

THE PEDOGENESIS OF A BLACK-GREY WOODED
SEQUENCE OF SOILS IN SASKATCHEWAN, CANADA

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ABSTRACT

THE PEDOGENESIS OF A BLACK-GREY WOODED SEQUENCE OF SOILS IN SASKATCHEWAN, CANADA

by Roland J. St. Arnaud

The soils studied represent a Black-Grey Wooded sequence in Saskatchewan, Canada. Chemical, physical, mineralogical and micropedological studies were made of Orthic Black, Orthic Dark Grey, Dark Grey Wooded and Orthic Grey Wooded profiles developed from relatively uniform glacial till material and selected within a relatively small area.

The general gradation of morphological properties observed in going from the Black to the Grey Wooded soils is reflected in the thickness of the Ah horizons and of the solum, the degree of expression of lime accumulation layers, the development of textural B horizons, and in the structure of the soil horizons.

All four soils are highly base-saturated, calcium being the dominant cation on the exchange complex. Increased intensity of leaching in going from the Black to the Grey Wooded soil is evidenced by the decrease in solum pH values and by the depth to which lime carbonates had been moved.

The fine clay fraction ($<0.2 \mu$) of the parent materials is composed almost entirely of montmorillonite and illite which occur in the ratio of approximately three to one. Trace amounts of kaolinite and chlorite are present. Montmorillonite and illite occur in about equal amounts in the coarse clay fraction ($2.0-0.2 \mu$) but account for less than three-quarters of the total weight; kaolinite, chlorite, and primary minerals make up the remainder of the fraction. Small but significant changes show up in the composition of the clay fractions. The fixation of potassium by expanding-type clay minerals has resulted in an increase in illite content within the solum of all four profiles. Illitization is most pronounced in the Ah horizon of the Black soil. The chlorite content of the clays decreases within the solum of all profiles, the greatest decrease occurring in the Ae of the Grey Wooded soil indicating more intensive weathering in the Podzolic than in the Chernozemic profile. There are indications that clay has been formed in situ within the Black soil and perhaps to a lesser degree within the Grey Wooded soil.

Micropedological studies indicate the fabric of the Ah horizon of the Black soil to be typical Chernozemic fabric. Although the fabric of the Ah horizons of the other three soils is similar in some respects to that of the Black Ah horizon, the inorganic fraction of the soil is

not as intimately associated with the organic fraction. As a consequence, there is a decrease in the degree of stabilization of soil colloids in going from Chernozemic to Podzolic soils. This accounts for the greater movement of clay out of the A horizon of the Grey Wooded soil than of the Black soil, and indicates that the development of textural B horizons is dependent to a large measure upon the nature of the overlying A horizons. The increased illuviation which occurs in going from the Black to the Grey Wooded soil is indicated by the degree of expression of cutans, channel fabric and flow structures in the B horizons. Mechanical analysis and bulk density measurements also serve to confirm the variations in illuviations which are observed.

Iron translocation within all four profiles appears to be closely associated with clay movement. A higher correlation between total iron and clay content than between free iron and clay content indicates that the horizon of maximum accumulation of free iron may not always coincide with the horizon of maximum accumulation of total iron and clay. The uniform iron content of the fine clay fraction of all four profiles indicates that the iron may occur as an integral part of the clay mineral structures and that the clays have undergone little alteration as a result of weathering.

Particle size distribution of quartz and of the total soil indicate that a redistribution of sizes has occurred within the solum of all four soils relative to the parent material. Such a redistribution is attributed to a process of physical breakdown of the larger rock fragments and minerals. Such breakdown is in part due to the action of frost and is greatest in the surface horizons underlain by heavy textural B horizons. The mineralogical composition of the fine sand fractions within the sola of the four soils is affected by such disintegration, and thus restricts the use of mineral ratios for assessing chemical weathering in these soils. The mineral suites of all horizons are qualitatively alike and attest to the uniformity of the materials from which the soils have developed. Quartz and feldspars dominate the light fractions (sp. gr. < 2.80), while hornblende, garnet, magnetite, tremolite and opaques make up the bulk of the heavy mineral fractions.

Humification and maintenance of a high base status appear to have been the two dominant processes affecting the formation of the Black Chernozemic soil. The dominant processes leading to the formation of the Grey Wooded Podzolic soil are: the development of an L-H layer and the related lack of humification of the mineral soil, the translocation of clays, the development of a thicker and more acid solum,

despite the persistence of a high base status, and the accumulation of silt in the Ae horizon resulting from the removal of clay and from the physical breakdown of coarser fractions.

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INTRODUCTION

Grey Wooded soils, which are recognized as a distinct group of podzolic soils, occupy the Boreal Forest area of Western Canada and form the dominant upland soils of northern Saskatchewan. They also occur as islands within the Black-Grey transition zone and within the Black soil zone. In certain areas within the Black soil zone, the change in vegetation from grasses to forest occurs gradually with increasing altitude, the gradation being very similar to that associated with increasing latitude. In such areas, the changes in vegetation are reflected in the associated soil types, so that it is possible to study soils ranging from chernozemic Black to podzolic Grey Wooded soils within a small area.

This is a report of the study of the pedogenesis of a Black-Grey Wooded sequence of soils in Saskatchewan. The sequence is represented by a group of four soils selected from the Touchwood Hills area of the province. These four soils, all developed from glacial till, range from chernozemic Black, through stages of podzolic degradation, to the podzolic Grey Wooded soils. They are representative of Orthic Black, Orthic Dark Grey, Dark Grey Wooded and Orthic Grey Wooded soils. It was considered that the study of such a sequence of soils could contribute greatly to a more complete understanding of the genesis of Grey Wooded soils. The occurrence of this sequence of soils within a relatively small area

provided an opportunity of studying different soil profiles developed under similar major climatic conditions and on uniform parent materials.

The principal objectives of the investigation were:

- 1) to describe and measure the features which serve to characterize the soils under study;
- 2) to determine the nature of the processes which have resulted in their formation;
- 3) to assess the intensity of such processes; and
- 4) to evolve a general concept with respect to the genesis of Grey Wooded soils in particular.

Physical, chemical and mineralogical properties of the major soil horizons of each profile were determined. In addition, special studies were made of the mechanical separates from the major horizons. Micropedological studies of the natural soil structure were also conducted.

REVIEW OF LITERATURE

Podzolization

The terms "podzolization process" and "podzolization" were first used to designate the overall reactions and processes which led to the development of Podzols. In recent years these terms have been used in a more general sense to include those reactions and processes which result in the formation of other soils, particularly some of the Podzolic soils such as Grey Wooded, Grey-Brown Podzolic and Red and Yellow Podzolic (134). Although some characteristic differences between these groups of soils are recognized, they at least have many similarities which serve to place them together so far as their mode of formation is concerned. A short review of the characteristics and properties of Podzols will serve to indicate the general concepts of Podzol soils and of the podzolization process in general. Many of the statements concerning Podzols will apply in a more limited degree to Podzolic soils.

It is generally recognized that Podzols are soils which have developed under climatic and biologic conditions that have resulted in the accumulation of an organic surface layer (L-H) and the formation of acidic products which result from the decomposition of organic matter (77). This generally occurs in moist, cool climates under forest or heath vegetation (77, 124, 134). The acid leaching of the profile has resulted in the formation of a light-colored eluvial horizon (Ae) from which sesquioxides and humus have been removed, and

of a darker colored illuvial horizon in which some of the translocated compounds have accumulated. Although Podzols may vary widely in their morphology depending upon local variations in soil forming factors, the above-mentioned are the main features which serve to characterize them and which set them apart from other soils.

The morphological and chemical features of typical Podzol profiles developed on loamy parent material as described by Joffe (76) represent the features generally recognized by most workers as being characteristic of these soils. The A_0 horizon consists of leaf mould and forest litter in varying stages of decomposition and is about one-half to one and a half inches thick. This horizon is characterized by its high cation exchange capacity and state of high base unsaturation as compared to that of the other horizons.

The bleached ashy-grey A_e horizon below the leaf layer averages from two to six inches in thickness, is loose and powdery when dry and shows some evidence of platiness. This eluviated horizon is the most important in characterizing a Podzol profile. Chemically, the A_e is highly weathered, possesses a low exchange capacity, is highly base unsaturated and generally lower in bases and sesquioxides and higher in silica than the underlying B horizon and parent material or the overlying A_1 horizon if one is present.

The B horizon, being the layer of illuviation, is compact and heavy, brown to dark brown in color and generally

exhibits nutty structure. It is distinguished by its lower silica content, higher sesquioxide and organic matter content, increase in bases and base exchange capacity and a lower base unsaturation than the Ae. The B may or may not be indurated (77, 88, 124). When firmly cemented or indurated the layer is referred to as "ortstein" whereas if it is not cemented, it is called "orterde". The entire solum is acid in reaction, with the lowest pH generally occurring in the A₀ or A₁ horizon.

Genesis of Podzolic Soils

There seems to be general agreement by most workers that the podzolization process operates in an acid medium and that maximum expression of podzolic features are found in soils developed from acid parent materials (59, 77, 92, 125). Where calcareous parent materials, or at least those having a high base status, are concerned, complete removal of bases seems essential before podzolization can occur. As indicated by Stobbe and Wright (134), unsaturation seems to be a pre-requisite conditioning of the parent material before podzolization can proceed.

Rode, as quoted by Joffe (77), reviewed and critically analyzed the world literature on the subject of podzolization up to 1937. In summarizing the development of the Podzol process of soil formation, he pointed out that the first phase had to do with the development of plant life and the accumulation of organic residues on the surface of the soil. The decomposition of these residues leads to the

formation of acids which are capable of replacing bases with hydrogen in the surface layers. The acidic conditions so produced give rise to a breakdown of primary into secondary minerals. The next phase, which relates to the increasingly acid conditions, consists in the disruption of the secondary minerals in the upper zone of the eluvial horizon. According to Rode, "the podzolization stage is ushered in at the moment when the disintegration of the secondary minerals surpasses their synthesis in the zone of the eluvial horizon". The association of acidic reaction in the surface horizons with the podzolization process has been noted by other pedologists (59, 92, 124, 125) and it seems likely that the high degree of base unsaturation of the surface horizons is indeed a prerequisite to the podzolization process itself.

The process of podzolization is generally understood to be primarily responsible for the solution, translocation and accumulation of sesquioxides and organic matter within the Podzol profiles. In Podzolic profiles the translocation of clay is also included as a part of the process, although some may regard clay movement as a conditioning process (134), much in the same way as the removal of bases is a conditioning process prior to podzolization.

The leaching of bases, sesquioxides and humus from the A horizon of Podzol and Podzolic soils and their subsequent accumulation in the B horizon is readily evidenced by chemical analyses of these soils. The causes of these

changes and of the processes by which they are brought about are, however, subjects of much controversy. Reports by Glinka (59) and Robinson (124) indicate that early workers regarded humic material as being of major importance in podzolization and recognized that humus was in some way associated with the translocation of sesquioxides within the profile. Glinka (59), in discussing this, claimed that the mechanical movement of iron in the form of finely divided hydroxide in suspension or of aluminum as a constituent of the clay could not explain the translocations observed, even though some mechanical translocation of the finest soil particles could occur. Robinson (124) while admitting that the mechanism of eluviation was not fully understood, suggested that the sesquioxides are peptized by the humus in solution.

Morrison and Sothers (108) while adhering to the concept that free oxides protected by humus can readily be translocated within Podzol soils, indicated that an explanation for their accumulation in the B horizon is required as well. Their contention was that during winter the moisture movement within a profile is mainly downward and that eluviation predominates, whereas with the drying out of the profile in summer, precipitation of oxides occurs. Robinson (124) rejects this idea on the basis that podzol profiles should be shallower in extremely wet climates owing to the shallower depth to which the profiles dry out and claims that this is not necessarily so. Robinson

preferred to think of the deposition of humus and sesquioxides in the B horizon as being caused by precipitation resulting from the higher base status, or from the restricted permeability of the horizon enriched by mechanical illuviation.

Winters (148) suggested that iron moves in soils by surface diffusion of ferrous iron within gels in an exchange reaction with gel particles. Mattson and Koulter-Anderson (98) advanced the theory that iron moves in the form of a positively charged iron-oxide sol in association with alumina and humus. They were able to prepare iron oxide sols in the laboratory, but were making use of iron solutions having concentrations much in excess of those found in podzolic soils. The iso-electric points of their prepared sols were near pH 8.5. Schuylenborgh (128), in pursuing similar studies, discovered that the iso-electric point of the iron-oxide sols decreased as the concentration of the solutions from which they were prepared decreased. One sol which he prepared had an iso-electric point of pH 3.2 which coincided with that of the iron-oxide accumulations in a soil he worked with. He therefore concluded that the translocation of iron during soil formation may not involve the positively charged iron oxides since the pH of the soil during weathering is generally above the pH at which these are electro-positive.

Another explanation of how iron moves during soil formation was advanced by Reifenberg (121). He suggested

that iron-oxide sols move under the protection of negatively charged silica. He found that in order to bring about dispersion of iron-oxide sols, a ratio of silica to iron-oxide equal to 13:1 was required. This apparently worked well under alkaline or slightly acid reactions. Little peptization occurred at a pH below 4. A later attempt by Bloomfield (16) to repeat Reifenberg's work proved unsuccessful. Edelman (51) also found that iron-oxide hydrates do not fix silica under ordinary conditions of soil pH. Deb (45) claimed that the movement of iron in podzolic soils could not be explained by the peptization of iron-oxide sols by silica since this would require that silica be removed from the A horizon more rapidly than iron. From the above, it appears that Reifenberg's idea of silica-protected sols being active in iron translocation is open to question.

The previously discussed mechanisms by which iron and aluminum may undergo translocation in podzolic soils would come under one of the currently held theories which, according to Bloomfield (16), assumes that free oxides are transported as humus- or silica-protected sols. Another hypothesis regards this movement as being due to the formation of soluble metal-organic compounds. The term "chelation" has been used to a considerable extent in recent years to describe the latter process (7, 135).

Gallagher, as quoted by Robinson (124), considered that the effective agent of podzolization is not the commonly

suggested soluble humus, but the simple organic acids, such as oxalic acid, which are liberated during the course of plant decomposition. He pointed out that the addition of colloidal humus to sols of aluminum and iron hydroxide cause immediate coagulation, thus making it impossible for the sesquioxides to be moved from the Ae to the B horizon. On the other hand, simple organic acids, such as oxalic, could render the sesquioxides soluble. As the iron and aluminum salts move through the soil, the acid radical is subjected to progressive saturation as well as to bacterial decomposition. This results in the production, first perhaps of basic salts but finally of free hydroxides or hydrated oxides. Gallagher further claimed that the capacity of oxalic acid as well as of hydroxy acids to form complex ions with iron and aluminum which remain soluble in alkaline solution would also explain the translocation of sesquioxides in alkaline as well as in acid soils.

In 1946, Bremner et al. (22) advanced the theory that in soils some of the polyvalent metallic cations are combined with part of the organic matter as co-ordination complexes, rendering the organic matter in the complexes insoluble in water and also in neutral solvents that do not themselves form complexes with the metals. Jackson and Sherman (71) claimed that certain types of organic matter, particularly organic acids, form complexes with the sesquioxide ions and move them from the upper horizon to the subsoil; some may even pass out into the ground water.

In discussing soil development, Barshad (7) stated that "the production or liberation from organic matter of substances with high chelating properties for iron and aluminum is, in part, responsible for the movement of uncombined iron from the surface to the subsoil horizon. On the other hand, the destruction by microorganisms of the chelating properties of these organic substances in the subsoil horizon could possibly explain the deposition and accumulation of iron and aluminum oxides in this horizon." These views appear to be the same as those expressed by Gallagher although the term chelation was not used by the latter.

The term "cheluviation" was introduced by Swindale and Jackson (135) to describe a process by which minerals are decomposed by chelation in solution and which then undergo eluviation. This process depends on the presence of moving water as well as on organic substances derived from the biosphere. It would bring about a more rapid removal of strongly chelated elements such as aluminum and iron than of weakly chelated elements such as silicon. The accumulation of iron and aluminum oxides at a lower depth in a profile would be interpreted as being evidence that the portion of the profile above the zone of accumulation has undergone "cheluviation".

In recent years several investigations have been directed towards determining the effect of leachates or

extracts from materials deposited by tree cover on the mobilization of iron and aluminum. Bloomfield, in his first paper dealing with a study of podzolization (10), reported that an aqueous extract of pine needles was capable of causing the non-biological solution of ferric and aluminum oxides; during dissolution, the ferric ion was reduced to the ferrous state. The ferrous iron and possibly the dissolved aluminum were claimed to be present in the form of organic complexes. In the fifth paper of this series (14), he further stated that aqueous extracts of aspen and ash leaves had been found to react with ferric and aluminum oxides to form soluble metal-organic complexes. In contrast to the conifers, the aspen extract retained its activity almost unimpaired at high pH values, thus providing an explanation for the development of a strong Ae horizon in certain neutral or only slightly acid soils.

DeLong and Schnitzer (46), in studying the capacities of leaf extracts and leachates to react with iron, concluded from their data that poplar leaf extracts were capable of leaching both iron and aluminum from each of the soil horizons studied (A_2 and B_2) and that, in general, a greater amount of aluminum than of iron was removed under the experimental conditions used. In a subsequent study (127), the same authors concluded that, under favorable conditions, both the forest canopy and forest floor contribute solutions capable of the mobilizing and transporting iron. Aluminum and calcium could also be transported in this way. They

were unable, however, to find any clear-cut evidence of the formation of chelation complexes and concluded that "the primary function of the organic material(s) in the solutions under investigation is to act as a peptizing agent and as a protective colloid."

Atkinson and Wright (3) in following up the work conducted by Bloomfield (10, 11, 12, 13, 14, 15, 16) and DeLong and Schnitzer (46, 127) subjected a column of calcareous soil material to leaching with solutions of EDTA¹ in an attempt to bring about changes analagous to those obtained in the field. For comparison, a column of similar material was leached with distilled water only. After leaching for a period of 17 months, a "profile" which resembled that of a Podzolic soil without an A₀ or A₁ had formed in the column leached with EDTA. Analysis of the column indicated that lime, iron and aluminum had been transported from the surface to lower depths, resulting in the formation of a bleached layer near the surface and a brownish B horizon below this, underlain by a lime accumulation zone. The water-leached column, on the other hand, showed little change other than a slight browning of the top half inch of soil. It was shown that under the artificial conditions of the experiment, the leaching of a calcareous soil material with a chelating agent in a solution of a certain strength had resulted in the mobilization, transport and redeposition of

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Ethylene diamine tetra-acetic acid

iron and aluminum and in the development of a profile with well defined horizons.

As indicated by Stobbe and Wright (134) unsaturation seems to be a prerequisite conditioning of the parent material before podzolization can proceed. This occurs rapidly on some parent materials, particularly on coarse textured acid materials with low base exchange capacity. The authors point out that on saline or calcareous materials, the removal of salts and free lime from the upper layers apparently brings about dispersion of the clay, resulting in clay movement and clay accumulation. Thus, as mentioned previously, clay movement may be considered as one of the first steps of podzolization. In many podzolic soils, clay peptization and movement seem to be the major processes involved. The movement of sesquioxides and organic matter may also be involved to some degree.

According to Fridland (56) there are currently two views regarding the translocation of clays in so-called podzolic soils, placing the latter into two separate groups. The first of these include soils in which the movement of clays from the upper to lower horizons occurs without alteration of the clay minerals being moved. The second group of soils include those in which the clay particles undergo breakdown in the upper part of the soil profile, with the subsequent removal of the products of this destruction. The process involving clay translocation without destruction is referred to as "illimerization" in Russian literature (56, 57)

and is considered to differ from the podzolization process during which clays presumably undergo breakdown or disintegration. According to Gerasimov (57) similar views had previously been expressed by Duchaufour, who referred to the removal of clay without destruction as "lessivage". This process, he claimed, prepared the way for the development of podzolization. Soils which had undergone the process of "lessivage" or leaching were termed "sols lessivés" in contrast to podzolics.

Fridland (56) and Gerasimov (57) explain how true podzolic soils differ from the "sols lessivés" or those having undergone illimerization. The soils in which clay has moved without destruction have a high silica content in the A, and high iron and aluminum contents in the B horizons. The differences in composition between the A and B layers are reflected by different silica-sesquioxide ratios. The composition of the clays from the various horizons, however, produce constant ratios of silica to sesquioxide, indicating that the clay has been translocated without alteration. In contrast to this, podzolic soils show varying silica-sesquioxide ratios for the clays as well as for the different horizons. Thus, total analyses of both the clay fraction and total soil will serve to indicate whether or not the clays have been altered during soil formation. For example, data presented by American workers (132) for a Grey-Brown Podzolic soil indicate that the clays in the illuvial B horizon are identical in composition to those of the other horizons.

Analyses of the whole soil show appreciable changes within the profile which can be explained by the movement of the clay.

The comparison of clay analyses to those of the soil horizons as a whole is certainly not new and has been useful in assessing the intensity of weathering in soils in the past (77, 124). The application of characteristic differences brought out in such comparisons has, however, not always been applied in more than relative terms, and may be significantly useful in interpreting pedological processes.

The foregoing review of literature indicates that the different meanings attributed to the term "podzolization" are based mainly on the nature of the illuviated components and of the illuvial horizons of soils recognized to have undergone podzolization. Thus, the extent of translocation and accumulation of sesquioxides, humus, and of silicate clays, serves as basis for separating podzolic soils. The term podzolization as it is used in this report is accepted as a general term referring to the processes by which soils are leached and have developed eluvial A horizons and illuvial B horizons. The development of a bleached Ae horizon is recognized as being characteristic of podzolic soils, regardless of the nature of the components which have been translocated within the profile. Other profile characteristics serve to further subdivide podzolic soils.

Grey Wooded Soils

Soils which would presently be designated as Grey Wooded were first described by Wyatt and Newton (150) and Joel (75). Wyatt and Newton in their original descriptions referred to them as "Podzol-like". Joel (75) in describing these soils simply called them "grey-bush" soils and correlated them to the Russian Podzols. Subsequently, Canadian soil survey reports and published papers referred to them as wooded, grey wooded, grey wooded podzolic and grey podzolic soils. The term Grey Wooded has come into common use since about 1940 (111); Leahey (86) and Mitchell and Riecken (103) were the first to publish papers in which they were designated as Grey Wooded. Similar soils in the United States described by Thorpe (139) and Marbut (91) appear to be more closely related to Grey Wooded soils than to the Podzols of Eastern United States and Canada.

Moss and St. Arnaud (111) suggested that on the basis of morphology alone Podzols and Grey Wooded soils are quite similar and may be difficult to separate. On the basis of chemical composition, the two groups are similar in the relative distribution of SiO_2 , Fe_2O_3 and Al_2O_3 within the profiles. The Grey Wooded soils differ, however, from the Podzols in that they generally have a higher pH and a correspondingly higher base status. They show less accumulation of organic matter and a greater accumulation of clay in the B horizons. Their structural development is also more pronounced.

