, occupying less than 0.5% of slide area.
Pedon C1	
B21t	Common primary ped and void argillans with moderate discontinuous orientation, commonly 0.10mm thick, also with strong continuous orientation, commonly 0.05mm thick; few embedded grain argillans with weak continuous orientation, commonly 0.025mm thick; total argillans occupy 2-3% of slide area.
B22t	Many primary ped and channel argillans with weak striated orientation, commonly 0.15 - 0.30mm thick, and with strong continuous orientation, commonly 0.1 - 0.15mm thick, occupying 5% of slide area.
Pedon P1	
B21g	Very few channel argillans with weak striated orientation, commonly 0.025 - 0.05mm thick, occupying less than 0.5% of slide area.
B22g	Very few channel argillans with weak striated orientation, commonly 0.05mm thick, occupying less than 0.5% of slide area.
B23g	Very few channel argillans with moderate discontinuous orientation, commonly 0.5 - 1.0mm thick; very few primary ped argillans with weak striated orientation, commonly 0.025 - 0.05mm thick; total argillans occupy less than 0.5% of slide area.
C	No argillans of any kind observed.

(Table C4 cont'd.).

Horizon	Description
Pedon M2	
B21t	Common primary ped and channel argillans with strong continuous orientation, commonly 0.10mm thick, and moderate discontinuous orientation, commonly 0.10 - 0.30mm thick, occupying 2-3% slide area.
B22t	Few compound cutans of some sort, possibly organo-argillans, present along ped faces and channel walls, isotropic, contains skeletal grains, occupies less than 0.5% of slide area.
B3t	Many secondary ped and channel argillans with strong continuous orientation, commonly 0.5 - 0.75mm thick; few channel and void argillans with thin continuous and thin discontinuous orientation, commonly 0.05 - 0.10mm thick; total argillans occupy 5% of slide area.
C1	Few channel argillans with moderate discontinous orientation, commonly 0.25 - 0.35mm thick, possibly embedded in calcitans, occupying 1-3% of slide area.
Pedon C2	
B21t	Common primary ped and channel argillans with strong discontinuous orientation, commonly 0.05 - 0.08mm thick; very few free grain argillans with weak continuous orientation, commonly 0.25mm thick; total argillans occupy 3-4% slide area.
B22t	Common primary ped and channel argillans with moderate discontinuous orientation, commonly 0.05 - 0.08mm thick; very few vugh argillans with strong continuous orientation, commonly 0.05mm thick; total argillans occupy 3-5% of slide area.
B3t	Few primary ped and channel argillans with moderate continuous and moderate discontinuous orientation, commonly 0.05 - 0.08mm thick; very few channel argillans with weak striated orientation, commonly 0.5mm thick; total argillans occupy 1-2% of slide area.
IIC1	No argillans of any kind present. No sign of any type of plasma separation or concentration.
Pedon P2	
B21g	No argillans or cutans of any kind present.
B22g	Very few secondary ped, channel, and vugh argillans with weak and moderate discontinuous orientation, commonly 0.03 - 0.05mm thick, occupying 0.5 - 1% of slide area.
C1	Very few channel argillans with weak striated orientation, commonly 0.05mm thick; very few channel argillans with moderate discontinuous orientation, commonly 0.05mm thick; total argillans occupy less than 0.5% of slide area.

(Table C4 cont'd.).