A review of the literature dealing with Grey Wooded soils (110, 111, 123, 144) forms the basis of certain statements which can be made with regard to the composition of these soils in western Canada. The horizons above the calcareous horizons are usually slightly to moderately acid but may range from slightly alkaline in the surface to strongly acid in the B horizons. The B horizons are often the most acid of the mineral horizons. The base status is generally high although this has not been confirmed for profiles developed on more acid, non-calcareous materials (111).

The Ae horizons are lowest in clay, bases and sesquioxides, whereas greater contents of these are found in the B horizons. There is often a slight accumulation of nitrogen and organic carbon in the B as compared to the Ae horizon. The clay minerals appear to be chiefly of the 2:1 layer lattice type (87, 144).

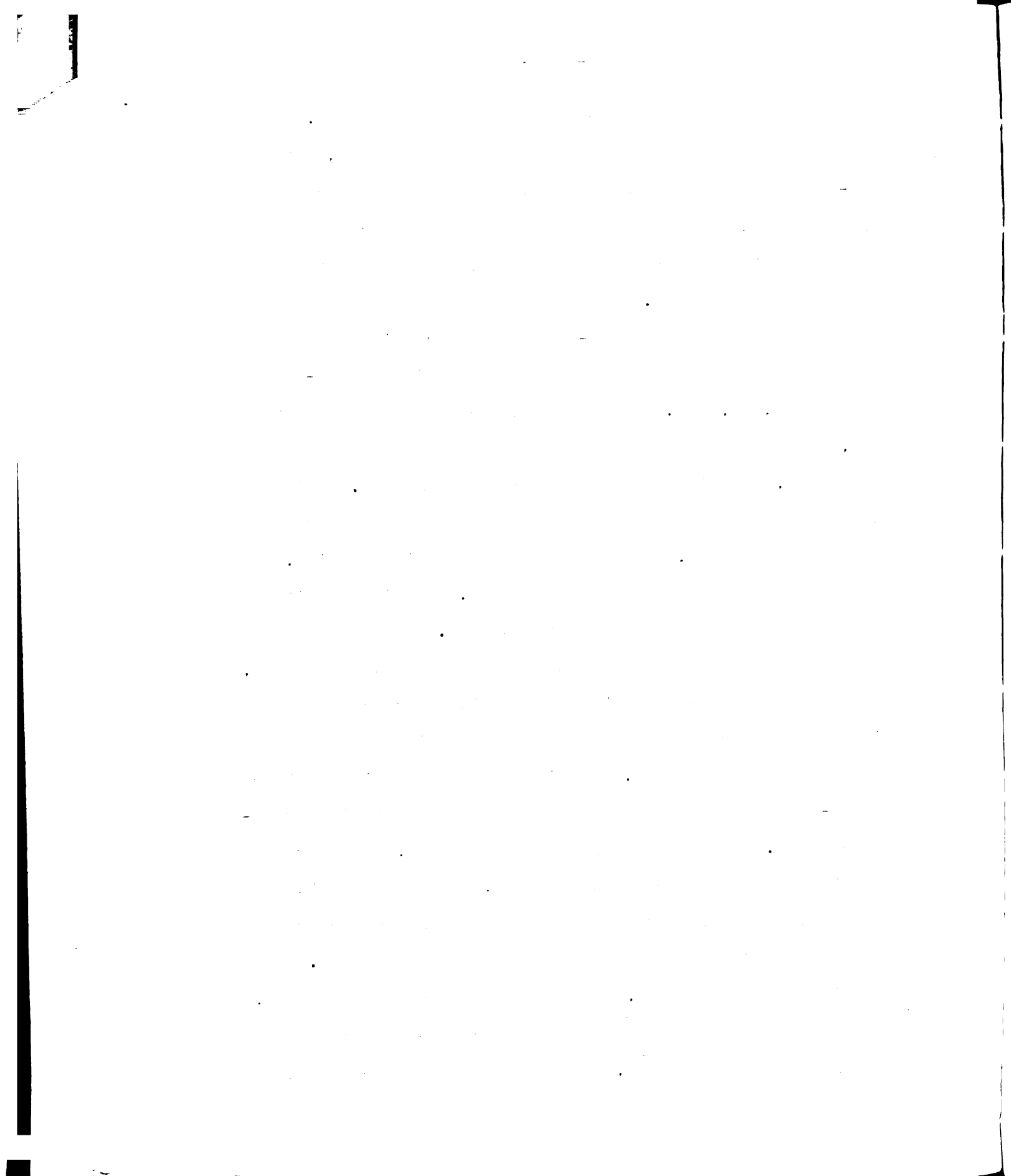
Most of the Grey Wooded soils of western Canada occur under a mixed-wood forest in which aspen and black poplar, white spruce and jackpine predominate on the upland, whereas black spruce, tamarack and willows are found in more poorly drained sites. Climatic conditions may be described as continental sub-humid microthermal, with a mean annual precipitation of about 15 inches and a mean annual temperature of 31° F. (101). The parent materials for the most part consist of calcareous glacial and post-glacial deposits overlying Cretaceous sediments (106).

Nygard et al. (114) in describing the characteristics of some Podzolic, Brown Forest and Chernozem soils of the Northern Lake States compare the Grey Wooded to other podzolic types. They claim that morphologically, the Grey Wooded soil resembles the Grey-Brown Podzolic soils more than the Podzols. It resembles the Grey-Brown Podzolic in structural and textural characteristics but differs "by the thicker A_0 horizon, whiter A_2 , virtual absence of A_3 and B_1 , greater enrichment of silicate clay in the B, better developed and more stable blocky structure in the B, higher pH and base status." It is suggested that the close resemblance of Grey Wooded soils to Podzols is mainly in the striking differentiation of horizons. The Grey Wooded soils of Minnesota are said to be similar to those described in western Canada. The authors conclude that the recognition of the Grey Wooded soils as being distinct from the Podzols is warranted and that the two should be classed as separate Great Soil Groups.

Stobbe (133) in discussing the genesis of Grey-Brown Podzolic soils of Eastern Canada describes the presence of Grey-Brown Podzolic - Grey Wooded intergrades. He points out that the Grey-Brown Podzolic and Grey Wooded soils do not differ significantly as far as the physical and chemical nature of the A_2 and B horizons are concerned but they do differ markedly in the A_0 and A_1 horizons. The Grey Wooded invariably have an A_0 and lack the mull-like A_1 which is characteristic of Grey-Brown Podzolic soils. Stobbe

attributes this to differences in climatic conditions. In transitional areas between these two types of soils, the Grey-Brown Podzolic soils have a considerably thinner A_1 than the modal types or else the A_1 shows evidence of degradation in the form of diffused greyish splotches throughout the horizon.

The genesis of Grey-Brown Podzolic soils has been discussed in a series of three papers by Cline and co-workers (39, 55, 99). Reporting on forested soils in New York, they point out that in the climatic environment of that state, leaching of bases progresses with time. While carbonates are still present in the solum and the base status is very high, there is intense biologic activity, and little or no evidence of an illuvial B. A soil at this stage would be called a Brown Forest soil. As the removal of bases continues and biologic activity decreases somewhat, the structural aggregates in the B horizon become coated with thick layers of oriented clays indicating a translocation and accumulation of clay. A soil at this stage is considered a Grey-Brown Podzolic and is characteristic of humid temperate regions. With continued removal of bases, the heavy illuvial B moves progressively deeper, biologic activity decreases and a faint "Bleicherde" layer forms directly below the leaf mat in what was formerly the A horizon. Immediately beneath this, and also in the former A horizon, is a zone of sesquioxide accumulation comparable to that in well developed Podzols. This soil is considered as a



Brown Podzolic.

Cann and Whiteside (35) studied a profile of a Michigan soil which would compare to the final developmental stage suggested by Cline and co-workers mentioned above. They also presented evidence of the B horizons being illuvial in nature but differing in the nature of the illuviated materials in the upper and lower B horizons.

Tavernier and Smith (136) in an extensive review of the literature on forested soils indicate that Grey-Brown Podzolic soils seem to develop on parent materials with an appreciable content of bivalent bases. The illuvial horizon characteristic of these soils shows an accumulation of silicate clays. This concentration of clays is probably due to their flocculation by the bivalent cations. With the continued leaching it is found that the B is destroyed and a Brown Podzolic or a Podzol tends to develop in the A₂ of the Grey-Brown Podzolic soil. The authors indicate that climatically these soils are found in somewhat warmer climates than the Podzols, or are restricted to young calcareous parent materials.

In Saskatchewan, the Grey Wooded soils occupy the Boreal Forest area (106) and form the dominant upland soils of the northern part of the province. They thus form a broad belt across the northerly portions of the soil map (Figure 1) and also occur as islands and outliers within the Black-Grey soil belt. Soils which grade between chernozemic Black soils and Grey Wooded are found between

the grassland and forest regions and were originally designated as degraded Chernozems by both Canadian and American pedologists (105, 106, 114, 147). Such soils possess both chernozemic and podzolic features in that they have well-developed textural, structural and color B horizons and the light colored, platy Ae horizons of the Grey Wooded, but still possess the relatively dark, humus-bearing Ah, incipient prismatic structure, slight to no acidity and high base status of the Black grassland soils. Most of these soils are regarded as former grassland profiles which have been changed by the influence of later invasion of trees (106) although some workers are undecided on this point (114). According to the Canadian system of classification (113), they would be classified as Dark Grey Chernozemic or Dark Grey Wooded soils, depending upon the degree of degradation expressed.

The Clay Fraction of Soils

In soils the clay fraction consists of all the materials that are less than two microns in size, and includes both inorganic and organic constituents. In mineral soils, the clay fraction is made up primarily of clay minerals which have basic crystal lattices, and which can be separated and classified into several groups according to their basic structure (29, 62, 94). Organic matter, silica, iron and aluminum oxides and other components may also occur and, if present, are generally intimately

associated with the clay minerals. The clay fraction represents the most active portion of the soil and determines in large measure its chemical and physical properties (124).

The structures and properties of clay minerals have been adequately described by Grim (62), Marshall (94) and Brindley (29). In recent years many methods have come into common use as aids in the identification of crystalline clay minerals: X-ray diffraction, thermal and optical, as well as chemical and physical methods are among the commonly used techniques. Although no one method ensures absolute identification, by combining two or more techniques it is usually possible to determine the dominant clay types and give a reasonable estimation of the clay or clays present in the colloidal soil fraction. Excellent monographs dealing with the identification of clay minerals by X-ray diffraction techniques (29) and by differential thermal analysis (90) have been published recently. Jackson (68) has also presented details of most of the methods used in clay mineral studies.

Clay Minerals in Soils

The relative abundance or distribution of minerals in soils varies with the five principal factors which govern soil formation. The time factor, climatic factors, relief factors and biotic factors as well as the characteristics of minerals present in the parent material, can be shown to have important independent effects on the clay mineral

composition of soils. (70). The parent material, aside from determining the types and amounts of minerals originally present in soils, also controls the course of chemical weathering in the soil through the relative susceptibility of its minerals to weathering and by affecting the chemical and physical properties of the soil. Time is important inasmuch as the longer the time, the more advanced will be the degree of weathering, even in temperate climates. Climate, in turn, affects the temperatures and amount of leaching which a soil is subjected to during its formation. Relief plays an important role in controlling the amount of leaching which occurs in soils; the degree of drainage, which is also associated with relief, affects oxidation and reduction conditions in the soil. Biotic factors affect minerals inasmuch as the biological characteristics of the surface soil affect its chemistry and physical condition and influence solubilization, peptization and subsequent translocation of soil components.

Considerable work has been directed towards establishing the effects of soil-forming processes on clay minerals. In some soils, colloidal clays present in the original materials may not be affected very much by weathering processes; in some soils simple translocation may occur, whereas in others the minerals may be altered or broken down into new products which may or may not in turn also undergo translocation. According to Russell (125) the effects of weathering on clay minerals can result in the

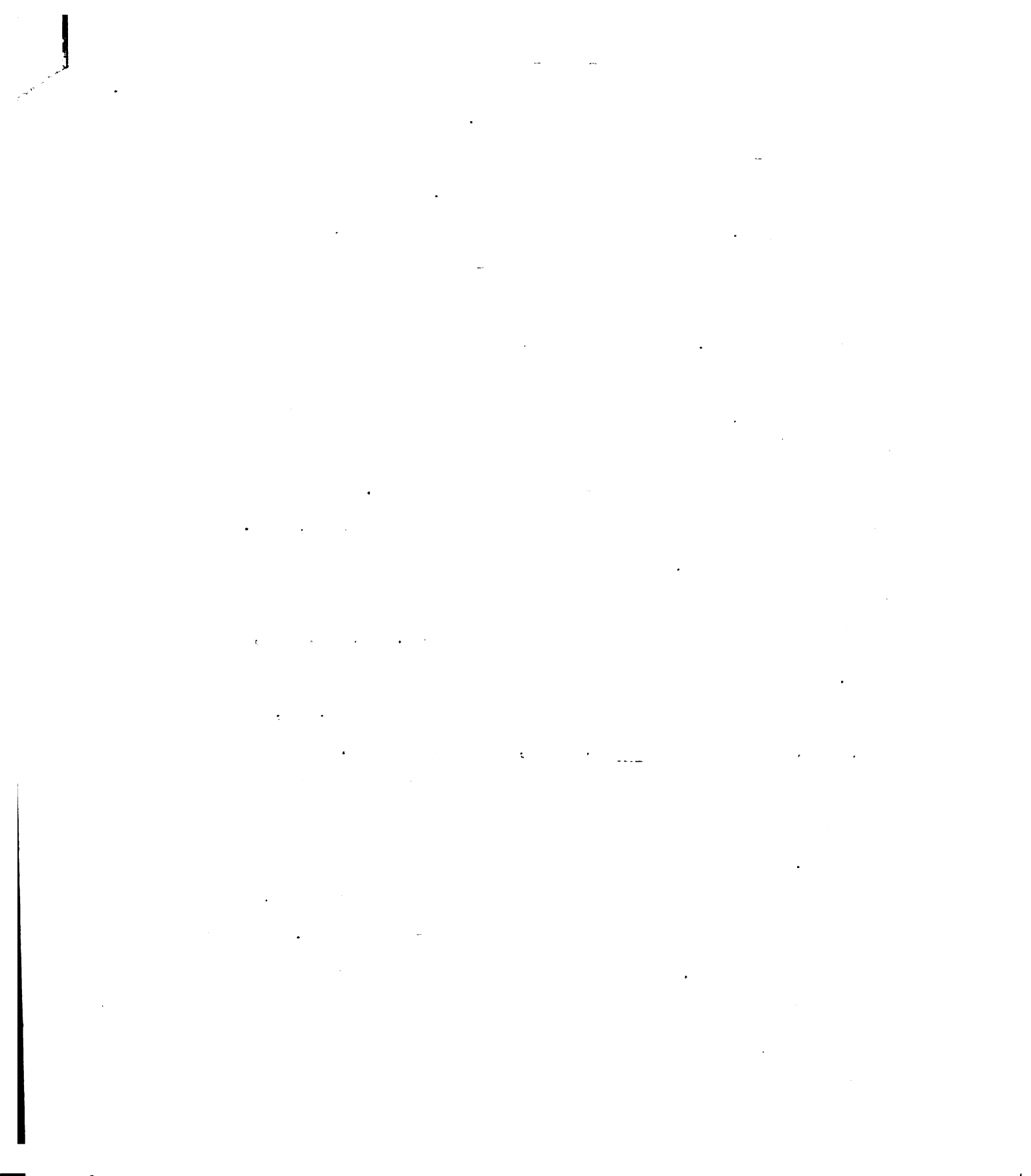
production of various types of clay minerals and various types of interlayering within minerals.

Jackson et al. (72, 73) determined the minerals present in the clay-size fraction of soils and arranged them into a weathering sequence. These authors found that, in general, one or two mineral species dominate the clay fraction of a soil and thereby characterize the soil and represent its stage of weathering. The latter will, to a large degree, be determined by the original composition of the parent material from which a soil has developed. According to the suggested weathering sequence, kaolinite, for example, is more resistant to weathering than montmorillonite, and montmorillonite is more resistant than illite. The stability of montmorillonite in temperate climates is indicated by the work of Beavers et al. (8), Kunze et al. (83) and others (52, 144).

In discussing the mechanism of chemical weathering of layer silicates, Jackson et al. (73) suggest that the weathering of mica results from four processes: depotassification, hydroxylation, de-alumination and desilication. Micaceous minerals, when subjected to these reactions, undergo stepwise transitions to mica-intermediates, vermiculite and finally montmorillonite. Illites, which may be considered to be clay-sized micas, have been reported to have undergone such a breakdown in soils (7, 58, 73, 112). Mortland et al. (109) reported the changing of biotite to vermiculite due to the extraction of potassium by growing plants.

As indicated by Jackson et al. (73) a reversal of the above-mentioned processes can and does occur where potassium is present in the soil solution. Dyal and Hendricks (50), Wear and White (145) and others (7, 109) have reported the change of expanding-lattice clays to illitic type clays by the fixation of potassium in the interlayer spaces. In many cases, where only certain "preferential weathering planes" (73) are affected by such processes, the resulting minerals take on properties intermediate between true mineral species and are known as interstratified or mixed-layer mineral types. Their occurrence in soils appears to be quite common (1, 58, 71).

In general, the kinds of clay minerals in soils in temperate climates seem to depend more on the kind of parent material than on pedogenic factors (8, 52, 58, 144, 149). For Chernozemic soils the predominant minerals usually reported are montmorillonite and illite (52, 85, 112, 144, 149). Larson et al. (85), Grossman et al. (63) and Bourne (19) indicated that in Chernozemic soils the surface horizons are relatively higher in illite than the subsoils. This is generally attributed to the translocation of montmorillonitic clays in preference to illitic types, as well as to potassium fixation by expanding-type clays. Winters and Simonson (149), in compiling data on the clay-mineral composition of the B horizons of profiles of the great soil groups, indicate that Podzolic soils contain dominantly illite with lesser amounts of montmorillonite and occasional



minor amounts of kaolinite, while Chernozemic soils are largely composed of illite and montmorillonite. This agrees with data provided by Knox, as reported by Grim (62).

The first extensive study of the mineralogical composition of the clay fraction of Saskatchewan soils was made by Warder and Dion (144). Covering a range of soils developed under grassland vegetation and also including a Grey Wooded soil, they concluded that the mineralogical nature of the clay fractions of the various soils was very similar to that of the parent materials. The weathering conditions and differences in vegetation produced no significant differences in the resulting clay minerals. On the basis of X-ray, differential thermal, and chemical analyses, they calculated the clay fraction (< .001 mm. size) to consist of approximately 45 percent illite with the remainder being a montmorillonite-beidellite type of mineral containing a high proportion of iron in the clay lattices. Brown (30), using X-ray diffraction, found montmorillonoids, hydrous mica, kaolin and calcite in the Grey Wooded soils of Alberta and Saskatchewan. He also found a mineral having a 14\AA spacing in the B horizon material which was not present in the materials of the A or C horizons. He suggested that recrystallization of the clay mineral was taking place. Clark et al. (38) found montmorillonite, beidellite, mica, kaolinite and quartz in the clay fraction of a Grey Wooded soil from Saskatchewan.

Ehrlich et al. (52), in studying the effect of

parent materials on soil formation, worked with Manitoba soils which included soils developed under both grass and forest vegetation. They found for all soils, except a Brown Podzolic and Podzol, that the mineralogy of the clay fractions was similar in many respects, the dominant minerals being montmorillonite and illite with lesser quantities of feldspars, micas and quartz. In the Brown Podzolic soil, iron oxides in addition to montmorillonite and illite were reported as the prominent components. Hematite was found to be present in the surface horizon while goethite occurred in the parent material. On the basis of the iron content alone, it was concluded that the Brown Podzolic soil had developed from a parent material differing in composition from the other soils examined. The Podzol was said to differ from the other soils in that it had a relatively higher content of feldspars and somewhat lower quantity of montmorillonitic and illitic clays. In summing up their results, the authors concluded that although the parent materials had a marked effect on the types of soils formed, in all cases there was little change in the mineralogical composition of the clays present.

Although the early mineralogical studies of the clay fraction of Western Canadian soils indicated relatively little change in composition between the profiles and their original parent materials, more recent work has brought out the fact that although differences are not pronounced, some differences do occur. The indication by Brown (30),

mentioned previously, that a $14\overset{\circ}{\text{\AA}}$ mineral occurred in the B horizon of the Grey Wooded soils, represents one case of this. Pawluk (115) reports the formation of chlorite in the B horizon of a Podzol in Alberta. He suggests that in the case of Grey Wooded soils, similar changes are not evident and that the major process has been illuviation of clay in the B rather than alteration of existing clay minerals or clay formation. Rice et al. (122) in a study which included three Saskatchewan Chernozemic soils reported that while montmorillonite and illite were the dominant minerals present in the clay fractions of these soils, the montmorillonite in the upper horizons had apparently undergone degradation. They suggested that the diffractometer patterns were being obscured by amorphous silica which had, they claimed, resulted from clay degradation. Mathieu (97), working with solodized-solonetz soils of Saskatchewan and Alberta, reported a degradation of the chlorite and montmorillonite in the coarse clay (2-0.2 μ size) fraction of the eluviated horizon, with accumulation of the degraded particles in the fine clay fraction of the illuviated zone.

In general, distribution patterns of both total and free iron within Grey Wooded soils coincides with the distribution of clay (87, 111). Whether the iron moves as an integral part of clay minerals, as coatings on clay minerals, as separate solid iron compounds, or in solution, has been a matter of much debate. Caldwell and Rost (34),

in studying a series of Chernozemic, Prairie and Podzolic soils, indicated no differences in the clay composition within the profiles studied, although clay and iron distribution varied within the profiles. Their studies indicated that Prairie and Grey-Brown Podzolic soils showed a concentration of iron in the B horizons whereas there was no evidence of iron accumulation in the Chernozemic soil studied. Simonson et al. (130) showed clay accumulations to occur in the B horizons of Wiesenboden, Grey-Brown Podzolic and Forested Planosols, whereas the iron bulge showed up only in the case of the Grey-Brown Podzolic and Brunizem soils. They concluded from this that free iron is not associated with clay distribution in the poorly drained Wiesenboden soils in the same manner that clay and free iron are associated in Brunizem and Grey-Brown Podzolic soils.

A detailed study of the nature and distribution of free iron in Grey Wooded soils of Saskatchewan was recently completed by Lutwick (87). He found that the distribution of total and free iron coincided with that of the clay fraction in these soils, and that a high correlation existed between the fine clay ($< 0.08 \mu$ size) and free iron. He attributed the accumulation of iron in the B horizons as being due to the translocation of an iron-rich montmorillonite very similar to nontronite. Goethite was also found to be present in the clay fraction. No appreciable weathering of the clay minerals had apparently occurred during the course of the development of these soils.

The Non-clay Fraction of Soils

The non-clay fraction of the soil is composed almost entirely of various minerals which vary widely in their resistance to chemical and physical destruction. As such, these minerals can be very important in assessing the degree of weathering which has taken place during soil formation. The distribution of minerals within certain size fractions of soils has come into common use as an index of weathering of soils (23, 65, 66, 95, 115, 120, 151). Also, certain resistant minerals have on occasion been used as inert indicators to assess the uniformity of deposits from which soils have developed and to assess, in quantitative terms, changes which have occurred in soils during their formation (5, 23, 65, 84). The following discussion will deal with some of the pertinent aspects of mineralogical studies of non-clay material in soils as they relate to studies in soil genesis.

Weathering of Minerals

The resistance of minerals to decomposition depends upon many characteristics such as hardness, cleavage, coefficient of expansion, original cracks in the crystal and solubility under a given environment (80, 117, 120). Pettijohn (117), by comparing the minerals in sedimentary rocks of increasing geological age with those of recent sediments, calculated an order of persistency of soil-

forming minerals. He proposed the following series in order of decreasing resistance: zircon, tourmaline, monazite, quartz, garnet, biotite, apatite, microcline, ilmenite, magnetite, epidote, hornblende, andalusite, topaz, titanite, augite, sillimanite, hypersthene, diopside, actinolite and olivine. Other workers list the stability series somewhat differently. Goldich (60) divided the minerals into three groups: (1) the least stable group, which included plagioclase, epidote, hornblende, titanite and apatite; (2) the moderately stable group of magnetite, biotite and orthoclase, and (3) the most stable group of zircon and quartz. Twenhofel (141) proposed another grouping in which chlorite, garnet, orthoclase, quartz and zircon were considered to be stable minerals, whereas the metastable to unstable minerals included augite, hornblende, ilmenite, magnetite and plagioclase. Apatite and olivine were considered to be unstable.

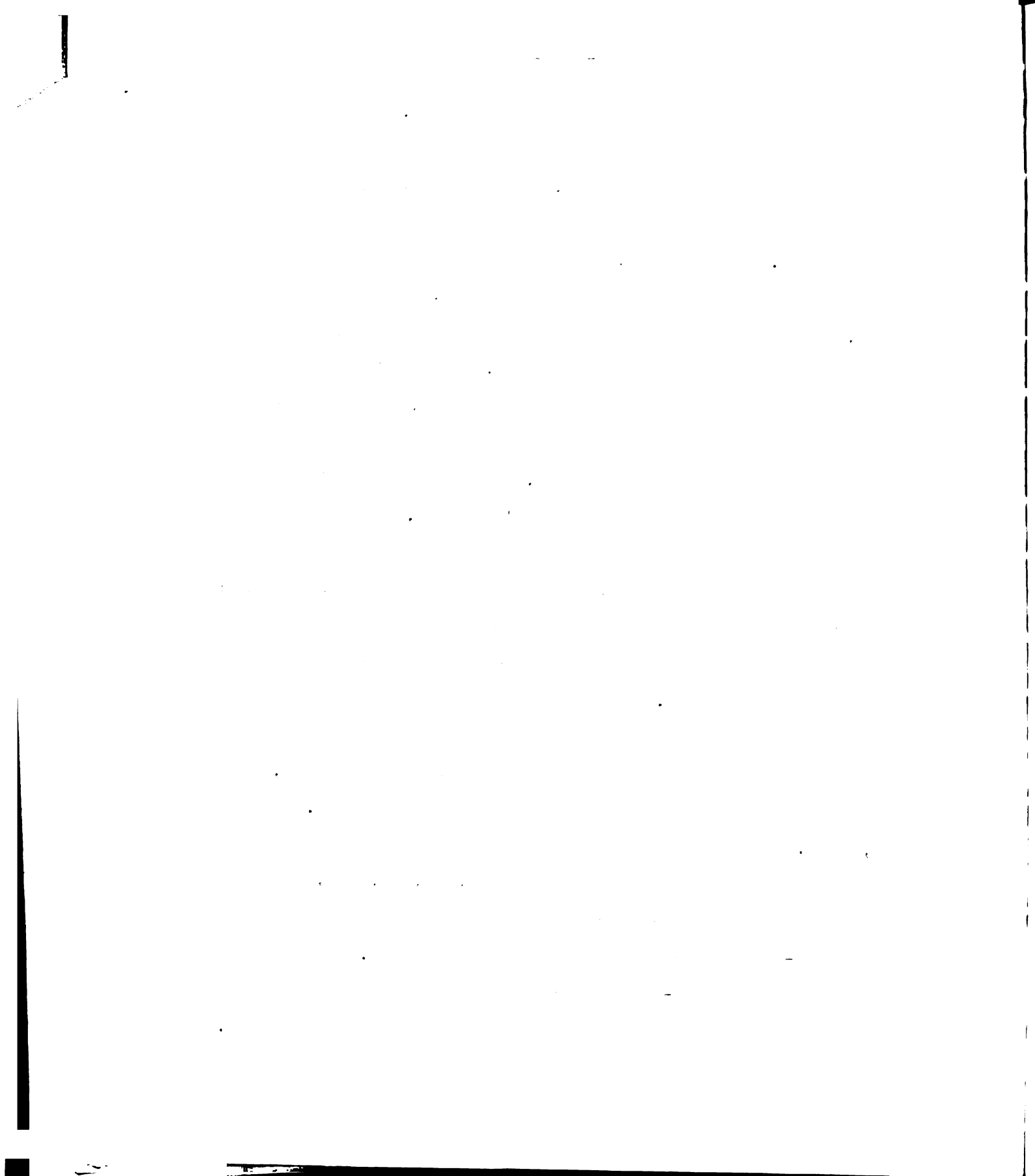
As previously mentioned, microscopic examination of the various minerals in the soil is often used to determine how extensively the parent material has weathered to form soil. Humbert and Marshall (66) investigated the heavy minerals of some Missouri soils weathered from acidic and basic igneous rocks to determine the extent of weathering and how greatly the parent material had been altered since deposition. Mick (102) working with some Michigan soils, found that the surface soils had a higher percentage of the resistant minerals than the subsoils. He concluded that the

less resistant minerals were weathered and the products removed in solution. Cady (32) compared heavy minerals from the A and C horizons of several Podzol and Brown Podzolic soils and showed that podzolization significantly reduces the amount of hornblende in solum horizons. Epidote, garnet and magnetite appear to be little affected. Pawluk (115) in reporting on mineralogical studies of Podzol soils of Alberta indicated that weathering of minerals has taken place in both the A and B horizons, the Ae horizon having lost a major portion of the feldspars and ferromagnesian minerals. Rice et al. (122), noted that in three Saskatchewan Chernozemic soils, the feldspars and ferromagnesian minerals within the sand fraction were strongly weathered, but the authors indicated that this was an inherited feature rather than having occurred in situ. Likewise, Arneman et al. (1) reported differences in the mineralogical properties of some Minnesota Prairie soils but noted that these are not pronounced, indicating relatively little weathering in these soils. They suggested that the distinguishing properties of these soils are mainly morphological rather than physical, chemical or mineralogical.

In 1942, Marshall and Haseman (95) advanced a petrographic theory for use in studies of soil genesis. This theory was based on the assumption that certain resistant minerals remain relatively unchanged during profile development. Two or more resistant minerals found in the various separates are used as indicators of depositional

or geological differences in parent materials. If the materials from which a soil developed were vertically uniform when weathering started, the ratio between any two of these mineral species should be constant throughout the profile. In addition, the use of zircon as a resistant indicator by Marshall and Haseman provided, for the first time, a means of studying quantitatively some of the changes that take place during soil formation. They pointed out that apart from the resistant heavy minerals, the coarser fractions of the soil might be just as useful indicators as zircon in soil genesis studies. Brewer (23) in his application of Marshall and Haseman's method, claimed that the value of zircon determinations was lessened because this mineral does weather in the upper horizons of Yellow Podzolic soils; also amounts are so small that accuracy of calculations based on zircon content is limited even when zirconium is determined chemically.

In an attempt to overcome some of the inherent difficulties which arise in using zircon as an indicator, some workers have suggested the use of quartz instead. (7, 118). The use of quartz as the indicator mineral has been demonstrated by several workers (5, 19, 35, 84). Cann and Whiteside (35) and Bourne (19) made use of the Geiger counter X-ray spectrometer in determining quartz. The application of the X-ray spectrometer to the determination of quartz had been previously reported by a number of workers. The reported stability of quartz (77) and its wide distribution



in soils of many regions would make it particularly suitable since it is generally present in sufficient quantities in soils to assure its accurate determination.

In mineralogical studies of soils, the mineral composition of one or more fractions from within the solum horizons is compared to that of the same fraction or fractions in the original parent material. The degree of weathering postulated to have occurred during soil formation is based upon such comparisons. The assumption that must be made in all cases is that these differences arise from weathering of minerals within the size fraction under study. Little consideration is given to the possibility of error introduced by the increase in mineral content within the fraction studied which could result either from chemical or physical weathering of material from coarser fractions within the same soil material. Since this error may be significant, literature relative to changes in particle size distribution which occur in soils as a result of soil forming processes merit some attention.

It is well recognized that both chemical and physical weathering are responsible for changes which occur in soils during their formation (71, 77, 124, 125). Generally, it is considered that as far as soil formation is concerned, chemical processes are largely responsible for pedogenic changes which occur, whereas the physical factors are chiefly instrumental in the comminution of rocks in forming the materials from which the soils developed. Physical breakdown

is generally considered to have occurred mainly prior to soil formation (124). Although physical breakdown may still occur during soil formation it is seldom mentioned. However, a few workers have suggested physical factors as causative agencies in soil formation. The chief contribution of the physical weathering of rocks and minerals to chemical weathering is the increase of specific surface of the material with attendant increase in reaction rate (71).

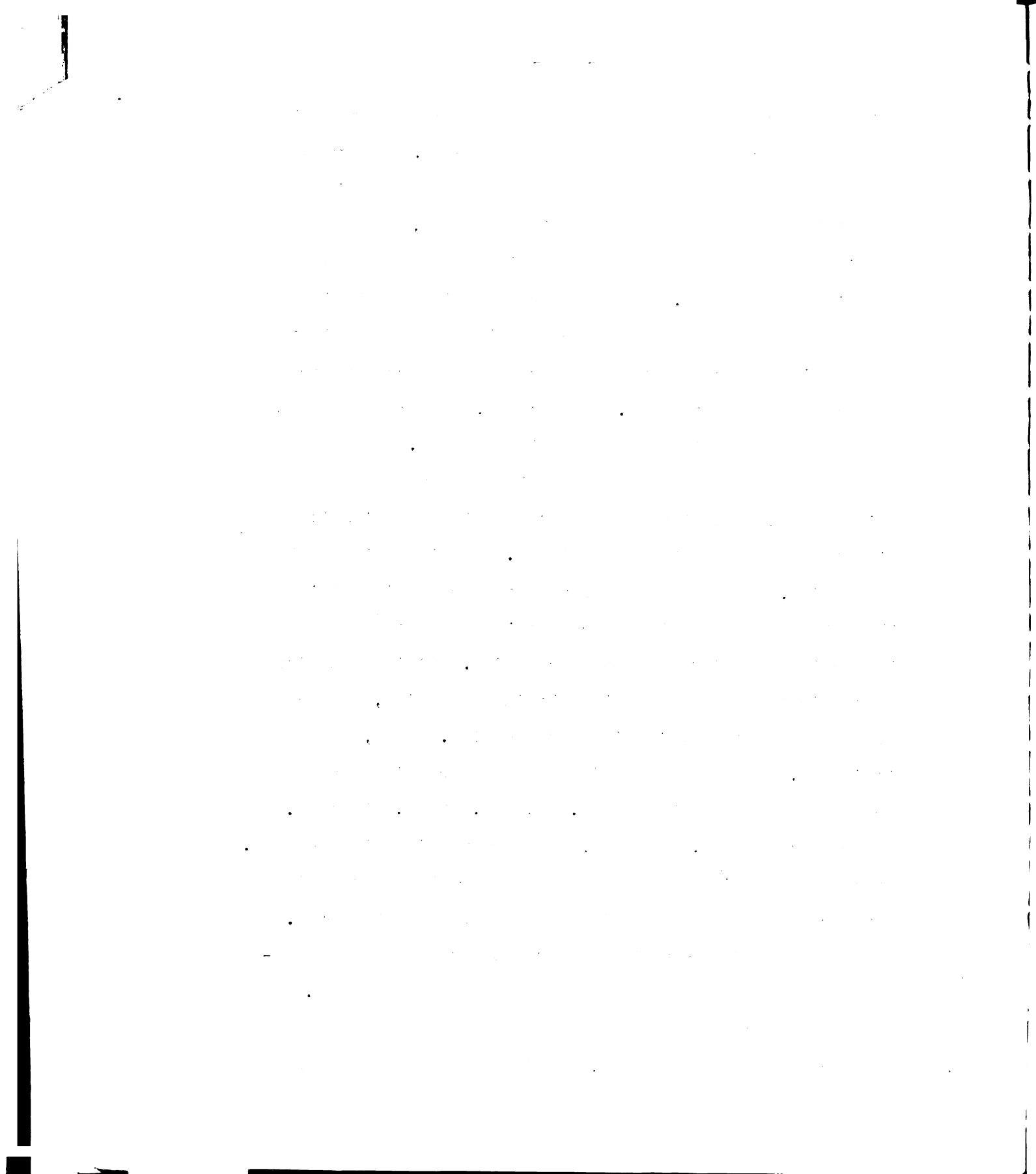
Humbert and Marshall (66) in studying a residual soil developed from granitic rock, noted that the size of quartz grains within the soil were much smaller than the quartz phenocrysts within the parent rock. The largest quartz crystals in the sand fractions measured only 1.9 mm. while quartz phenocrysts in the unweathered rock measured up to 3 mm. in diameter. They attributed the differences in size to a process of physical breakdown. The quartz phenocrysts had displayed cracks and fractures which had made them susceptible to such breakdown. Mick (102) attributed the decrease in sand in the A and B horizons relative to the parent material in a Grey-Brown Podzolic soil to disintegration which had resulted from soil forming processes. He noted that an increase in the quantity of silt complemented the disintegration of sand particles.

Ehrlich et al. (52) determined the amount of rock fragments present in the horizons of a group of Manitoba

soils and found there was a decrease in rock fragments in the solum as compared to the parent material. Although they attributed the decrease to the weathering of limestone and disintegration of shale within the solum, they had considered but discarded the possibility of disintegration as being responsible. Examination of their data indicates that the loss of easily weathered shales as well as loss of dolomite through solution effects cannot account for the entire decrease noted. Apparently, physical breakdown may have occurred in the soils being studied.

The role of frost action in the development of soils and the relation of frost to aeolian deposits is discussed in detail by Zeuner (152). In discussing soil weathering, he cites many German references which claim that fine sand and silt in frost soils are due not only to sorting but also to frost weathering. Giving examples of particle size distribution within such soils, Zeuner notes that they contain little or no clay. This, he indicates, means that the size limit of breaking down by frost can be set at between 0.01 and 0.002 mm. diameter. Mature frost soils, he notes, have a very high silt content. Zeuner also claims that frost may be largely responsible for much of the loess found in the loess belt of Europe.

Much interest in the processes of physical breakdown has been shown by French workers in recent years. Birot (9) found that rock samples of granite and syenite and large crystals of muscovite, biotite and orthoclase lost



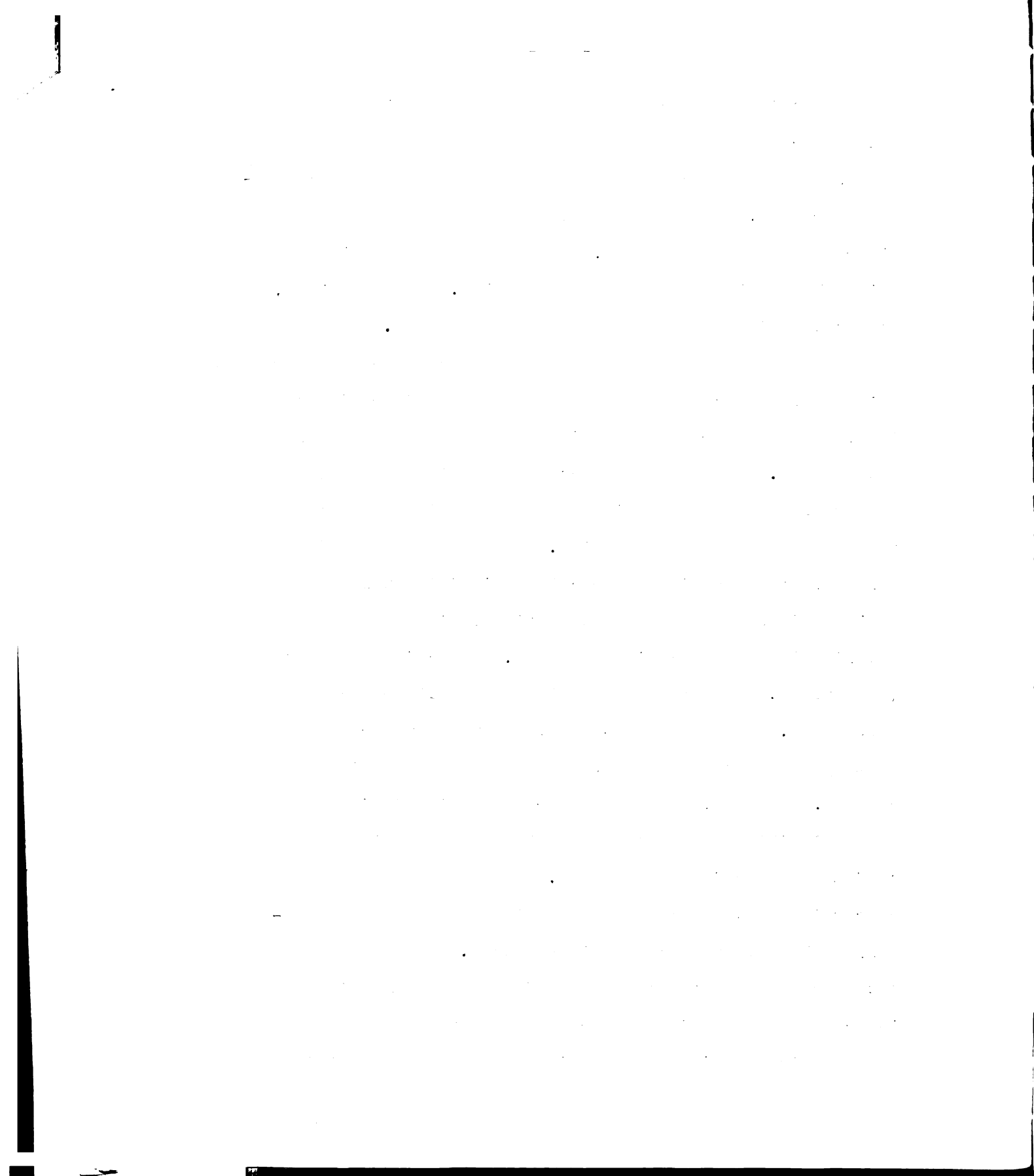
from 1 to 6 percent of their weight by disintegration into sand particles after being alternately wetted at room temperature and dried at 70° C. over a period of several months. Caillère et al. (33) obtained the breakdown of 6 percent of a slightly weathered gabbro into sand by alternate wetting and drying. Some clay which resembled montmorillonite was also formed. Rocks which contained hypersthene, labradorite and anorthite never produced clay but broke down to sand size upon being subjected to similar treatment. Demolon and Bastisse (47) obtained about a 9 percent reduction in sand content of a sieved granite sample after fifteen years of weathering in a lysimeter. Increase in the fractions ranging from 200 microns to colloidal size varied from 17 up to 51 percent. Although the wetting and drying treatments to which rock materials were subjected in the above experiments cannot be considered entirely as the only factors causing disintegration, since clays were formed in some cases, the experiments do indicate that disintegration of rock materials does occur and must be taking place in soils under natural conditions.

Stability of Quartz

The use of quartz as an index mineral in studies of soil genesis has been mentioned previously. Also, since quartz makes up a large proportion of the non-clay fraction in soils, its stability is important inasmuch as it relates

to the previously discussed effect of changes in particle size distribution on the use of mineralogical studies in assessing changes occurring in soils as a result of weathering processes. Numerous references occur in pedological literature regarding quartz, the consensus of opinion being that it is resistant to weathering. A few workers, however, admit its stability with reservations.

Polynov (119) stated that "primary quartz is such a stable substance and undergoes so little alteration that it may be considered to be quite passive in the zone of weathering". Russel (125) accepts this view and rates quartz as the commonest mineral in most soils and the most resistant to decomposition. Barshad (7) claimed that quartz and albite underwent no significant change during soil formation and that their particle size distribution would remain unchanged. According to Joffe (77) quartz, being one of the final residual products of weathering, is stable and cannot, under natural conditions of temperature and pressure, undergo further chemical changes. However, he cites references which indicate that solubility of quartz is possible and that it is subject to leaching in solution. He further states that conclusive evidence of the solubility of quartz is demonstrated by its presence in river waters. Raeside (120) questions this last conclusion and suggests that silica is transported in river waters not as quartz but as monosilicic acid in true solution or as amorphous silica

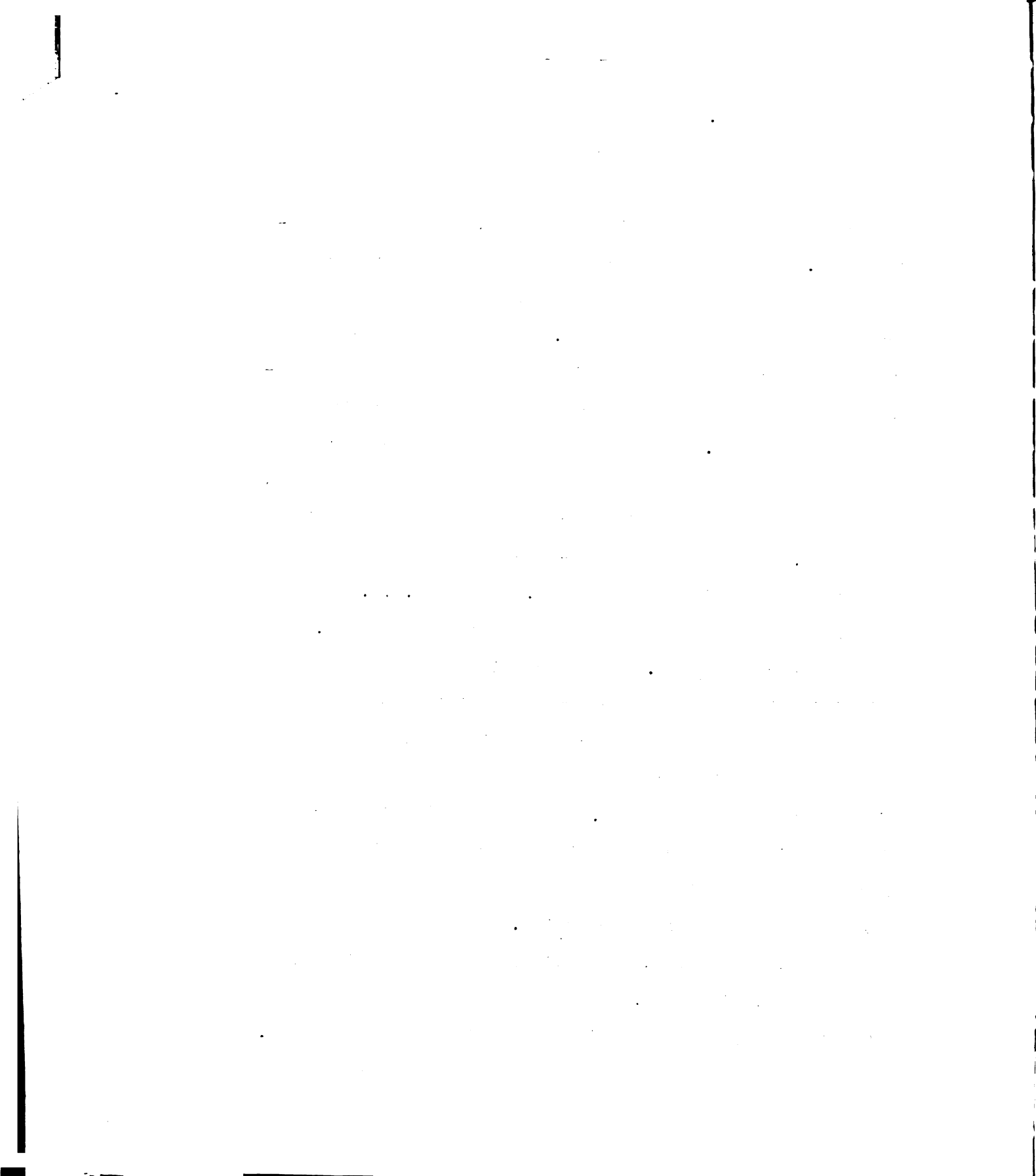


in colloidal form.