Horizon	Description
Pedon M3	
B21t	Many primary ped argillans with strong continuous orientation, commonly 0.07 - 0.10mm thick; common primary ped argillans with weak discontinuous orientation, commonly thick; total argillans occupy 5% of slide area.
B22t	Common primary ped and channel argillans with moderate discontinuous orientation, commonly 0.05 - 0.10mm thick, occupying 2-4% of slide area.
B3t	Very few secondary ped argillans with weak discontinuous orientation, commonly 0.05 - 0.07mm thick, occupying less than 0.5% of slide area.
C1	Very few channel argillans with strong discontinuous orientation, commonly 0.07 - 0.10mm thick, occupying less than 0.5% of slide area.
Pedon C3	
B21t	Many primary ped, channel, and vugh argillans with strong continuous orientation, commonly 0.05 - 0.07mm thick; few channel and vugh argillans with weak to moderate discontinuous orientation, commonly 0.05 - 0.25mm thick; very few embedded grain argillans with moderate discontinuous orientation, commonly 0.025mm thick; total argillans occupy 5% of slide area.
B22t	Common primary ped and channel argillans with moderate discontinuous orientation, commonly 0.1 - 0.15mm thick; few vugh argillans with weak striated orientation, commonly 0.05mm thick; total argillans occupy 2-3% of slide area.
B3t	No argillans of any kind observed.
C1	No argillans of any kind observed.
Pedon B1	
B21tg	Very few embedded grain and vugh argillans with weak striated orientation, commonly 0.05 - 0.1mm thick, occupying less than 0.5% of slide area.
B22tg	Few embedded grain and vugh argillans with weak striated orientation, commonly 0.05 - 0.1mm thick, occupying 0.5% of slide area.
B3tg	Few embedded grain and vugh argillans with weak striated orientation, commonly 0.05 - 0.08mm thick; few primary ped argillans with weak discontinuous orientation, commonly 0.05 - .1mm thick; total argillans occupy 1% of slide area.

(Table C4 cont'd.).

Horizon	Description
Pedon M4	
B21t	Common primary ped argillans with weak discontinuous orientation, commonly 0.05mm thick; few embedded grain argillans with moderate continuous orientation, commonly 0.05mm thick; total argillans occupy 1-2% of slide area.
B22t	Common channel argillans with strong discontinuous orientation, commonly 0.075 - 0.10mm thick; few embedded grain argillans with moderate continuous orientation, commonly 0.05mm thick; total argillans occupy 1-2% of slide area.
IIB3	Very few embedded grain argillans with moderate discontinuous orientation, commonly 0.05mm thick, occupying 0.5-1% of slide area.
IIC1	No argillans of any kind present.
Pedon C4	
B21t	Very few embedded grain argillans with weak striated orientation, commonly 0.03 - 0.05mm thick; very few channel argillans with weak discontinuous orientation, commonly 0.05mm thick; total argillans occupy less than 0.5% of slide area.
B22t	Very few embedded grain and vugh argillans with weak striated continuous orientation, commonly 0.03 - 0.05mm thick, occupying less than 0.5% of slide area.
B23t	Few secondary ped and channel argillans with weak striated orientation, commonly 0.1 - 0.15mm thick; few embedded grain argillans with weak to moderate discontinuous orientation, commonly 0.03 - 0.05mm thick; total argillans occupy 2-3% of slide area.
IIIC2	No argillans of any kind present.
Pedon B2	
B21tg	Few primary ped and channel argillans with weak striated orientation, commonly 0.05 - 0.1mm thick; very few embedded grain and vugh argillans with weak continuous orientation, commonly 0.03 - 0.05mm thick; total argillans occupy 0.5-1% of slide area.
B22tg	Very few embedded grain and vugh argillans with moderate discontinuous orientation, commonly 0.03 - 0.05mm thick, occupying less than 0.5% of slide area.
B23tg	Very few channel argillans with weak striated orientation, commonly 0.05 - 0.1mm thick, occupying less than 0.5% of slide area.
C1	No argillans of any kind present.

Table C5. Soil moisture readings (% by volume).

Depth (cm)	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Horizon
	Pedon M1														
30	21 27	26 27	26	24	27				22	27 25	17 17	16 23	17 18	14 13	A1, A2, B1
60	22 23	29 30	30	30	29				29	30 28	23 22	21 25	22 22	22 21	B21t
90	22 22	29 30	29	29	44				30	30 28	25 24	23 25	24 24	23 23	B22t
120	24 24	26 27	26	27	61				29	35 28	25 24	24 24	24 23	26 24	B3t
150	25 25	27 27	26	62	64				65	66 28	26 26	25 24	25 25	23 25	C1
180	26 26	27 27	27	64	62				69	69 34	27 26	25 25	25 25	26 25	
210	28 28	31 28	28	59	42				68	66 66	33 30	26 26	25 26	27 23	C2
240	29 30	45 38	37	41	43				43	42 46	31 28	29 27	28 26	29 28	
	Pedon C1														
30	27 30	48 44	34	35	36				33	42 31	24 25	23 31	24 25	23 23	A1, B1g, B21tg
60	24 25	61 61	62	62	62				34	65 31	27 27	28 30	26 26	25 25	B22tg
90	23 26	62 63	63	62	64				66	66 32	27 25	26 28	24 24	24 24	
120	24 26	65 66	66	65	65				68	65 33	28 26	25 27	24 25	23 24	
150	26 27	61 63	63	63	64				70	69 69	28 27	27 27	26 25	24 26	
180	28 29	44 50	52	49	49				66	64 68	42 28	27 27	26 25	24 29	C
210	27 28	42 43	43	42	41				45	44 63	63 30	28 27	27 26	26 33	
240	31 30	53 42	42	42	41				42	43 45	45 46	31 36	34 29	27 35	
	Pedon P1														
30	34 37	– –	65	–	67				57	59 60	64 67	50 62	29 45	33 29	A1, B1g, B21g
60	32 32		67		64				55	56 56	60 60	57 61	49 47	45 41	B22g
90	35 42		63		55				52	55 55	56 56	53 56	44 59	42 42	B23g
120	64 65		66		51				45	51 52	54 54	52 52	57 59	52 49	
150	81 80		84		46				41	43 47	53 53	54 54	55 55	54 54	C
180	62 62		62		40				41	41	54	54			
210	64 57		51												
240	47 49		45												

(Table C5 Cont'd.).

Depth (cm)	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Horizon
	Pedon M2														A1
30	23 31	33 33	32	29	28				27	33 29	21 24	23 28	22 23	19 21	A+B
60	27 35	39 39	38	44	35				33	35 32	29 28	28 34	29 29	27 27	B21t
90	26 34	37 37	35	50	31				31	43 30	28 27	27 30	27 27	26 26	B22t, B3t
120	28 30	33 34	33	60	57				32	63 29	28 28	27 29	27 26	25 25	
150	27 28	30 30	30	61	59				50	60 31	29 28	27 29	27 27	26 28	C1
180	29 30	31 31	30	55	43				44	46 43	33 29	28 30	28 30	27 32	
210	30 31	35 33	33	47	42					44 44	39 35	30 36	32 33	32 35	C2
240	33 32	37 34	34	43	41						40	39		35	
	Pedon C2														A1
30	29	60 63	34	32	32				29	62 29	22 23	23 25	20 22	20 20	B+A, B21t
60	23	60 60	61	61	56				31	62 31	29 25	24 24	24 23	23 23	
90	28	60 62	62	63	60				40	63 34	29 26	26 24	23 24	23 23	B22t
120	29	58 60	60	61	58				62	63 64	31 30	29 26	26 28	25 22	B3t
150					60				62	63 64	33 32	29 29	28 29	29 28	
180					66				69	68 71	65 35	33 32	30 32	31 31	IIC
210					48				64	69 67	73 72	34 46	33 33	32 33	
240					41				47	50 50	64 57	63 72	37 48	33 48	
	Pedon P2														
30	38 42	70 69	66	46	46				40	64 43	43 41	39 43	38 39	36 37	A1, B21g
60	37 64	64 64	65	64	63				40	67 42	37 37	36 46	36 36	35 34	
90	31 63	63 64	62	64	64				66	65 67	34 34	34 65	33 34	33 32	B22g
120	34 62	63 62	64	62	61				63	61 61	32 32	57 66	32 32	31 31	
150	64 64	64 65	65	64	64				68	65 66	64 36	64 60	44 33	32 33	
180	66 67	66 65	68	67	64				68	69 66	68 66	65 65	65 63	35 24	C
210	66 62	53 53	56	54	46				55	66 68	68 66	68 66	66 66	64 66	
240	48 50	47 46	46	47	42				48	48 54	69 69	68 67	67 68	68 67	

(Table C5 Cont'd.).