There is a considerable literature referring to the solubility of silica but only a limited number of references to the solubility of quartz, many of them conflicting. Mategnon and Marchal (96) demonstrated that appreciable quantities of silica can be dissolved from quartz by cold carbonated water. Moore and Maynard (107) confirmed earlier work which indicated that water containing calcium and magnesium carbonates was an effective solvent of quartz. Partial replacement of quartz by carbonates in sediments has been reported by Walker (143). Siever (129) in summarizing recent views on the solubility of silica, used published free-energy data to calculate a theoretical solubility range of 7.25 to 14 p.p.m. which agrees fairly well with the observed range of values.

Jackson et al. (72) have pointed out that quartz solubility is a linear function of specific surface and therefore quartz may be expected and is found to decrease tenfold in quantity for each tenfold decrease in particle size of fraction considered. Raeside (120) points out that solution of quartz in soils changes not only the total amounts of quartz in the sand and silt fraction but also changes particle size distribution.

Raeside (120), in considering the stability of index minerals in soils, indicates that quartz may not possess the physical stability generally attributed to it. He argues that although quartz possesses no well-defined



cleavages along which easy splitting can occur such as in amphiboles for example, it is nevertheless susceptible to strain effects which show up distinctly on the microscope stage as undulose extinction, strain shadows or irregular and uneven extinction. These strains express local dislocations of the crystal lattice and would, in turn, lead to stresses during thermal expansion. He states that the examination of quartz grains in soils shows that such disruption does occur and that incipient and well-defined fracturing is associated with local strain. His views are shared by Humbert and Marshall (66) who attribute the fractures and strains apparent in quartz phenocrysts in rocks to have resulted from the α to β inversion of quartz.

Rupture of quartz has often been attributed to pressure exerted by both gaseous and solid inclusions. Recent work by Ingerson (67) has shown that appreciable pressure is not exerted by gaseous inclusions at normal pressures, and that these, at least, cannot therefore be accepted as disruptive agents. As suggested by Raeside (120) the freezing of water in microfissures in the upper horizons of certain temperate and sub-arctic soils may accelerate quartz breakdown but before this process can be effective, these microfissures must be enlarged sufficiently to permit freezing of the contained water. The presence of clay-like material in grain fissures may accelerate the disruption of an already fissured crystal. The penetration of an iron pan into apparently homogenous

quartz stones or boulders has been observed by many workers. This is effected by the deposition of iron oxides from soil solutions in microfissures which in one case cited (120) were mostly less than three microns wide.

MICROPEDOLOGY

In recent years, micropedological techniques have come into common use and have been a valuable aid in the study of morphological characteristics of soils. Up until 1938, the year in which Kubiena published the first book on the fundamental principles of micropedology (81), very few micro-investigations of soils had been undertaken except in the field of soil microbiology. As indicated by Kubiena, chemical and physical analyses conducted on the various horizons of a soil profile may give an overall picture of the chemical and physical changes which have occurred as a result of soil forming processes but fail to give a complete picture as to the exact nature of these changes and the mechanisms by which they are brought about. The study and interpretation of soil micro-structures and micro-fabrics provides an additional means of assessing and understanding pedogenic changes which occur in soils.

One of the most common procedures used for the microscopic examination of soil structural features involves the preparation of thin sections. Thin section techniques were well established in petrology and metallurgy long before their use was applied to soil studies (81). One

of the main difficulties in the preparation of soil thin sections lies in the need to impregnate soils with special hardening substances so as to preserve the natural soil fabric. Parrafin wax, bakelite, lacquer, Kololith, Castolite, and Lakeside 70, are among the many substances which have been tried for impregnating soils for thin section preparation. Many of these materials were found to be too soft for grinding or the refractive indices unsuitable for petrographic work. Soil structures vary so widely that no one impregnating medium appears suitable for all soils. Lakeside 70 (43, 151) and castolite (18, 97, 100) have been used extensively in recent years and appear to give satisfactory results for many soils.

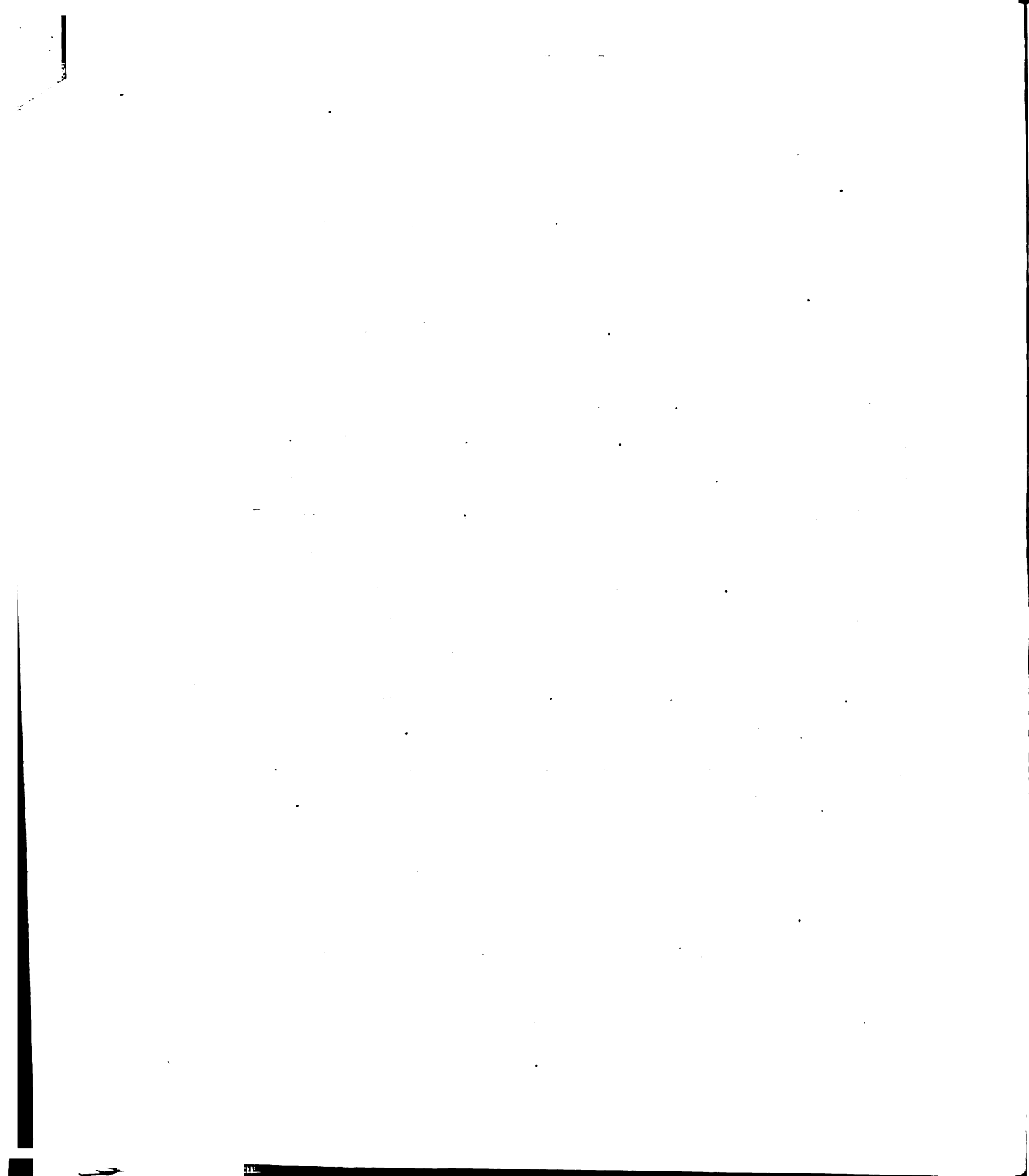
Terminology

Much confusion has surrounded the general use of such terms as texture, structure and fabric to describe the physical characteristics of soils. In petrology, the essential characteristics of the physical constitution of rocks have been enumerated and grouped in various ways, but these inevitably deal with the size, shape, arrangement and crystallinity of their component solid particles. Kubiena (81) realizing that the terms texture and structure as used by pedologists did not conform to the meanings attributed to them by petrologists, tried to avoid their use as much as possible. He preferred to speak in terms of soil fabric which he referred to as "the arrangement of

the constituents of a soil in relation to each other". In this sense, soil fabric was used as a counterpart of rock fabric.

Brewer and Sleeman (28), condoning rather than avoiding the inconsistent use of the terms texture and structure, attempted to promote their use by assigning them acceptable definitions. They define soil texture as the physical constitution of a soil material as expressed by the size, shape, arrangement and crystallinity of its component particles. In contrast, soil structure, as they define it, refers to the physical constitution of a soil material as expressed by the size, shape and arrangement of the solid particles (both primary and compound) and associated voids. Finally, soil fabric is defined as the physical constitution of a soil material as expressed by the spatial arrangement of the solid particles and associated voids. By definition, therefore, fabric is a part of structure, which in turn is a part of texture. Fabric is the element of structure which deals with arrangement and, as such, was given prominent importance by Kubiena (81). Brewer preferred to stress both structure and fabric since both are concerned in the physical constitution of soil materials.

In considering soil materials, it must be realized that they are composed of two broad groups of constituents having quite different properties; one group includes components which are quite stable, whereas the other is



composed of materials capable of movement, concentration and reorganization during soil formation (28). Kubiena (81) referred to the stable constituents as "fabric skeleton" and the mobile, active elements as "fabric plasma", whereas Brewer and Sleeman preferred to speak of them simply as "skeleton grains" and "plasma". Skeleton grains, being relatively stable, would include mineral grains and resistant siliceous or organic bodies larger than colloidal size (28). Plasma, on the other hand, refers to the portion of soil material which is capable of being translocated, reorganized, and/or concentrated as a result of soil forming processes.

Kubiena (81) in classifying soil fabrics, considered that fabrics could be broken down into two units-- simple (or elementary) and compound. Elementary fabric referred to the arrangement of the constituents of lowest order in the soil and their relation to each other. Compound fabrics, in turn, had to do with more complex features of soils and represented the arrangements pertaining to aggregates, wall complexes, cleavage blocks or any other units of higher order. Using these as the fundamental units he was able to describe and name characteristic fabrics, which he recognized as representing specific types and which he associated with certain soils. As far as possible, he attempted to explain the mechanisms involved in the soil-formation processes which led to the development of various fabric types. In addition, he was able to reproduce certain fabrics in the laboratory by subjecting soil material to various treatments

intended to simulate natural processes operating in soils.

Although many of Kubiena's techniques have been used in subsequent micropedological investigations, few workers make use of the names suggested by him for the different soil fabric types. The reason for this is not too apparent. It may be that most studies have been concerned with specific aspects of soil genesis in which the workers have been more concerned with special details of the microfabric rather than the soil fabrics as such. Also, there is the possibility that Kubiena's descriptions lack the detail necessary or that his association of certain fabrics to specific soil types has made workers hesitate to apply specific names to fabrics of soils outside of Europe. Brewer, in recent literature (28) has attempted to outline a more systematic approach to the study of micro-structures and microfabrics which may lead to a more unified means of describing these and eventually lead to an acceptable terminology in the naming of them.

Brewer and Sleeman (26, 28) in considering the organization of soil constituents, pointed out that soil-forming processes lead to the development of a series of features with specific fabrics and structures. These they called "pedological features". These may be designated as recognizable units within a soil material, which can be distinguished from the enclosing material for any reason such as origin, differences in concentration of some fractions of the plasma, or differences in arrangement of the

constituents. Pedological features can be grouped into two classes, those which are inherited from the parent material, and those which are formed in situ as a result of soil forming processes. The latter group would include plasma concentrations, plasma separations and fossil formations-- the names implying their mode of origin. Plasma concentrations are due to local accumulations of plasmic materials, whereas plasma separations result from a reorientation of materials rather than accumulations. Fossil formations represent preserved features such as animal burrows, worm casts and root channels resulting from biological activity.

Brewer (26) proposed the term "cutans" for a broad group of pedological features which consist of concentrations and separations of fractions of the plasma associated with natural surfaces within soil materials. These include clay skins which surround skeleton grains, peds and various kinds of voids. The main differentiating characteristics of cutans relate to the kind of surface with which they are associated, the mineralogical nature of the cutanic material and the fabric of the cutans themselves. Brewer claims that on the basis of their characteristics, cutans can be interpreted in terms of the genetic processes which resulted in their formation. This permits separation of cutans into classes based upon their mode of origin, such as those resulting from illuviation, diffusion and stresses within soil materials.

The degree of orientation of cutanic material is an important characteristic which aids in diagnosing the mode of origin of certain cutans. For instance, a high degree of orientation of cutanic materials is generally, although not always, indicative of concentration of colloidal clays resulting from processes of illuviation (24). Cutans resulting from in situ formation of clays or due to diffusion processes may, on the other hand, be crystalline in nature or show indeterminate orientation (24, 26, 28).

GENETIC INTERPRETATION OF MICROMORPHOLOGICAL FEATURES

The changes which occur in soils as a result of soil forming processes invariably bring about changes in the fabric and morphological characteristics of the soil materials affected. As indicated by Kubiena (81), every microscopic happening in a soil has left its picture in the fabric. Thus, the history of a soil can be read in the soil fabric, if we are able to interpret that which we find in it. The proper interpretation of micromorphological features in soils can be very useful in promoting a better understanding of the soil forming processes which resulted in their development. Kubiena (82) following extensive micropedological investigations of European soils, was able to introduce a classification of soils giving great weight to soil genesis and making much use of micromorphological observations in recognizing

and describing soil types. The number of studies which include descriptions of the pedological features and microfabrics of soils has increased in recent years and serve as evidence that microscopic studies of soils are invaluable in complementing the more commonly accepted means of studying the soil.

Although it is not possible to consider all the microscopic features which may reflect the type of processes which bring about the formation of different soils, a brief summary of some pertinent studies may suffice to indicate how some micromorphological features are interpreted in terms of soil genesis. For example, "chernozemic fabric", which is characteristic of the surface layers of chernozemic soils, was studied by Kubiena and he was able to interpret it in terms of soil genesis. In this type of fabric the mineral grains generally appear bare and free of coatings. They are united with each other by inter-granular braces or are embedded in a porous groundmass of flocculated colloids.

The fabric plasma is dark brown to blackish in color and consists of black humus particles, coagulated inorganic colloids, fine rock fragments and peptized brown humic substance. This humic substance often forms a brownish film around the mineral grains. It is insoluble in water and as such imparts great stability to the aggregates formed as a result of its presence in the intergranular braces.

On the basis of observations and laboratory tests

designed to reproduce the processes involved in the formation of chernozemic fabric, Kubiena was able to postulate its mode of formation. He claims that this type of fabric is produced "because most of the inorganic and organic colloids are flocculated or in an undissolved state, although some of the humic substances are dissolved or peptized in the soil solution". He suggests that as the soil dries out, the soil solution becomes more alkaline and causes dissolution of portions of the organic matter present in the soil. Upon further drying the dissolved material acts as a cementing agent which, being insoluble in water, helps in the formation of stable aggregates. Thus, a high base status, high organic matter content and a climate in which wetting and drying occur frequently seem to be necessary prerequisites to the formation of chernozemic fabric.

Many eluvial horizons in soils are distinguished morphologically by their leached appearance and platy structure. The occurrence of well developed platy structure gives rise to what is generally referred to as banded fabric. As described by Kubiena (81) banded fabric appears microscopically to consist of alternating layers of enrichment and depletion of plasmic materials. Actually, each band shows a gradation in plasma content with the highest content of colloidal material being near the top of the plate. The bands can vary in density, thickness, color and shape. As indicated by Kubiena, although banded fabric generally

suggests more or less uniform conditions in soils, these conditions must vary inasmuch as alternating aerobic and anaerobic cycles are also suggested.

Kubiena (81) has advanced theories based on his observations which serve to explain how some types of platy structure have developed. He claims that banded fabric occurs in compact soils which have a uniform skeletal fabric and which do not form cleavage blocks or fragments, so that relatively large channels or cracks are lacking. Dissolved or dispersed colloidal materials such as humus, clay and sesquioxides tend to accumulate in the form of bands within such soils. Kubiena suggests that drying of the soil from the top down produces a zone of enrichment of colloidal material at the evaporating surface. This accumulation in turn results in a "capillary draft" into the zone causing more colloids to be drawn to it. When the adjacent eluvial layer directly below it dries out, transportation is interrupted for a time, but is then resumed at a new evaporation surface within the soil system. The occurrence of layers relatively rich or poor in plasma follow one another in a rhythmic pattern throughout the skeletal material of the soil. The denser accumulation zones, in contact with the depleted ones, form an easy horizontal plane of parting. The eventual breaking of the soil mass along these planes gives rise to platy structure. McMillan and Mitchell (100) in describing the nature of banded fabric in Saskatchewan

soils note that the plates formed are darker on one side than the other. This is explained by the occurrence of clean skeletal material on one side of the aggregate and skeletal material enriched by soil plasma on the other. Although Peterson (116) associated platy structure with high kaolinite content of soils, this apparently does not hold for many Saskatchewan soils (which are low in kaolinite but which still exhibit well developed banded fabric). Czeratzki (42) offers still another explanation for the formation of platy structure. He attributes platy structure in compacted soils as being due to the formation of ice lenses; as the water in a soil freezes, more water flows to the freezing zone thus causing clear sheets of ice to develop. The pressures due to the freezing water cause the soil to fracture along horizontal planes.

Although banded fabric as described by Kubiena (81) has been observed in the leached horizons of Saskatchewan podzolic soils (100) a different type of banded fabric appears in the leached layers of solonetzic soils. The platy A_e horizons of a solonetic and a podzolic-solonetzic soil were described by McMillan and Mitchell (100) as having "isoband" fabric. The term "isoband fabric" was suggested for bands apparently having complete uniformity in both skeletal and plasmic materials. No explanation is offered as to the mode of formation of this type of fabric. Frei and Cline (55) in their study of Grey-Brown podzolic soils show a micrograph of platy

structure occurring in a "B" horizon. These bands show no gradation in texture and could also possibly be classified as an isoband fabric according to McMillan and Mitchell (100).

The B horizons of many soils show very little accumulation of clay or other colloidal material while many others show definite accumulations. Illuvial horizons which are characterized, analytically, by a greater clay content than their associated A horizons, have been of particular interest to pedologists. The problem in relation to soil genesis is to determine the mechanism by which the clay-size material accumulates in the illuvial zone, whether it be due to illuviation or to in situ formation.

Clay accumulations in soils often occur as clay coatings or clay skins; these would fall into the group of pedogenic features described by Brewer as cutans (26). The presence of clay skins have been reported in soil profiles of many great soil groups, including Solonchic (97), Grey-Brown Podzolic (39, 55), Brown Podzolic (55) and Humic Glei (132). The occurrence of optically oriented clay layers surrounding mineral grains, peds, channels and pore spaces has been accepted by many workers as an indication of clay migration and deposition, either by clay synthesis from solution or from colloidal suspension. Buol and Hole (31) suggest three possibilities by which clay skins may develop in soils: clay material along

with organic compounds may move down the profile in percolating water in the form of constituents which become synthesized as clay minerals which are deposited below; or they may move down as clay suspensions, passing through and being deposited along cracks in the soil; or clay skins may form in place from constituents released by decomposition of plant roots and weathering of minerals; or they may be the result of pressures exerted by expanding or shifting of soil masses.

Brewer, in describing clay accumulations, stresses the orientation demonstrated by clay films inasmuch as this reflects the possible mechanism involved in their formation (26). A high degree of orientation is generally indicative of the illuvial nature of the clays. Brewer (24) points out that soil properties such as bulk density, porosity and particle size distribution should be taken into account in attempting to differentiate between illuviated clays and those formed in situ. For example, clays formed in situ may show a certain amount of orientation due to wetting and drying effects but should be accompanied by no or little change in the bulk density and porosity of the soil materials in which they occur. This points out the fact that micropedological observations should be used in conjunction with other physical, chemical and mineralogical studies to explain pedogenic processes.

As previously indicated, one of the main problems in explaining the accumulation of clay in B horizons of

many soils is to determine whether this is due to illuviation or due to in situ formation. Mick (102) after calculating "weathering indices" from the ratios of certain resistant minerals to show the conformity of soil and parent material, concluded from physical and mineralogical determinations that the increase in clay content in the B horizon of a Grey-Brown Podzolic soil was not necessarily caused by illuviation, but that clay may have formed in place. Illuviation, he claimed, possibly played a more minor role in Grey-Brown Podzolic soil development than had been previously supposed. This view has been substantiated by Brewer (23) by a careful study, using similar methods, of a Yellow Podzolic soil in which clay had been presumably formed in situ in the B horizon. Thin sections were used to demonstrate this and to show that the micromorphology associated with clay movement was lacking.