Depth (cm)	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Horizon
	Pedon M3														
30	21 30	29 29	28		29				27	33 30	22 24	27 21	26 27	22 22	A1, B+A, B21t
60	23 31	31 31	32		32				31	32 30	26 26	26 24	26 26	25 26	B22t
90	22 44	36 35	36		35				35	34 34	27 28	28 27	27 26	27 26	B3t
120	25 38	36 36	36		35				36	37 35	33 33	31 29	30 28	27 28	
150	24 36	33 35	33		32				34	36 34	35 33	32 30	31 30	28 31	
180	22 34	30 33	32		33				32	34 32	32 32	32 30	31 31	30 29	C1
210	21 35	28 33	32		29				32	36 32	29 30	29 28	29 28	28 25	
240	17 23	22 22	23		13				29	36 33	33 29	27 26	26 26	25 28	
	Pedon C3														A1
30	33 51	46 60	41		64		-		42	- 53	35 35	37 31	35 37	34 36	B+A
60	23 65	69 66	68		67				36	71	28 30	32 29	31 32	31 30	B21t, B22tg
90	17 60	64 68	64		71				70	69	29 27	27 23	30 28	29 32	
120	19 74	70 69	72		52				72	74	36 29	27 26	35 31	34 74	B3t
150	21 48	45 60	45		44				51	51	52 35	35 35	65 70	72 56	
180	28 43	43 44	42		43				45	46	44 54	54 47	53 56	56 47	
210	30 42	43 43	42		42				45	44	44 46	47 44	46 48	46 45	C
240	32 43	44 44	43		44				43	43	43 45	44 44	44 44	44 43	
	Pedon B1														A1
30	39 -	69 69	70				-		75	- -	36 -	89 39	65 71	56 47	B1g
60	33	63 62	63						68		64	66 47	70 67	66 68	B21tg
90	33	62 62	63						65		67	66 68	69 69	63 60	B22tg
120	32	63 62	63						66		69	66 68	67 65	60 61	
150	52	76 74	69						73		65	67 68	61 59	58 57	B3tg
180	50	45 45	58						53		69	58 58	57 57	56 60	
210	42	41 41	42						43		46	65 66	66 65	63 56	C
240	42	42 42	43						43		43	45 47	46 47	48 46	

(Table C5 Cont'd.).

Depth (cm)	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Horizon
	Pedon M4														
30	25 33	29 29								32	27 30	29 30	29 31	28 27	A1, A+B, B21t
60	19 37	32 34								38	33 35	32 36	35 35	32 33	B22t
90	11 31	25 27								32	27 31	30 30	30 29	26 24	IIB3
120	16 18	20 27								30	27 30	28 27	29 26	25 25	
150	19 18	18 20								28	27 32	31 28	32 29	30 27	
180	20 21	18 19								27	27 28	28 28	27 27	27 27	IIIC
210	15 14	14 15								34	32 28	27 27	27 26	26 26	
240	19 19	17 19								41	39 36	30 26	34 27	30 31	
	Pedon C4														
30	31 50	39 45	42		48		-		63	- -	40 57	43 42	42 43	40 41	A1, B+A, B21tg
60	25 48	52 53	56		60				56		41 59	50 48	43 58	37 37	B22tg
90	30 58	58 60	60		63				64		45 65	60 64	67 67	61 66	
120	31 60	62 62	61		60				69		65 65	67 64	66 66	64 65	B23tg
150	31 92	91 90	96		84				93		66 67	70 88	69 71	76 74	IIC1
180	45 39	42 43	40		35				40		40 63	61 70	64	65 64	
210	35 36	37 35	36		36				37						IIIC2
240	37 36	36 37	36		36				37						
	Pedon B2														
30	50 -	52 49	49		61		-		-	- -	51 -	72 49	51 47	51 51	A1, B21tg
60	34	34 34	33		65						48	65 41	38 36	36 36	B22tg
90	30	31 31	33		64						45	65 66	39 33	31 30	B23tg
120	33	62 64	62		63						66	66 66	65 65	33 33	
150	30	67 66	64		72						65	67 63	66 64	62 60	
180	63	54 74	60		52						67	68 66	66 68	68 64	C
210	64	48 52	49		47						68	67 63	65 68	58 75	
240	41	46 46	46		40						54	56 55	70 56	51 52	

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