CHARACTERISTICS OF THE SOILS INVESTIGATED

Profiles Selected

Four soil profiles, ranging from chernozemic Black through stages of degradation to podzolic Grey Wooded soils were selected for this study. The four soils, representative of Orthic Black, Orthic Dark Grey, Dark Grey Wooded and Orthic Grey Wooded types, were all developed on calcareous medium textured glacial till, probably of Valderan age (37), and occurred within a relatively small area located in the Touchwood Hills of Saskatchewan. (Figure 1) The Touchwood Hills form an island within the main boundaries of the Black soil zone and rise approximately 400 feet above the surrounding plain, reaching a maximum elevation just over 2,200 feet above sea level. The changes in vegetation and in associated soil types resulting from the increase in elevation are similar to those observed with increasing latitude within this region, except that the former occur within a much shorter distance. This vertical zonation facilitated the selection of profiles on much more uniform parent material than would have otherwise been possible.

As indicated above, the four soils selected for this study represent a group of soils which range from the chernozemic Black soils through various stages of degradation to podzolic Grey Wooded soils. The Orthic Black and Orthic Dark Grey soils fall within the Chernozemic

THE SOIL ZONES OF SASKATCHEWAN



LEGEND

1. Brown Soils of the open prairie, the most arid section of the province. Wide variations in crop yields and frequent severe droughts.
 2. Dark Brown Soils of the prairie, less arid than the Brown Soils. Variable crop yields but less frequent severe droughts.
 3. Black Soils of the parkland. Better moisture conditions and better average yields than on the prairie. Severe droughts rarely experienced.
 4. Deep Black and Greyish Black Soils of the parkland-forest belt. Good moisture conditions and high crop yields.
 5. Grey Wooded Soils of the forest region. Moisture conditions good, but soils are low in organic matter and general fertility.
 6. Grey Soils and Muskeg of the unsettled Northern Provincial Forest.
- Boundary of Northern Provincial Forest Reserves.

Figure 1. Map of the southern portion of Saskatchewan indicating the major soil zones and specific area (see arrow) from which the four soils under study were selected.

Order according to the Canadian system of soil classification (113), whereas the Dark Grey Wooded and Grey Wooded soils would be classified within the Podzolic Order. The classification of these soils by both the Canadian (113) and proposed American (132) systems of classification are presented in Table 1.

Climate of the Area

Although no climatic or meteorological data are available for the sites from which the four profiles were selected, data recorded at Hubbard, Saskatchewan, some fifty miles south-east of the site locations, will serve to illustrate the climatic conditions which prevail in the general area of the Touchwood Hills. Records collected over a 20-year period (101) indicate the mean annual temperature to be 32° F. and the mean annual precipitation to be 16.17 inches.

In this area, great extremes in temperature between summer and winter are characteristic, summer temperatures of over 100° F. and winter temperatures of below -50° having been recorded. There are also frequent wide fluctuations in temperature from day to day and between day and night. During the winter, low temperatures prevail and the ground may remain frozen for four to five months of the year. Although no records of soil temperatures are available for the area, soil temperature records at Saskatoon (64) indicate that depth of frost may at times exceed six feet.

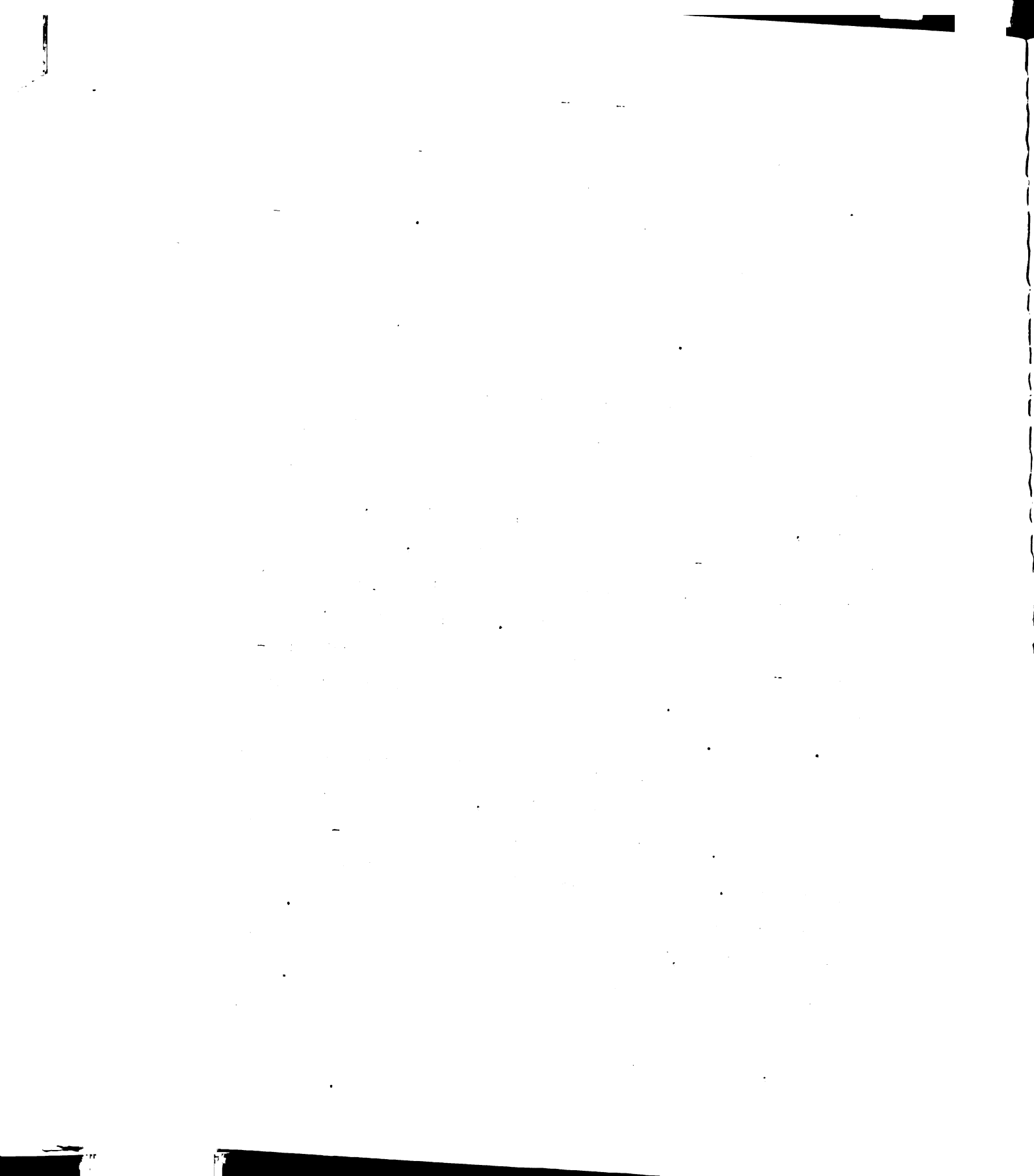


TABLE 1. CLASSIFICATION OF THE FOUR SOILS STUDIED

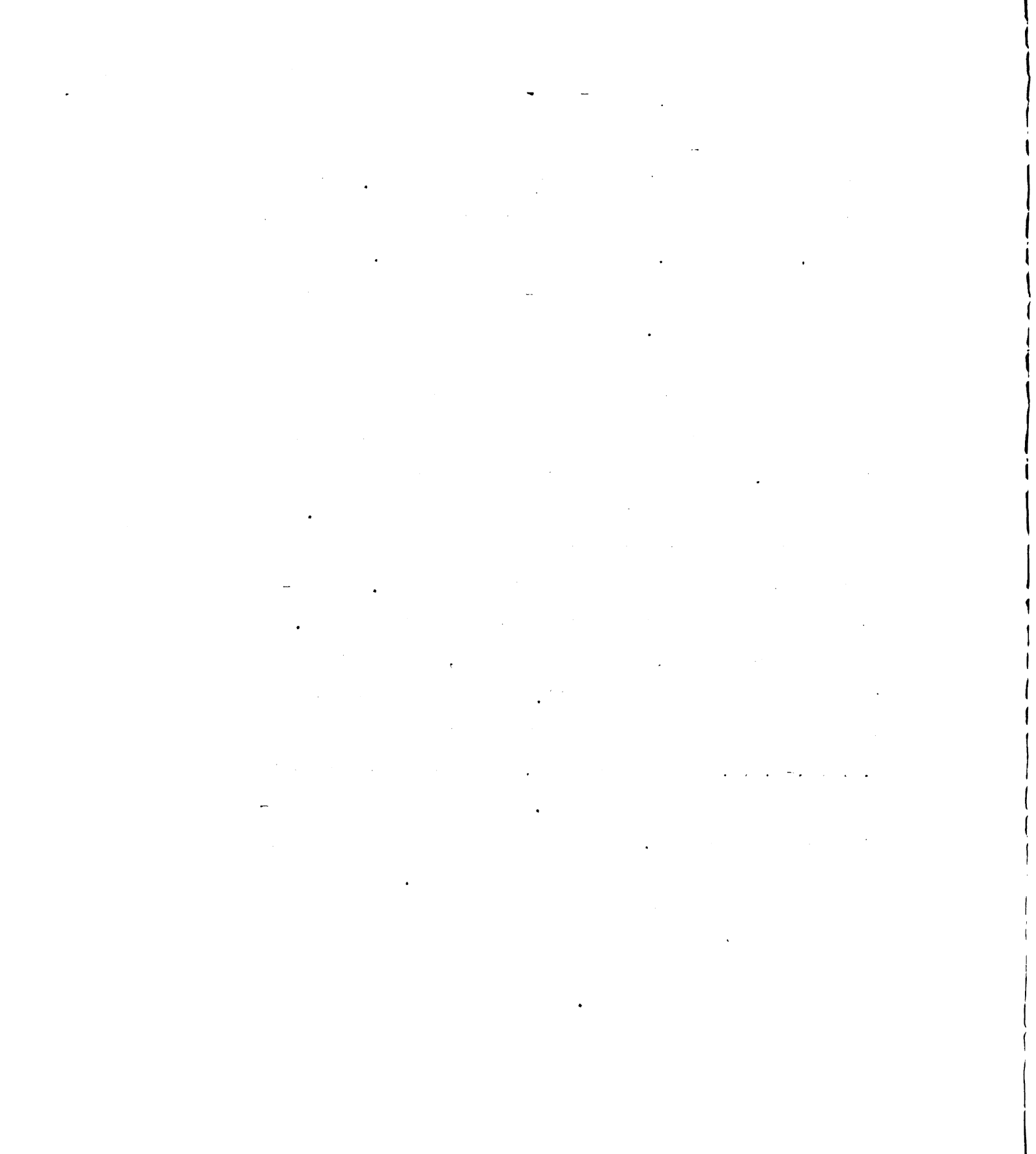
<u>CANADIAN SYSTEM (113)</u>			<u>PROPOSED U.S.D.A. SYSTEM (7th Approximation) (132)</u>		
<u>Order</u>	<u>Great Group</u>	<u>Sub-Group</u>	<u>Order</u>	<u>Sub-Order</u>	<u>Great Group</u> <u>Sub-Group</u>
1. Chernozemic	Black	Orthic Black	Mollisols	Altoll	Argaltoll Orthic Argaltoll
2. Chernozemic	Dark Grey	Orthic Dark Grey	Mollisols	Altoll	Argaltoll Alfalfic Argaltoll
3. Podzolic	Grey Wooded	Dark Grey Wooded	Alfisols	Altalf	Typaltalf Orthic Typaltalf
4. Podzolic	Grey Wooded	Orthic Grey Wooded	Alfisols	Altalf	Typaltalf Orthic Typaltalf

Over one-half of the total annual precipitation falls between the months of April and September. Wide variations in the amount of precipitation occur from year to year, a low of 10.5 inches and a high of 28.9 inches having been recorded over the 20-year period for which records are available.

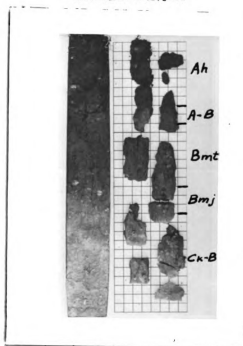
Soil Profile Descriptions

Descriptions of the four profiles selected are given below. Horizon designations are those recommended by the Canadian National Soil Survey Committee (113). The symbols in italics immediately below each designated horizon are those suggested by Whiteside (146). Photographs of the four soil profiles are shown in Plate 1.

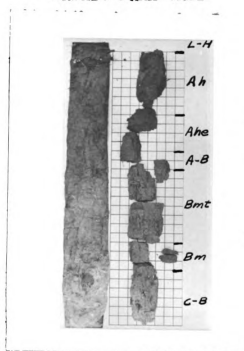
Terminology, for the most part, agrees with that in the Soil Survey Manual (131). Dry soil colors are reported according to the Munsell notations and the I.S.C.C.-N.B.S. color names (78). Textures were determined by hand at the time of sampling. Both moist and dry consistence is described. The latter was determined in the laboratory after the samples had been dried.



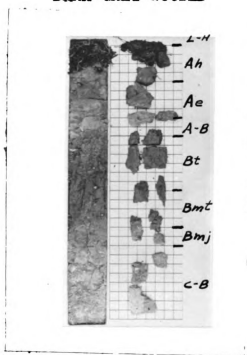
ORTHIC BLACK



ORTHIC DARK GREY



DARK GREY WOODED



ORTHIC GREY WOODED

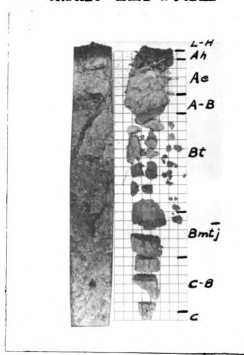


Plate 1. Photographs of the four soils studied showing the macro-structural units and horizons. (One inch grid.)

ORTHIC BLACK

Location: N.E. $\frac{1}{4}$. Sec. 3, Twp. 32, R. 16, W. 2.

Vegetation: Prairie grasses

Drainage: Well drained

Slope: 3.5% Southwest

Topography: Undulating

Land Form: Moraine

Elevation: 1,950 ft.

Horizon	Depth (inches)	Description
Ah (Vh)	0-7	Loam; dark grey to brownish-grey (10 YR 3/1); weak, medium to coarse blocky, breaking to moderate fine granular structure; very friable when moist, soft when dry.
A-B (V/I)	7-9	Loam; brownish grey to moderate olive brown 2.5 Y 4/2); weak, medium prismatic breaking to moderate, fine granular structure; friable when moist, slightly hard when dry.
Bmt (It)	9-16	Clay loam; greyish yellowish brown (10 YR 4/2) to dark greyish yellowish brown (10 YR 2/2); strong, medium prismatic structure breaking to strong, medium blocky to irregular shaped aggregates; firm when moist, hard when dry.
Bmj (I/S)	16-19	Loam; greyish yellowish brown (10 YR 4/2) tending towards moderate yellowish brown (10 YR 5/4); faintly prismatic breaking to weak, fine granular structure; firm when moist, hard when dry.
Ck-B (Sk)	19-31	Loam; light olive brown (2.5 Y 6/2); faintly prismatic but mostly massive structure, breaking readily into weak, fine granular; white flecks of lime throughout; calcareous; friable when moist, slightly hard when dry.



Horizon	Depth (inches)	Description
C ₁₋₁ (Pu1)	31-40	Sandy clay loam; light olive brown (2.5 Y 6/2 to 5/2); till with small pebbles and occasional stones, a few clayey shaly fragments scattered throughout; white streaks and flecks of lime as well as a few rusty streaks appear throughout; massive but showing faint platy tendency, breaking to weak granular; friable when moist, slightly hard to soft when dry.
C ₁₋₂ (Pu2)	40-48	Material similar to C ₁₋₁ .
C ₁₋₃ (Pu3)	48-54	Material similar to C ₁₋₁ .

ORTHIC DARK GREY

Location: N.W. $\frac{1}{4}$, Sec. 10, Twp. 32, R. 16, W. 2

Vegetation: Aspen grove, light undergrowth

Drainage: Good

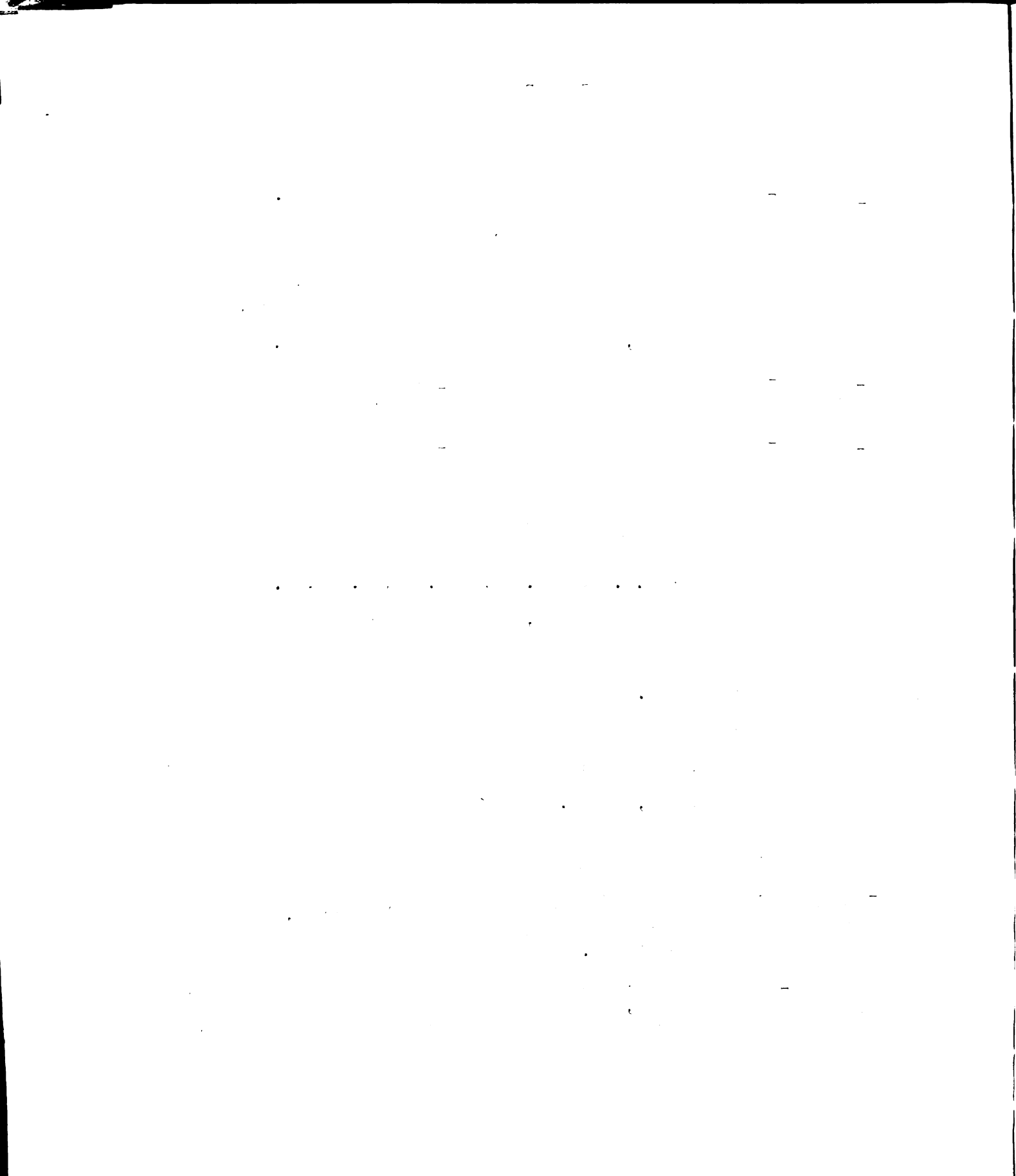
Slope: 3.5% to Northwest

Topography: Undulating

Land Form: Moraine

Elevation: 1,950 ft.

Horizon	Depth (inches)	Description
L-H (Od/Of)	3/4-0	Dark grey to brownish grey (10 YR 3/1); to almost black (10 YR 2/1); leaves, twigs and partially decomposed plant residues.
Ah (Vh)	0-7	Loam; dark grey to brownish grey (10 YR 3/1); weak, coarse blocky breaking to weak fine granular structure; very friable when moist, soft when dry.



Horizon	Depth (inches)	Description
Ahe (Ve)	7-11	Loam; brownish grey (10 YR 4/1); moderate, medium to coarse blocky structure showing very faint platiness, crushing to a powder under slight pressure; very friable when moist, slightly hard when dry.
A-B (V/I)	11-13	Loam; brownish grey (10 YR 4/1) to greyish yellowish brown (10 YR 5/2); weak, medium prismatic breaking to moderate fine granular structure; firm when moist, slightly hard when dry.
Bmt (It)	13-21	Clay loam; greyish yellowish brown (10 YR 5/2 to 4/2); strong, medium prismatic structure breaking to nut-like aggregates; thin coatings on many peds; firm when moist, hard when dry.
Bm (I/S)	21-23	Clay loam; greyish yellowish brown (10 YR 5/2) but more drab than the Bmt; strong, medium prismatic breaking into nut-like aggregates; some peds exhibit colloidal coatings; very firm when moist, hard when dry.
C-B (W)	23-31	Clay loam; yellowish grey (2.5 Y 7/2) to light olive brown (2.5 Y 6/2); weak, medium to coarse prismatic structure, not as pronounced as in the Bm, often breaking into platy segments about 1/8" thick and crushing to structureless condition; calcareous; friable when moist, slightly hard when dry.
C ₁ -1 (Pu1)	31-38	Sandy clay loam to loam; light olive brown (2.5 Y 6/2 to 5/2); till with small pebbles and occasional stones, with white streaks or flecks of lime and a few yellowish to rusty specks or concretions scattered throughout; massive, but showing tendency to faint platiness, breaking to weak fine granular conditions; friable when moist, slightly hard to soft when dry.
C ₁ -2 (Pu2)	38-46	Material similar to C ₁ -1.
C ₁ -3 (Pu3)	46-50	Material similar to C ₁ -1.

DARK GREY WOODED

Location: N.E. $\frac{1}{4}$, Sec. 3, Twp. 32, R. 16, W. 2

Vegetation: Mature aspen grove, dense underbrush

Drainage: Good

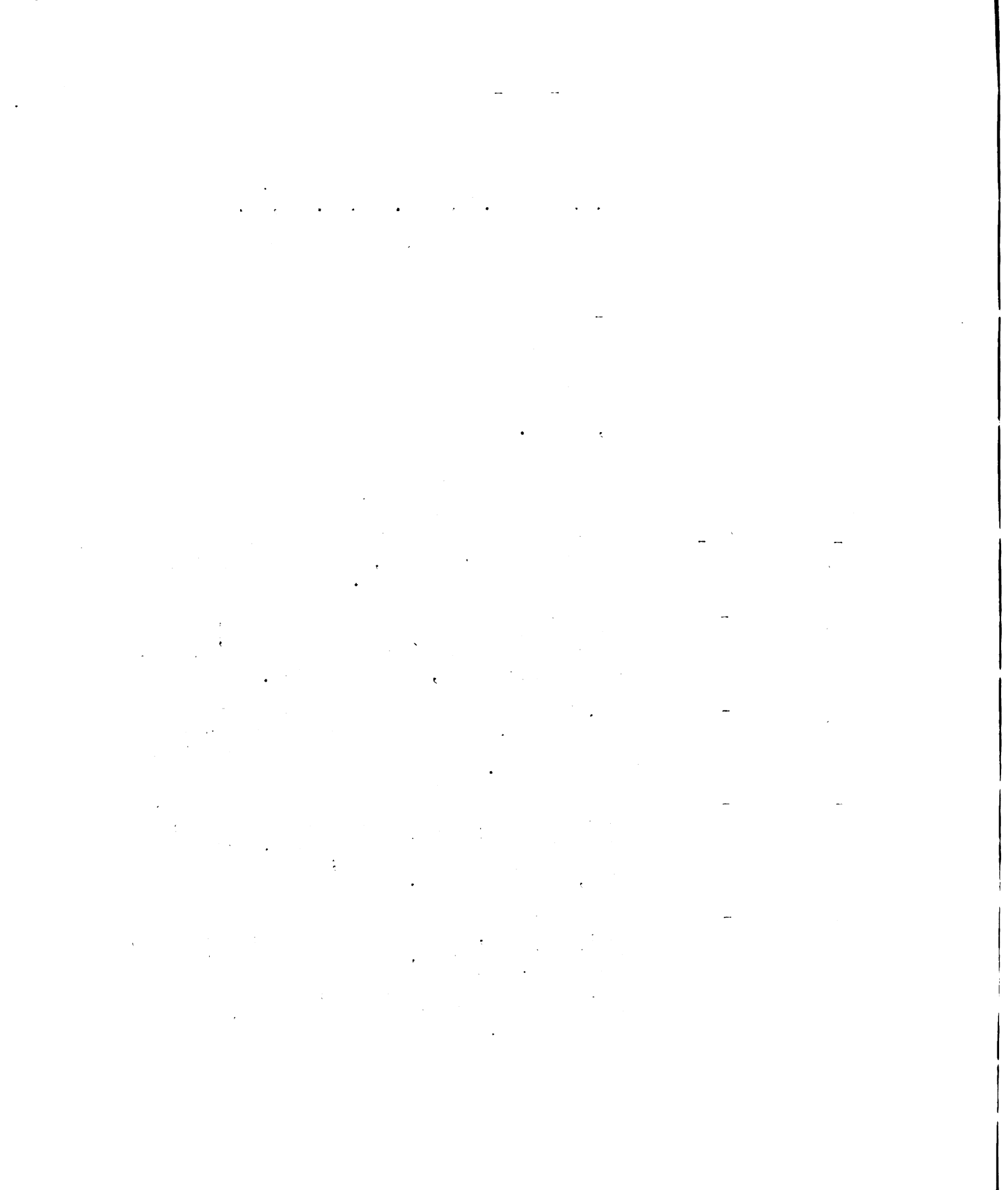
Slope: 3-4% North

Topography: Undulating

Land Form: Moraine

Elevation: 1,975 ft.

Horizon	Depth (inches)	Description
L-H (Od/Of)	3/4 - 0	Brownish grey (10 YR 3/1) to dark greyish yellowish brown; leaves, twigs and partially decomposed plant residues.
Mh (Vh)	0-4	Loam; brownish grey (10 YR 3/1); weak, medium blocky showing faint platiness; breaking to moderate fine granular structure; friable when moist, soft when dry.
Ae (Em)	4-8	Loam, light greyish yellowish brown (10 YR 6/2); strong, medium to thick platy structure crushing to fine powder; friable when moist, soft when dry.
A-B (E/I)	8-10	Loam; greyish yellowish brown (10 YR 5/2); firm; moderate, irregular coarse prismatic structure showing faint platiness, breaking to fine granular aggregates; firm when moist, hard when dry.
Bt (It)	10-16	Clay loam; greyish yellowish brown (10 YR 4/2); moderate, irregular prismatic structure, breaking into strong, fine angular blocky aggregates; dark coatings are present on peds, but are not as pronounced as in the Grey Wooded profile; firm when moist, very hard when dry.



Horizon	Depth (inches)	Description
Bmt (W1)	16-20	Clay loam; greyish yellowish brown (10 YR 4/2) to moderate olive brown (2.5 Y 4/4); weak prismatic breaking into moderate, fine blocky structure; firm when moist, hard when dry.
Bmj (W2)	20-22.5	Loam; greyish yellowish brown (10 YR 5/2); massive, breaking into fine granular; moderate lime content; friable when moist, slightly hard when dry.
C-B (Sk1)	22.5-31	Sandy clay loam; light olive brown (2.5 Y 6/2), with a yellowish tinge and white streaks or flecks of lime; massive structure tending to coarse platiness, breaking into fine granular structure; calcareous; friable when moist, soft when dry.
C ₁ -1 (Pu1)	31-48	Sandy clay loam; light olive brown (2.5 Y 6/2) with yellowish tinge; till with stones, partially decomposed shaly particles and yellowish and rusty streaks or concretions and white streaks of lime scattered throughout; massive but with weak laminated structure, breaking to weak fine granular aggregates; friable when moist, soft when dry.
C ₁ -2 (Pu2)	48-54	Material similar to C ₁ -1.
C ₁ -3 (Pu3)	54-59	Material similar to C ₁ -1.

ORTHIC GREY WOODED

Location: N.E. $\frac{1}{4}$, Sec. 26, Twp. 30, R. 16, W. 2

Vegetation: Solid aspen, shrubs, chokecherry,
pincherry.

Drainage: Good.

Slope: 4% North

Topography: Gently rolling

Land Form: Moraine

Elevation: 2,150 ft.

Horizon	Depth (inches)	Description
L-H (Od/Of)	1-0	Dark greyish yellowish brown to almost black (10 YR 2/2 to 2/1); mat of slightly to highly decomposed leaf litter.
Ah (Vh)	0-1	Loam; dark grey to brownish grey (10 YR 4/1); fine granular to weak platy structure; very friable when moist, soft when dry.
Ae (Em)	1-5	Loam, light grey to yellowish grey (10 YR 7/2 to 7/1); moderate, thin platy structure breaking readily to a loose, powdery condition when dry; very friable when moist, soft when dry.
A-B (E/I)	5-7	Clay loam; greyish yellowish brown (10 YR 5/2 to 4/2); massive to coarse platy structure breaking into nutty to moderate, fine angular blocky aggregates, these aggregates are light colored on the surface (silica coatings) and greyish yellowish brown (10 YR 4/2) on the inside; when dry this layer crumbles readily to form hard nutty aggregates; firm when moist, slightly hard when dry.
Bt (It)	7-18	Clay loam, slightly finer textured than the A-B; yellowish brown (10 YR 4/2 to 5/2); strong, fine subangular blocky structure; aggregates are harder and larger than in the A-B; dark coatings on peds; very firm when moist, very hard when dry.
Bmt ^j (I/W)	18-23	Clay loam; light olive brown (2.5 Y 5/2 to 5/4); massive to medium blocky structure; firm when moist, very hard when dry.

Horizon	Depth (inches)	Description
C-B (W)	23-29	Loam; light olive brown (2.5 Y 6/2 to 6/4); massive to fine granular structure; white flecks of lime evident throughout; calcareous; very friable when moist, slightly hard when dry.
C ₁ -1 (Pu1)	29-38	Sandy clay loam; light olive brown (2.5 Y 6/2); glacial stones and decomposing rock fragments, white streaks and flecks of lime and yellowish to rusty colored streaks and concretions; massive but with moderately laminated structure crushing easily into soft granular aggregates; friable when moist, slightly hard when dry.
C ₁ -2 (Pu2)	38-44	Material similar to C ₁ -1 .
C ₁ -3 (Pu3)	44-50	Material similar to C ₁ -1.

LABORATORY PROCEDURES

Physical Analyses

Mechanical Analysis: The < 2.0 mm. material from each horizon was treated with dilute HCl (pH of the soil lowered to 4.0) and 30% H_2O_2 in order to destroy free lime and organic matter, and was then dispersed using sodium metaphosphate adjusted to pH 9.0 as a dispersing agent. The sands were sieved off using a 300 mesh sieve and then separated into different fractions by dry sieving. The size distribution of the $< 50 \mu$ fraction was determined by the pipette method (79). Fine clay ($< 0.2 \mu$) was determined using a No. 2 International Centrifuge. The results were calculated as percentage of the oven-dry weight of the acid insoluble mineral fraction.

Bulk Density: Four cores of soil were taken with a 2 inch hand corer from each horizon to determine bulk density.

Chemical Analyses:

pH: Soil pH was determined by the soil paste method utilizing a Beckman Zeromatic glass electrode pH meter.

Conductance: Electrical conductivity of the saturation extract from the soil samples was measured using a conductivity cell and conductivity bridge, the values being reported in millimhos per centimeter at $25^\circ C$.

Total Nitrogen: The semi-micro Kjeldahl technique which was used to determine total nitrogen is essentially a modification of that used by Bremner (21), using the micro-Kjeldahl distillation unit described by Markham (93). The distilled ammonia was collected in a 4 per cent. boric acid solution containing a mixed indicator of brom cresol green and methyl red. Standard sulphuric acid was used to titrate the boric acid solution to the desired end point.

Organic Carbon: The organic carbon content of the soil samples was determined by subtracting the inorganic carbon from the total carbon values. The dry combustion method as outlined in the AOAC manual (2) was used for the total carbon determinations. However, the carbon was adsorbed in a sodium hydroxide tower rather than in a Nesbitt tube and then precipitated with 15 per cent. barium chloride. The excess sodium hydroxide was titrated with standard hydrochloric acid using phenolphthalein as an indicator.

Inorganic Carbon: Carbonate carbon was determined by the AOAC method (2) using hydrochloric acid, and stannous chloride. The method was modified to the extent that heat was applied to the samples. The liberated carbon dioxide was absorbed in sodium hydroxide towers, and precipitated with barium chloride; a back titration of the excess base provided a means of determining the inorganic carbon present in the samples.

Free Iron and Aluminum: Mackenzie's method (89), with a minor modification suggested by Kilmer*, was used to determine free iron and aluminum. Dry sodium hydrosulphite was added to the soil suspensions instead of adding the salt as a solution to the wetted soil. Two extractions were made on each sample unless otherwise stated. Iron and aluminum were measured colorimetrically in the same solution by using ferron as proposed by Davenport (44).

Exchangeable Cations: Normal ammonium acetate adjusted to pH 7.0 was used to extract exchangeable cations. Exchangeable potassium and sodium were determined with the Beckman DU flame photometer. Calcium and magnesium were determined by a modified method similar to that of Cheng and Bray (36) in which calcium is precipitated as the oxalate and titrated with standard potassium-permanganate solution, while a versene titration using Eriochrome Black T is used to determine magnesium.

Cation Exchange Capacity: The procedure as outlined in Chemical Methods of Soil Analysis (4) was used with some modification. After saturation with ammonium ions, these were replaced using normal potassium chloride instead of 10 per cent. sodium chloride. Nitrogen was determined by the semi-micro Kjeldahl method.

*

Personal communication.

Total Analyses: Total potassium and iron content of the clay fractions as well as total iron content of the soil samples were determined by decomposing samples by the method described by Jackson (69). This consisted of treating the samples with hydrofluoric, sulphuric and perchloric acids to bring the constituents into solution. Potassium was then determined by the flame photometer, and iron was determined titrimetrically using a permanganate titration(69).

Mineralogical Analyses

Soil Fractionation: The following size fractions were separated:

Very coarse, coarse and medium sand	2.00 - 0.25 mm.
Fine sand	0.25 - 0.10 mm.
Very fine sand	0.10 - 0.05 mm.
Coarse silt	50 - 20 μ
Medium silt	20 - 5 μ
Fine silt	5 - 2 μ
Coarse clay	2 - 0.2 μ
Fine clay	<0.2 μ

The separation of the soil samples into their component size fractions was carried out using the method described by Jackson (68) with some modification. The soils were first treated with dilute hydrochloric acid at room temperature until the pH remained at 4 for at least one hour.

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H₂O₂ was then added in order to destroy organic matter. After the peroxide treatment, the samples were washed with water and then with 95% ethanol until free of chlorides. The soils were heated in 2% Na₂CO₃ for five minutes, the temperature being kept just below the boiling point. After centrifuging, the samples were suspended in water, the resulting suspension having a pH of about 9.5.

After shaking overnight, the sands were separated from the silt and clay by decanting the suspension through a 300 mesh sieve. Dry sieving was used to separate the sand into coarse (2 - 0.25 mm.), fine (0.25 - 0.10 mm.) and very fine (0.10 - 0.05 mm.) fractions. The silts and clays were fractionated using a combination of Sharples' Supercentrifuge and an International # 2 centrifuge. The separated clay fractions were flocculated by lowering the pH to 4 with dilute acid in order to concentrate the clays into a smaller volume. Treatment with 2% Na₂CO₃ with subsequent washing with water and ethanol left the clays salt-free and in a sodium saturated state. A portion of the clays was kept in suspension for X-ray analysis, while the remainder was dried and ground for the other analyses.

X-Ray Diffraction of Clay Fractions: Clay suspensions containing 20-30 mg. of clay in a volume of approximately 10 ml. were treated with 4-6 drops of glycerol and allowed to stand overnight. The glycerol-saturated clay was plated

on a ceramic plate and was irradiated with Cu , $\text{K}\alpha$, X-radiation after each of the following successive treatments:

- a) Leaching with three increments of 0.1 N CaCl_2 solution containing 3% glycerol by volume, followed by four or five increments of 3% glycerol solution.
- b) Leaching with three increments of 0.1 N KCl , washing with distilled water, and drying at 110°C . overnight.
- c) Heating to 550°C . for two hours.

Differential Thermal Analyses of Clay Fractions: One gram samples of clay, pretreated by being stored over a saturated solution of calcium nitrate (56% R.H. at 18.5°C .) for four days, were used for differential thermal analysis. The samples were packed uniformly into a platinum holder, aluminum oxide being used as the inert material in another similar holder. The samples were inserted into a furnace, the temperature of which was raised from room temperature up to $1,000^\circ \text{C}$. at a rate of 10°C . per minute. The furnace and differential temperatures were recorded by means of thermocouples connected to two Brown Elektronik Recorders. These provided thermograms of the clay fractions. The inversion temperature of quartz (573°C .) was used to check the accuracy of the temperatures recorded.

Total Specific Surface of Clays: The ethylene glycol method proposed by Bower and Geschwend (20) was used for the determination of the specific surface of the clay fractions.

Mineral Analysis of the Fine Sand Fraction: The fine sands (0.25-0.10 mm.) which were saved after fractionation of the soil, were treated with warm 0.2 N HCl and then separated into light and heavy fractions using tetrabromoethane and nitrobenzene at a specific gravity of 2.8. The double-tube centrifuge method (74) was used. The light and heavy fractions were weighed and saved for petrographic studies.

The light fractions were mounted on slides smeared with thin films of Canada Balsam. The slides were then exposed to hydrofluoric acid fumes and dipped successively into solutions of sodium cobaltinitrite and malachite green for staining of the feldspars (68). The proportions of quartz, potassium feldspars and plagioclase feldspars were then determined by grain counts using the petrographic microscope.

The heavy minerals were mounted in Aroclor # 4465, a resin having a refractive index of 1.66. Grain counts of the minerals present were made using the petrographic microscope.

Quartz Determination by X-Ray Diffraction: The quartz content of the different sized fractions from the major horizons of the four profiles studied was determined using an X-ray diffraction technique. Preliminary work indicated that the fine clay fractions ($<0.2 \mu$) contained no detectable amounts of quartz, so that quartz content of the fine clays was not

determined. The method involved the use of a spinner-mount on a General Electric Geiger Counter X-ray Spectrometer. The intensities of the $3.35 \overset{0}{\text{\AA}}$ quartz line were measured in counts per second using the scaler of the X-ray unit, the percentage quartz being read from a standard quartz curve.

In preparation of the standard quartz curve, samples of ground rose quartz and orthoclase were mixed in varying proportions. The quartz and orthoclase were first ground manually, using an agate mortar, to pass through a 140 mesh sieve, then ground in a Spex Mill/Mixer for a period of thirty minutes using a steel chamber and steel balls. This procedure assured the breakdown of all particles to less than 50 micron size. Appropriate weights of the two minerals to give 20%, 40%, 50%, 60% and 80% quartz were then weighed out and mixed for 20 minutes in the Spex Mill using plastic vials and balls. Homogeneous mixtures were thereby obtained.

The ground samples were spread on a piece of plate glass and the spinner mount pressed into the sample. A circular motion applied to the mount while pressure was still applied facilitated the filling of the cavity and removal of excess sample. The mount was then lifted off the plate, inverted and the excess powder removed with the edge of a glass microscope slide. For some coarser soil fractions high in quartz difficulty was encountered in that

the sample occasionally slipped out of the rotating disc, which is mounted in a vertical position on the X-ray unit. A very thin layer of vaseline applied to the inside of the mount prior to filling the cavity overcame this difficulty.

The X-ray unit used was a General Electric Diffractometer Model XRD-5. The X-ray tube contained a tungsten filament and a copper target. A nickel filter was used to filter out radiation of shorter wavelengths than the copper $K\alpha$. The settings used were as follows: Beam slit - 1° M.R.; soller - medium resolution; detector slit - 0.2° ; target angle - 4° ; scaler unit setting - log 100; KV - 50; M.A. - 16.

Intensities of the 3.35 \AA quartz line of the mounted samples were recorded in counts per second using the scaler of the X-ray unit. The proper 2θ angle was selected by mounting the pure quartz standard in the machine and scanning the region between 24 and 27 degrees 2θ from both directions several times. From the recorded graphs, the average setting which gave the greatest intensity was obtained. This setting, determined each time the unit was put into operation, was used for further counting. A daily check on the intensity of the X-ray beam was made by recording a "direct beam count" using the line-up slit. This was necessary since the unit was being used for both diffraction and X-ray fluorescence measurements. The constancy of the direct beam count assured proper

alignment and uniformity of the beam intensity for the period of use. The variation in direct beam count was found to be within ± 0.5 per cent. over the period of use.

The soil samples were ground and mounted in the same manner as the standard quartz mixtures. Duplicate mounts of each sample were prepared and a minimum of 100,000 counts was registered for each. The 100% quartz standard was run after every four or five samples to ensure proper operation of the unit. Quartz percentage values corresponding to the counts per second readings were obtained from the standard graph (Figure 18, Appendix). The standard deviation of the mean of the quartz percentages determined for all the samples analyzed, was calculated to be 0.95, indicating good precision of the method.

Thin Section Studies

Thin sections were prepared from oriented clods taken from the major horizons of the four soils studied. The soil clods were impregnated with castolite, according to the procedure of Bourbeau and Berger (18). The samples were placed in 50 ml. crucibles, and castolite, to which hardener had been added and which had been preheated to a temperature of 48° C., was poured over them until they were completely covered. The crucibles were then placed in a dessicator which was gradually evacuated until a suction

equivalent to 20 inches of mercury had been applied. After one hour, the samples were removed from the dessicator and were kept at room temperature for seven days. After this time, they were heated for one hour at 82° C., and then cooled to room temperature. The casts readily fell out of the crucibles when they were gently tapped on a hard surface.

The impregnated soil clods were cut into slices using a diamond saw, and one surface was polished using 80 mesh and 600 mesh grinding powders successively on a lapidary machine. The polished side of the section was mounted on a glass microscope slide using Lakeside 70 cement. The section was finally ground down to a thickness of 0.05 to 0.03 mm., the final polishing being done by hand on a piece of plate glass and using 600 mesh alundum powder and kerosene as a lubricant. Finally, the sections were covered with a cover glass using Canada balsam and were ready for microscopic examination. Photographs of pertinent features from the prepared thin sections were taken using Ektachrome Type B film in an Asahiflex camera mounted on the microscope.

DISCUSSION OF RESULTS

Profile Characteristics

Physical and chemical data for the four profiles under study are given in Tables 2, 3 and 4. In all cases, values reported represent the averages of duplicate determinations, except for the bulk density values, for which the averages of four determinations are reported.

Mechanical Composition and Bulk Density

Mechanical analysis data are presented in Table 2. The mechanical composition of the C horizons indicates that the parent materials of the four profiles contain approximately 50 percent. sand, 30 percent. silt and 20 percent. clay. The uniformity in particle size distribution of the four parent materials and the similarity in mechanical composition of each parent material with depth indicate the relatively uniform nature of the glacial till in the area from which the soils were selected. It may therefore be assumed that the four soils under study have developed from, or at least are underlain by, similar material.

In all four profiles, there is a decrease in the gravel content of the solum horizons relative to the parent material. Likewise, there is generally a decrease in the amounts of coarse and fine sands in the solum as compared to the C horizon, with corresponding increases in the intermediate

TABLE 2. MECHANICAL COMPOSITION OF THE FOUR PROFILES
(expressed as percentage of oven-dry weight of mineral soil)

Horizon	Gravel [*] (> 2mm)	Coarse Sands (2-.25mm)	Fine Sand (.25-.10mm)	Very Fine Sand (.10-.05mm)	Coarse Silt (.05-.02mm)	Medium Silt (.02-.005mm)	Fine Silt (.005-.002mm)	Clay (<.002mm)	Fine Clay (<.0002mm)
<u>ORTHIC BLACK</u>									
Ah	2.4	17.9	16.2	17.6	11.2	11.7	4.9	20.5	10.9
A-B	2.1	20.0	18.1	17.1	10.6	10.5	4.0	19.7	11.2
Bmt	3.0	17.5	15.7	13.3	10.4	10.9	3.9	28.3	18.2
Bmj	2.2	17.2	15.8	13.7	11.4	11.6	4.5	25.8	15.4
Ck-B	3.6	20.0	16.5	13.2	12.6	11.7	4.6	21.4	11.8
C1-1	5.1	21.5	17.3	14.4	12.4	12.2	4.1	18.1	7.5
C1-2	5.6	20.9	16.8	13.4	11.6	13.6	4.6	19.1	10.8
C1-3	--	21.0	16.0	13.2	12.2	13.1	4.6	19.9	11.1
<u>ORTHIC DARK GREY</u>									
Ah	1.2	12.9	10.6	13.0	16.1	18.5	5.9	23.1	14.7
Ahe	0.4	12.4	11.2	16.1	15.3	18.6	6.0	20.3	8.6
A-B	0.2	13.6	9.6	14.2	13.3	17.8	5.1	26.4	17.8
Bmt	1.3	15.2	12.9	18.7	10.5	11.8	4.4	26.5	13.7
Bm	4.8	22.9	17.0	14.7	7.9	10.7	4.2	22.6	15.2
Ck-B	12.5	25.3	15.5	14.6	9.1	10.8	4.4	20.3	12.3
C1-1	5.4	20.5	14.9	12.4	12.8	12.2	5.1	22.1	10.5
C1-2	--	20.6	13.5	12.6	12.9	12.3	5.6	22.4	12.1
C1-3	--	19.0	13.9	12.8	13.6	12.7	5.6	22.4	11.9
<u>DARK GREY WOODED</u>									
Ah	3.2	17.6	12.6	14.8	16.1	18.6	5.4	14.9	7.6
Ae	2.8	16.6	13.5	19.5	13.3	17.3	5.8	13.9	6.9
A-B	3.3	16.8	13.0	13.9	12.6	13.8	4.7	25.2	16.4
Bt	4.6	17.5	11.6	13.1	8.5	10.4	4.1	34.8	17.7
Bmt	7.5	21.6	16.1	15.5	10.6	10.8	3.8	23.4	16.1
Bmj	8.5	20.0	14.8	14.2	11.7	11.2	4.3	24.0	15.6
C-B	7.8	28.2	14.0	7.6	11.9	11.6	4.5	22.2	11.1
C1-1	7.1	20.4	14.4	15.6	9.8	12.4	5.8	21.6	12.7
C1-2	--	20.2	14.7	13.1	12.3	11.8	6.4	21.4	11.3
C1-3	--	19.6	14.7	13.2	12.8	12.2	5.7	21.9	11.2
<u>ORTHIC GREY WOODED</u>									
Ah	0.0	12.7	8.9	11.8	23.2	25.7	5.7	12.4	4.2
Ae	1.5	14.3	10.2	18.1	16.5	24.0	7.6	9.3	2.8
A-B	2.1	13.5	10.4	12.4	14.1	15.1	5.3	29.2	17.7
Bt	2.4	14.9	12.1	14.1	8.5	12.2	4.9	33.2	24.1
Bmt	5.7	18.6	12.5	13.6	11.6	12.0	4.7	27.0	16.5
C-B	7.8	19.0	14.1	14.7	12.5	12.0	4.8	22.9	13.3
C1-1	4.8	19.3	12.9	14.8	9.7	13.7	5.4	24.1	12.4
C1-2	--	20.2	14.7	12.2	11.8	12.9	5.1	23.0	12.7
C1-3	--	18.0	14.3	12.2	12.5	14.0	5.3	23.6	13.1

*Gravel is reported as percentage of air-dry weight of soil.

fractions. Although these differences occur in all four profiles, the differences become greater in going from the Orthic Black to the Orthic Grey Wooded profile. It is noted that the increase in percentages of intermediate sized fractions occurs mainly within the very fine sand to medium silt range. Also the changes in particle size distribution, relative to the C, are more pronounced in the upper portion of the solum or A horizons than in the lower or B horizons.

In each of the four profiles the B horizons are characterized by a higher percentage of clay, especially of fine clay, than either the A or the C horizons. The B horizons with the highest clay contents occur in the Dark Grey Wooded and Grey Wooded profiles. In all profiles except the Orthic Black, the clay accumulation within the B horizon is associated with a decrease in clay in the A horizon, indicating its illuvial nature. The clay bulge in the B horizon of the Orthic Black soil can not be explained as being due to the movement of clay out of the A horizon, since the clay content of the latter is very similar to that of the parent material. This would indicate that this profile may not have developed from material similar to that underlying it, or that clay has been formed as a result of pedogenic processes.

Bulk density values, presented in Table 3, indicate a general increase in volume weight with depth in all four profiles. The values for the B horizons are considerably

TABLE 3. PHYSICAL AND CHEMICAL PROPERTIES OF THE FOUR PROFILES

Horizon	Bulk Density	pH	Cond. mmhos/cm.	% Total Nitrogen	% Organic Carbon	% Inorganic Carbon	% Free Iron (Fe ₂ O ₃)		% Al ₂ O ₃	% Total Fe ₂ O ₃
							2 Extr.	4 Extr.	2 Extr.	
<u>ORTHIC BLACK</u>										
Ah	1.04	7.2	0.38	0.39	4.58	0.10	0.68	1.00	0.03	3.12
A-B	1.43	7.4	0.39	0.12	1.33	0.03	1.06	1.35	0.22	3.89
Bmt	1.44	7.4	0.31	0.08	0.96	0.01	1.28	1.68	0.16	4.26
Bmj	1.43	7.6	0.35	0.07	0.77	0.22	1.38	1.77	0.16	2.83
Ck-B	1.49	7.9	0.34	0.05	0.59	2.66	0.71	--	0.05	2.57
C ₁₋₁	1.65	8.3	0.38	0.03	0.31	2.35	0.47	0.70	0.00	2.78
C ₁₋₂	1.71	8.3	0.40	0.02	0.39	2.57	--	--	--	--
C ₁₋₃	--	8.3	0.42	0.01	0.12	2.34	--	--	--	--
<u>ORTHIC DARK GREY</u>										
L-H	--	6.5	--	1.15	15.23	0.07	--	--	--	--
Ah	1.01	6.3	0.29	0.31	3.94	0.01	0.90	1.17	0.06	--
Ahe	1.10	6.5	0.25	0.22	2.60	0.02	0.94	1.20	0.06	--
A-B	1.18	6.3	0.28	0.11	1.13	0.02	1.50	--	0.27	--
Bmt	1.56	6.5	0.26	0.05	0.45	0.03	1.24	1.59	0.09	--
Bm	1.46	7.1	0.34	0.06	0.55	0.28	1.20	--	0.15	--
C-B	1.58	7.7	0.33	0.04	0.34	2.34	0.84	--	0.06	--
C ₁₋₁	1.66	7.7	0.33	0.02	0.29	2.54	0.59	0.86	0.02	--
C ₁₋₂	1.66	8.0	0.31	0.02	0.25	2.60	--	--	--	--
C ₁₋₃	--	8.0	0.31	0.02	0.25	2.54	--	--	--	--
<u>DARK GREY WOODED</u>										
L-H	--	6.5	--	1.15	16.80	0.13	--	--	--	--
Ah	1.18	6.8	0.44	0.25	3.37	0.05	0.68	0.90	0.19	--
Ae	1.54	6.9	0.31	0.05	0.58	0.03	0.75	0.94	0.23	--
A-B	1.56	6.8	0.28	0.04	0.44	0.01	1.52	--	0.22	--
Bt	1.55	6.9	0.39	0.04	0.39	0.01	1.36	1.80	0.19	--
Bmt	1.62	7.3	0.35	0.05	0.45	0.98	1.03	--	0.13	--
Bmj	1.58	7.5	0.39	0.04	0.53	1.69	--	--	--	--
C-B	1.65	7.6	0.35	0.02	0.30	2.80	0.90	--	0.10	--
C ₁₋₁	1.63	7.8	0.35	0.01	0.17	2.78	0.53	0.73	0.15	--
C ₁₋₂	1.76	7.9	0.33	0.01	0.17	2.28	--	--	--	--
C ₁₋₃	--	7.8	0.31	0.01	0.12	2.34	--	--	--	--
<u>ORTHIC GREY WOODED</u>										
L-H	--	5.8	--	1.11	19.67	0.10	--	--	--	--
Ah	0.60	5.8	--	0.65	7.49	0.06	0.81	--	0.15	2.53
Ae	1.56	6.3	0.23	0.03	0.47	0.04	0.81	0.97	0.04	2.19
A-B	1.41	6.1	0.26	0.04	0.49	0.05	1.63	1.97	0.29	3.67
Bt	1.61	5.9	0.25	0.04	0.53	0.01	1.31	1.78	0.00	4.76
Bmt	1.56	7.2	0.40	0.05	0.43	0.71	1.24	1.54	0.12	3.28
C-B	1.65	7.5	0.34	0.03	0.26	2.06	0.80	--	0.06	2.55
C ₁₋₁	1.67	7.7	0.32	0.02	0.23	2.65	0.57	0.79	0.00	2.88
C ₁₋₂	1.72	8.0	0.34	0.02	0.19	2.60	--	--	--	--
C ₁₋₃	--	8.0	0.33	0.02	0.26	2.53	--	--	--	--

higher than those for the overlying A horizons, reflecting the higher organic matter content of the surface horizons and the higher clay contents of the B horizons. The highest bulk density values, however, do not always occur in horizons with the maximum clay content. The mechanical analysis and bulk density data indicate that the B horizons become much more dense in going from the Orthic Black to the Grey Wooded soil. These data confirm the trends which have previously been noted from observations in the field. The Orthic Chernozemic soils developed from glacial till such as that underlying the four soils under study are characterized by good internal drainage within the entire solum. In the profiles which have undergone more pronounced leaching than that represented by the Orthic Chernozemic types, the translocation of colloidal materials from the A to the B horizons has led to the development of more dense, less pervious subsoils, thus restricting internal drainage of the soils. This trend is evident in the range of soils covered by the four profiles under study.

pH, Conductivity and Inorganic Carbon

The pH values in Table 3 indicate that an increase in leaching has occurred in going from the Orthic Black to the Orthic Grey Wooded soil. A general decrease in the pH values from above pH 7.0 in the Black to values below pH 6.0

in the Grey Wooded soil are evidence that the degree of leaching increases from the Chernozemic to the Podzolic soils. The pH of the Bt horizon in the Grey Wooded profile is 5.9, which is slightly lower than that of either the Ae or A-B horizons, but above that of the thin Ah layer. Earlier work (111) has shown that the B horizon in Grey Wooded soils is often the most acidic of the mineral horizons. It may be added that the Ah horizon is often absent and is not regarded as a differentiating feature of the Grey Wooded profile.

Conductivity values for all horizons of the four profiles are low and reflect the absence of any appreciable soluble salt concentrations. Inorganic carbon values are low in the A and upper B horizons, with maximum values appearing in the C-B or C horizons.

Nitrogen and Organic Carbon:

The distribution and amounts of nitrogen and organic carbon within the four profiles are shown in Table 3. The values are high for the surface horizons and decrease sharply down the profile. Only very slight increases are noted in the B horizons, these occurring in all but the Orthic Black profile. These increases indicate a slight accumulation in one part of the B horizons relative to the horizons immediately above them. In other words, the nitrogen and organic carbon

contents of the Bmt horizons are slightly greater than those for the overlying Bt horizons in the two Podzolic profiles. Such differences would not appear to be significant, but a definite trend is indicated. A slight increase in nitrogen and organic carbon in the B horizon as compared with the Ae has been reported for Grey Wooded soils (87, 111).

Cation Exchange Capacity and Exchangeable Bases

The cation exchange capacity and exchangeable base data for the non-calcareous horizons of the four profiles are reported in Table 4. The values for total exchange capacity are closely related to the amounts of colloidal material present. The Ah horizons generally have the highest exchange capacity due to their high organic matter content. The low values for the Ae and the correspondingly higher values for the Bt horizons of the Dark Grey Wooded and Grey Wooded profiles are due to the differences in clay content which have resulted from translocation of this fraction within these soils.

Calcium is the dominant cation on the exchange complex in all four soils. Although exchangeable hydrogen was not determined, the amounts would be small in terms of total exchange capacities, since the sum of the bases closely approximates total exchange capacity. In horizons with a pH above 7, the sum of the bases slightly exceeds

**TABLE 4. CATION EXCHANGE CAPACITY AND EXCHANGEABLE CATION DATA
FOR NON-CALCAREOUS HORIZONS OF THE FOUR PROFILES**

Horizon	pH	CBC	Ca (milliequivalents per 100 grams)	Mg	Na	K
<u>ORTHIC BLACK</u>						
Ah	7.2	25.3	24.0	3.7	0.1	0.5
A-B	7.4	14.5	13.6	3.4	0.1	0.3
Bmt	7.4	15.8	16.1	4.9	0.1	0.5
Bmj	7.6	17.0	17.8	4.4	0.1	0.4
<u>ORTHIC DARK GREY</u>						
Ah	6.3	26.0	18.6	4.6	0.1	0.9
Ahe	6.5	22.7	15.9	4.5	0.1	0.5
A-B	6.3	21.2	15.1	5.8	0.1	0.5
Bmt	6.5	17.6	13.5	5.6	0.1	0.5
Bm	7.1	15.1	13.2	5.2	0.1	0.4
<u>DARK GREY WOODED</u>						
Ah	6.8	19.0	14.9	3.7	0.1	0.7
As	6.9	8.8	7.2	1.8	tr.*	0.4
A-B	6.8	18.1	14.3	4.2	tr.	0.8
Bt	6.9	22.0	16.1	6.0	tr.	0.9
Bmt	7.3	14.5	14.4	4.0	tr.	0.5
<u>ORTHIC GREY WOODED</u>						
Ah	5.8	43.8	34.8	4.0	tr.	1.1
As	6.3	6.2	5.0	1.2	tr.	0.4
A-B	6.1	16.9	12.0	4.6	tr.	0.8
Bt	5.9	21.5	14.4	6.5	tr.	0.3
Bmt	7.2	16.5	15.4	5.1	tr.	0.5

* Trace

the exchange capacity, whereas when the soil is slightly acidic, the values are equal to or slightly less than the exchange capacity. Magnesium, potassium and sodium are present as exchangeable bases in smaller amounts than calcium, sodium often being present in traces only. A high base saturation for all four soils, including the highly leached Grey Wooded soil, is evident from the data.

Free Iron and Aluminum

The percentages of free iron (Fe_2O_3) and aluminum (Al_2O_3) extracted by sodium hydrosulphite are given in Table 3. The amounts of aluminum extracted are comparatively small and no significant trends are observable other than that the maximum occurs in the A-B horizons of all four profiles. There are, however, definite differences in the extractability of iron from the various horizons of the four soils studied. Values for both two and four extractions are reported for some selected horizons.

The close association between clay and free iron distribution with depth in Podzolic soils has been previously reported (87, 136). The trends in clay and iron distribution within the profiles under study are seen in Figure 2. The distribution of total clay, fine clay and free iron is given for all four profiles. In addition, total iron distribution

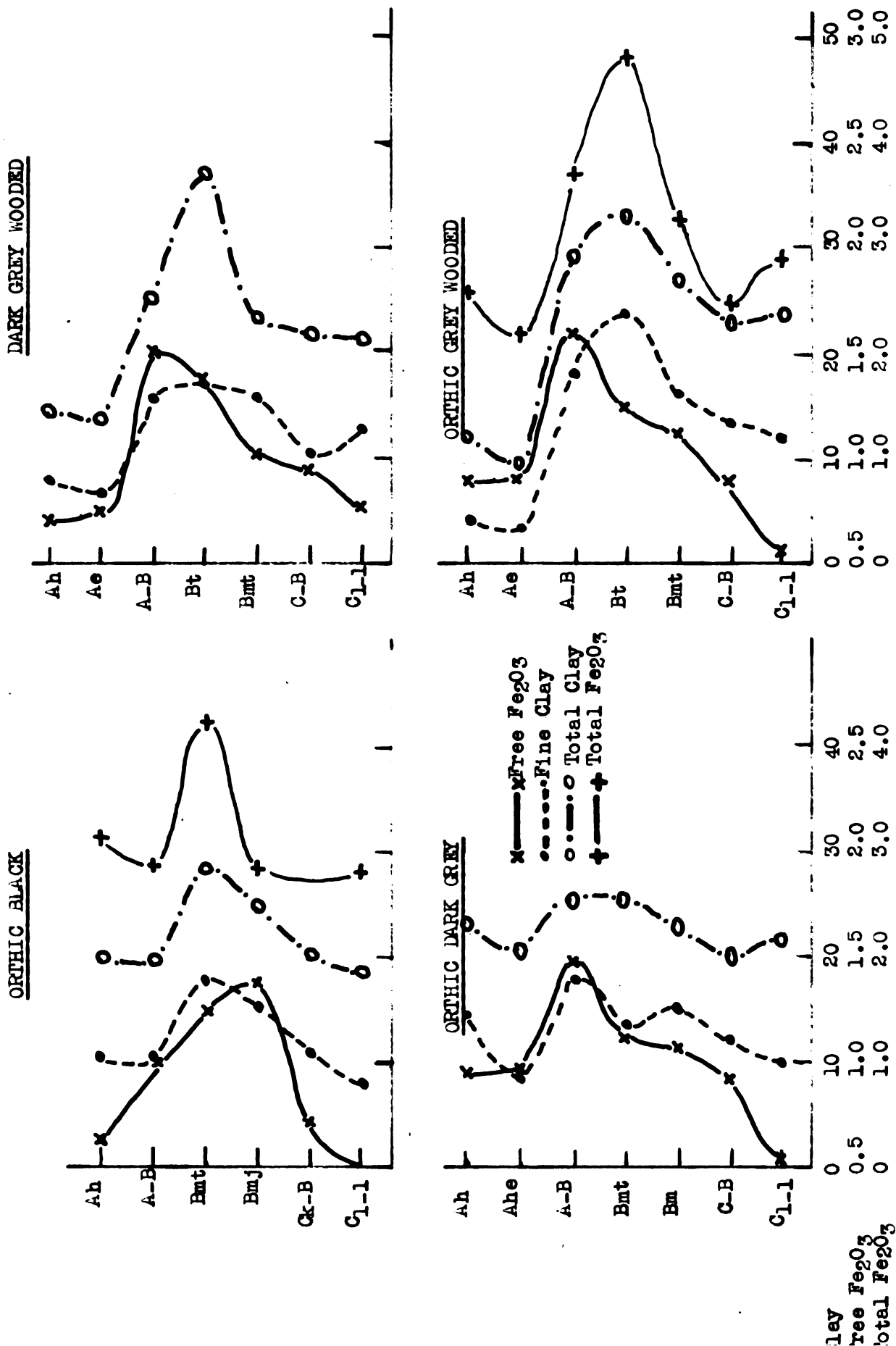
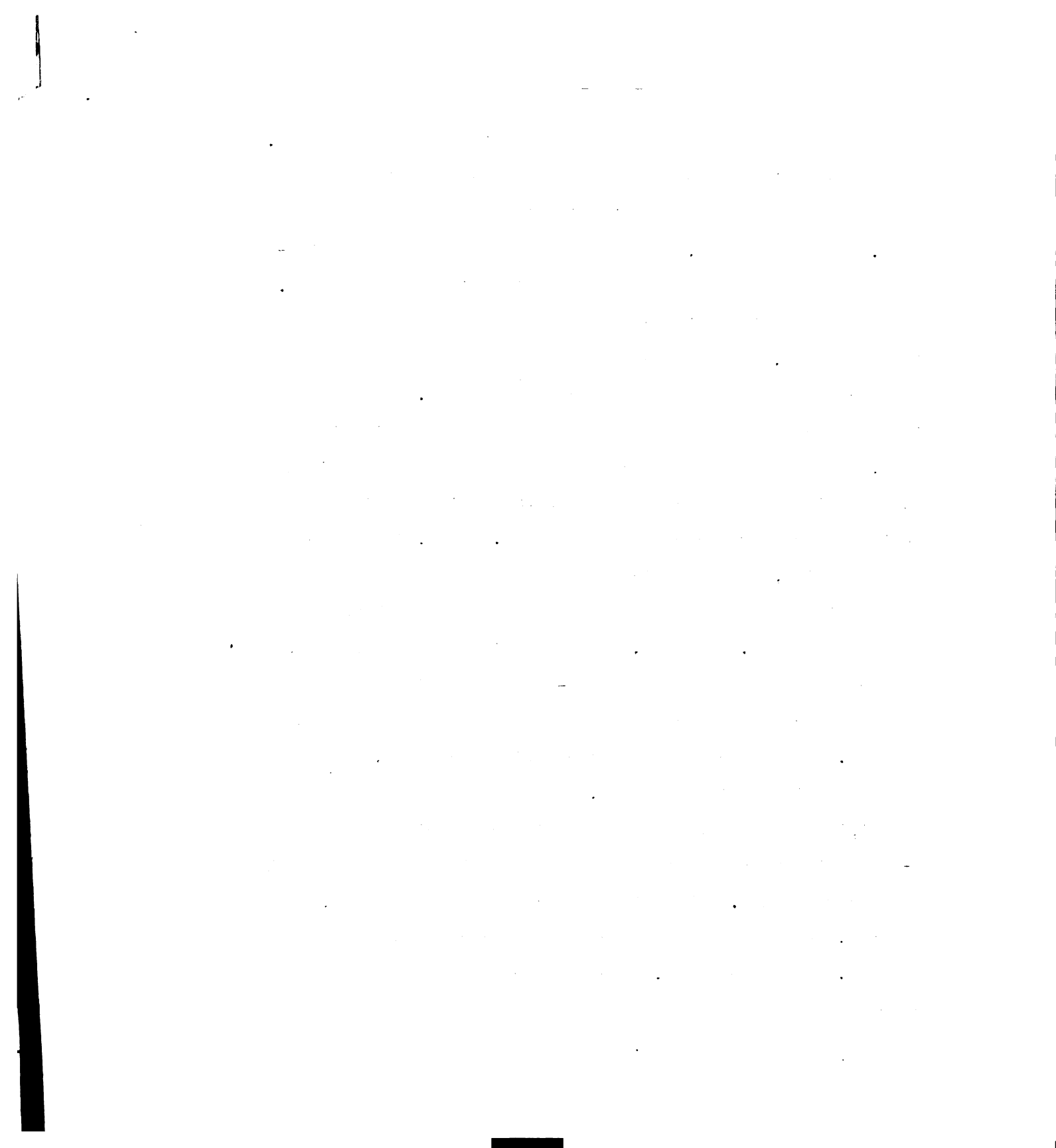


Figure 2 . Distribution of total clay, fine clay, total iron and free iron within the four profiles.

is plotted for the Orthic Black and Orthic Grey Wooded soils. The distribution of free iron and total iron within the profiles is similar to the distribution of total and fine clay. In other words, there appears to be a close relationship between clay and iron translocation within these soils. Although there is a high correlation between the content of iron and clay, it is not certain that these two substances are necessarily moved or translocated together. If free iron is a measure of iron that is regarded as being mobile in the soil, the present data indicate that the horizon of maximum accumulation of free iron may not always coincide with the horizon of maximum accumulation of clay. Thus, in the Orthic Black profile, the total iron and clay maxima appear in the same horizon (the Bmt) but the free iron maximum shows up at a lower depth. However, in the Orthic Grey Wooded soil, the free iron is highest in the A-B horizon while the clay and total iron concentrations show up below this in the Bt horizon. It appears that as degradation increases, the extractability of iron changes, the layer of maximum iron solubility moving upwards from the lower B horizon to the A-B transition zone above the layer of maximum clay and total iron accumulation. The total iron content of the soils, however, does appear to be markedly affected by the clay content. In other words, there appears to be a higher correlation between total iron and clay content than between free iron and clay content.



Two hydrosulphite extractions seem just as satisfactory in showing free iron distribution within a profile as four extractions (Table 5). This is in agreement with Mackenzie's findings (89). The first two extractions remove the largest amount of iron and, in most cases, after the relatively soluble iron has been removed, the extractability of iron remains fairly constant at about 13-16% of the total iron remaining in the soil. In cases where the extractability is very high (e.g. Orthic Black, Bmj, Tables 3 and 5) the first two extractions do not remove all of the readily soluble iron and more is extracted in the following two extractions. Less iron is extracted from horizons containing free lime carbonates, such as the C₁-1 horizons (Tables 3 and 5).

The amount of aluminum extracted by sodium hydrosulphite is small in comparison with the iron extracted. High aluminum values could indicate a breakdown of silicate minerals. If this is so, one could conclude that the low values suggest that the hydrosulphite treatment is not disrupting the lattices to any great extent and that iron extracted is not being released from within the clay lattices. Although the clay fraction is high in iron, the iron may be present as coatings on the surface of clay particles or in the form of definite iron compounds of clay size rather than as an integral part of the silicate clay minerals themselves.

TABLE 5. PERCENTAGE OF TOTAL IRON REMOVED
FROM THE BLACK AND GREY WOODED PROFILES:
BY TWO AND FOUR SODIUM HYDROSULPHITE EXTRACTIONS

ORTHIC BLACK

% Fe₂O₃ removed by:

	<u>a) First two extractions</u>	<u>b) Third and Fourth extractions*</u>
Ah	22	13
A-B	37	16
Bmt	30	13
Bmj	49	27
C ₁₋₁	17	10

ORTHIC GREY WOODED

% Fe₂O₃ removed by:

	<u>a) First two extractions</u>	<u>b) Third and Fourth extractions*</u>
Ae	37	11
A-B	45	16
Bt	28	14
Bmt	38	15
C ₁₋₁	20	8

* Expressed as per cent. of total Fe₂O₃ remaining
after first two extractions.

The high correlation obtained between fine clay and free iron in Grey Wooded soils led Lutwick (87) to suggest that iron must exist as an integral part of the clay minerals within the clay fraction. Total iron content of the fine clay fractions (to be discussed later) was found to be quite uniform in all horizons of the four soils under study, suggesting that the iron may occur as an integral part of the clay minerals. Although some of this may be extracted by sodium hydrosulphite, the free iron values indicate that some other source of iron is contributing to the iron extracted from the total soil.

Characteristics of the Clay Fractions

X-ray diffraction patterns, differential thermal curves, total iron and potassium contents, specific surfaces and cation exchange capacities of the coarse (2.0-0.2 μ) and fine ($<0.2 \mu$) clay fractions were obtained for the major horizons of the four profiles under study. These data have served to establish the mineralogical composition of the clay fractions and to assess changes which have resulted due to pedogenesis.

X-Ray Analysis

As indicated under Laboratory Methods, the clay fractions were subjected to X-ray analysis after three treatments, namely, 1) calcium saturation and glyceration, 2) potassium saturation and heating to 110° C., and 3) potassium saturation and heating to 550° C. X-ray diffraction patterns for the four profiles are given in Figures 3 to 10 inclusive. X-ray patterns are shown for only the first and last treatments since the 110° C. treatment did not materially aid in clay mineral identification. A broad band occurred in the X-ray patterns over the 10° Å to 15° Å range for clays saturated with potassium and heated to 110° C. The reason for this is not clear. It could serve as an indication of interstratification of chlorite with illite or montmorillonite type clays but the complete collapse to 10° Å upon heating to 550° C. would seem to rule out this possibility. It appears as though the interlayer water is not removed entirely upon heating to 110° C. This is no doubt a characteristic of the clay minerals in these soils since the same phenomenon occurred for all the fine clays and to a lesser degree for the coarse clays.

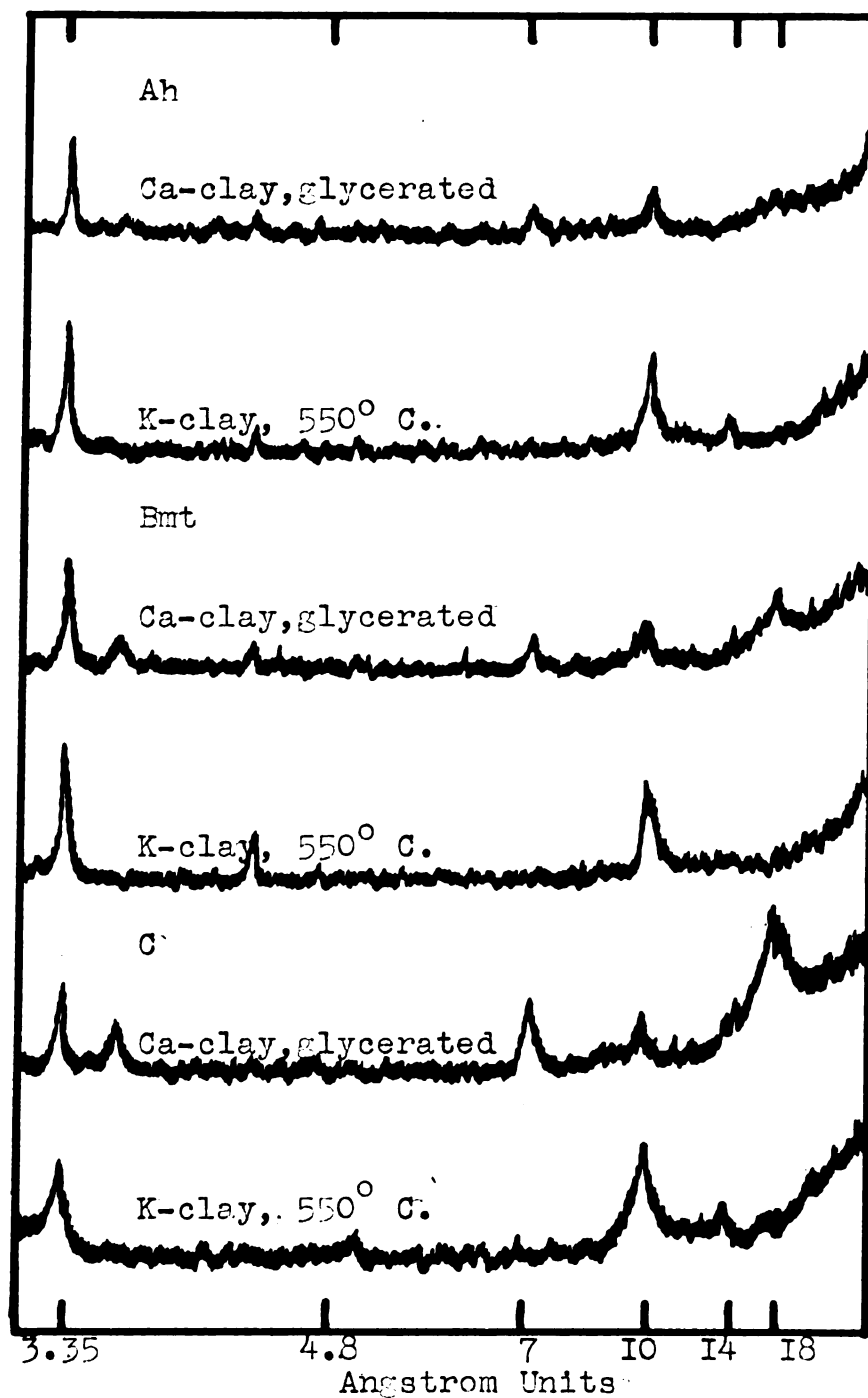


Figure 3 . X-ray diffraction patterns of the coarse clay (2.0-0.2 μ) from the major horizons of the Orthic Black profile, subjected to glycerol, cation and heat treatments.

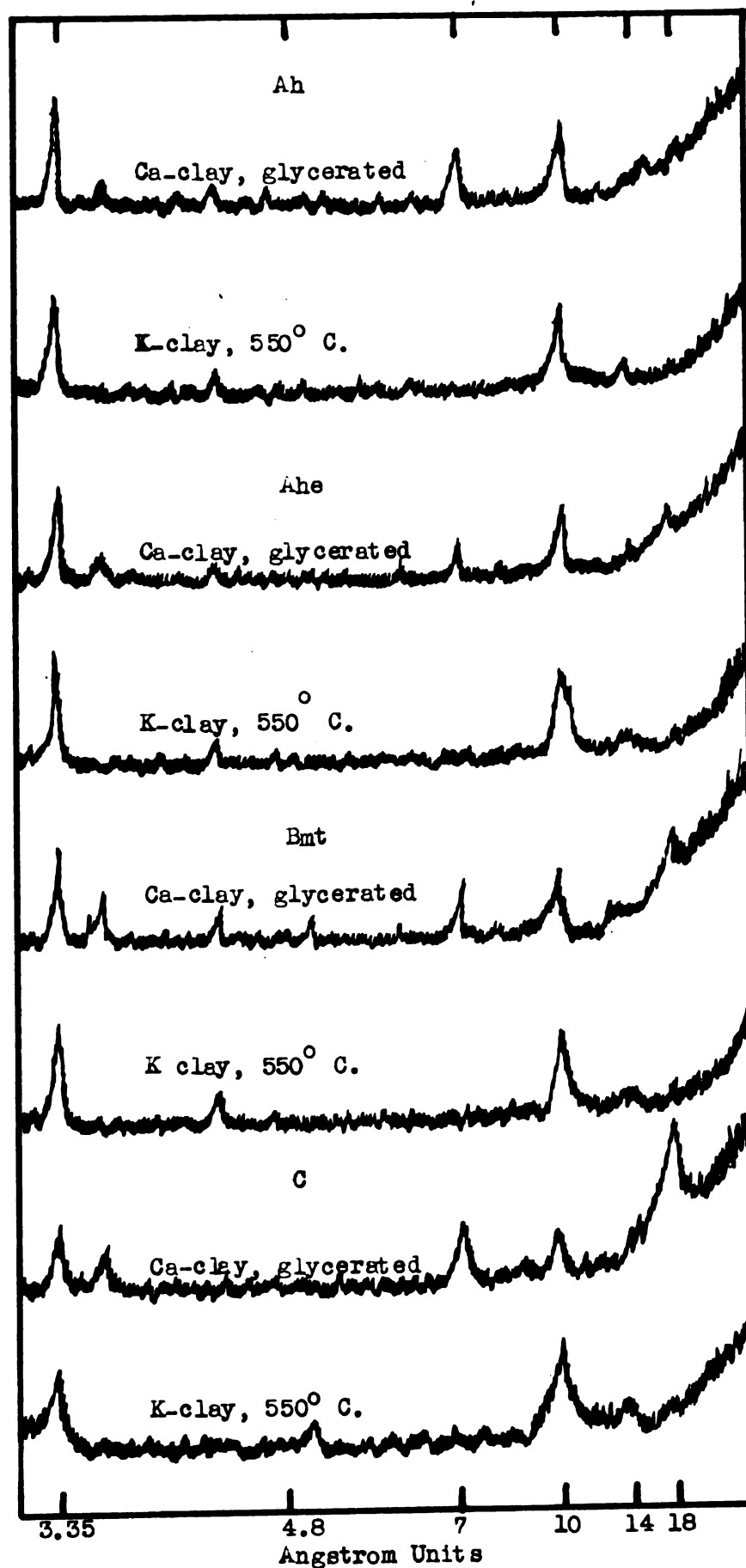


Figure 4 . X-ray diffraction patterns of the coarse clay (2.0-0.2 μ) from the major horizons of the Orthic Dark Grey profile, subjected to glycerol, cation and heat treatments.

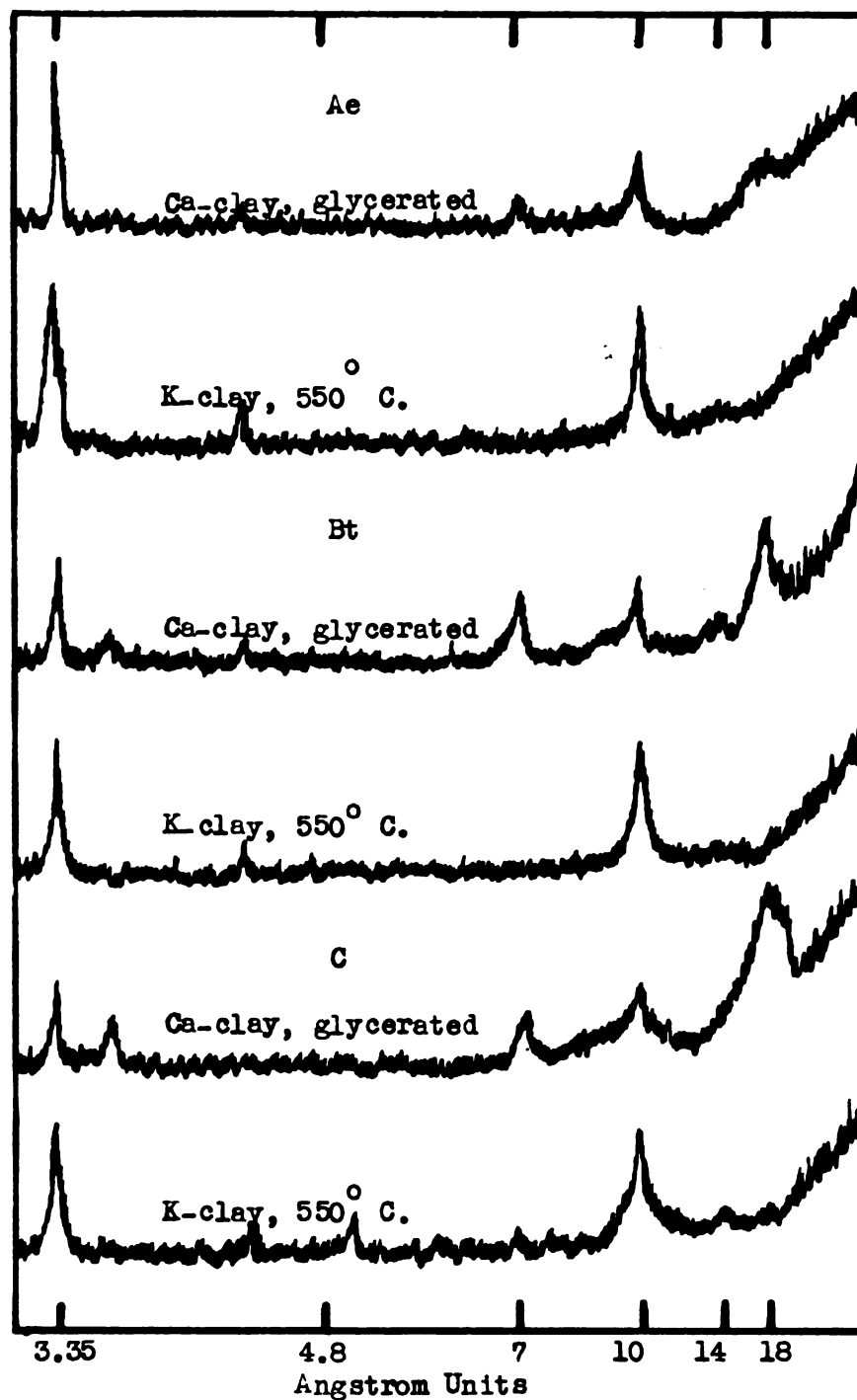


Figure 5 . X-ray diffraction patterns of the coarse clay (2.0-0.2 μ) from the major horizons of the Dark Grey Wooded profile, subjected to glycerol, cation and heat treatments.

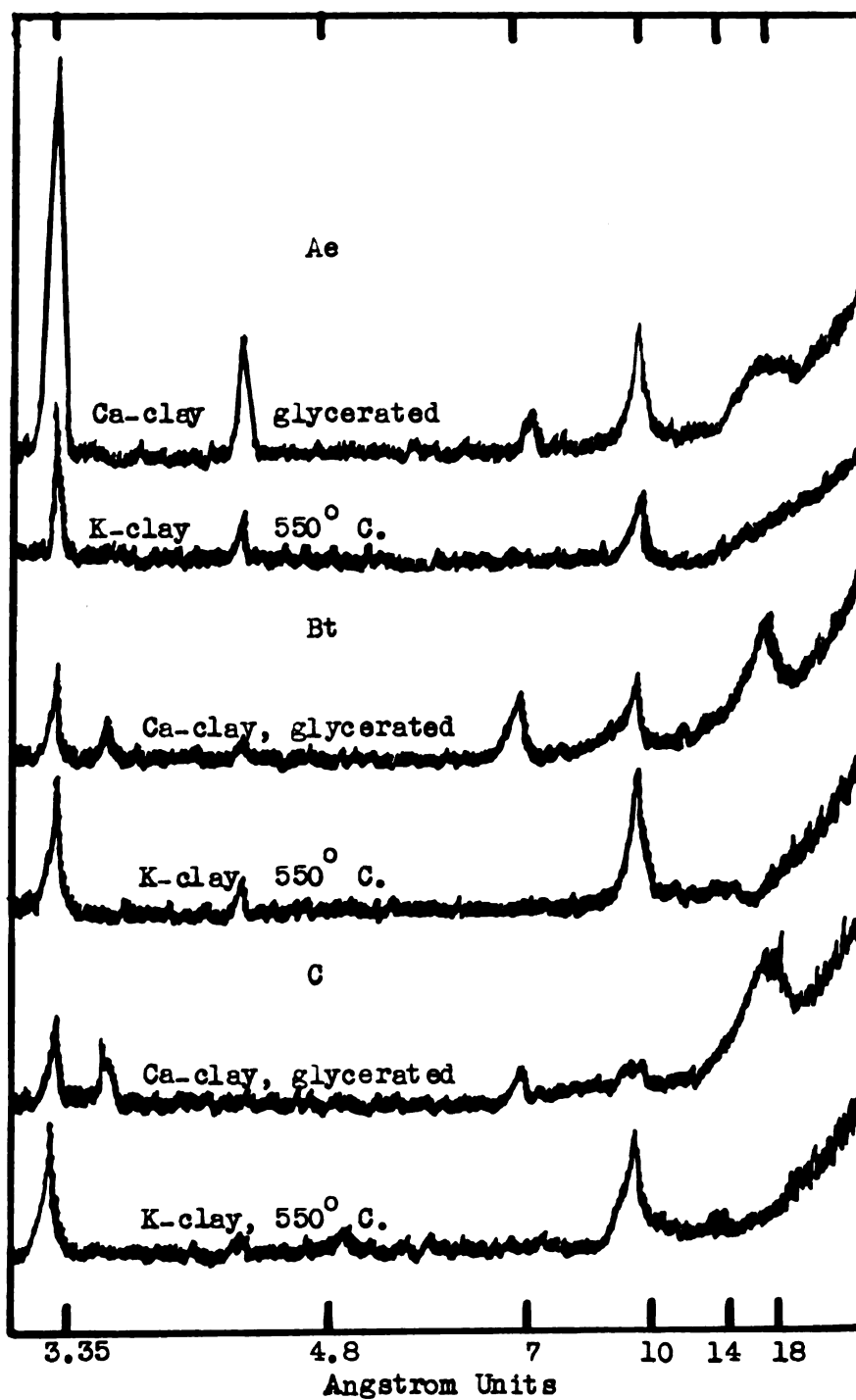


Figure 6 . X-ray diffraction patterns of the coarse clay (2.0-0.2 μ) from the major horizons of the Orthic Grey Wooded profile, subjected to glycerol, cation and heat treatments.

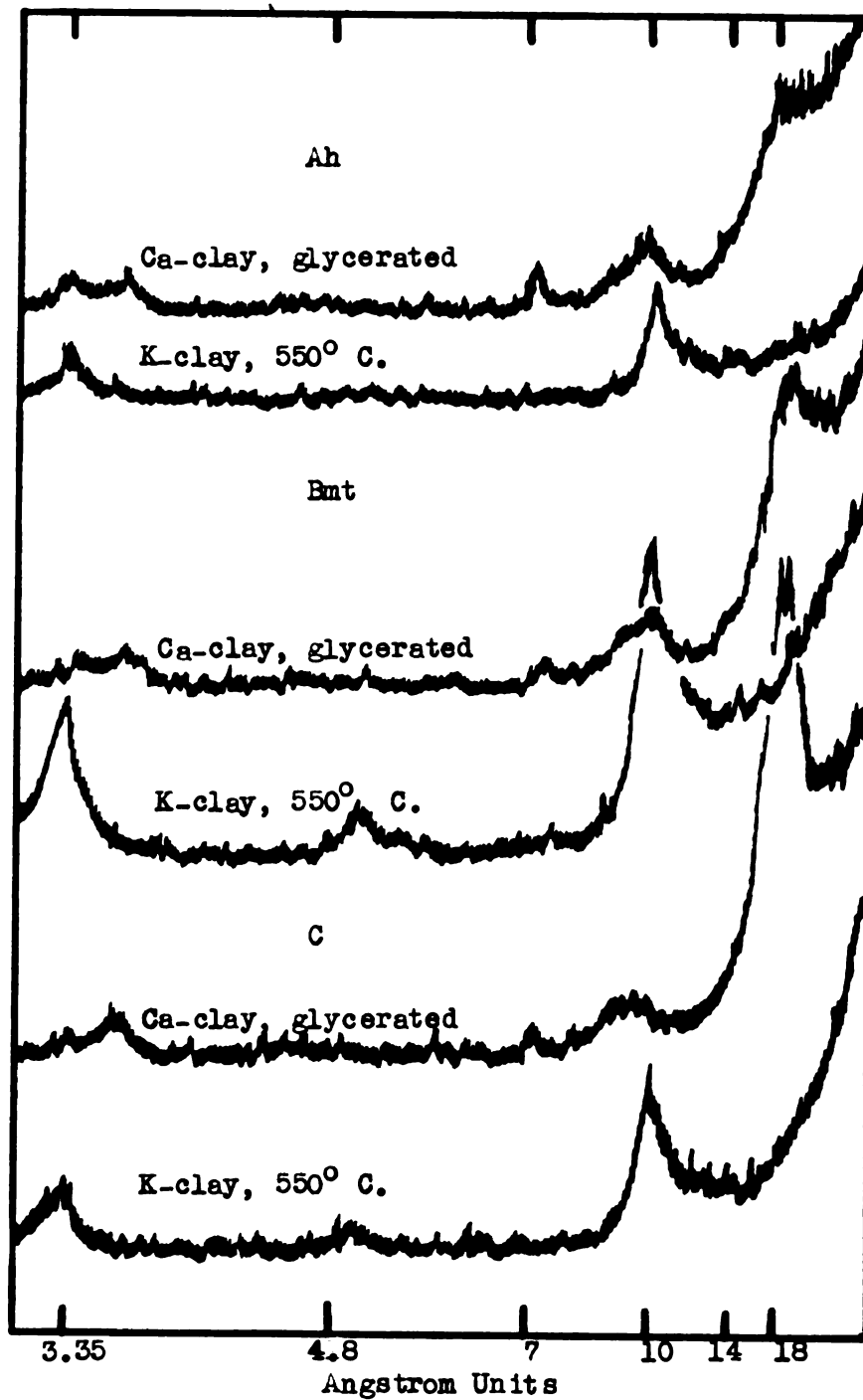


Figure 7 . X-ray diffraction patterns of the fine clay ($< 0.2 \mu$) from the major horizons of the Orthic Black profile, subjected to glycerol, cation and heat treatments.

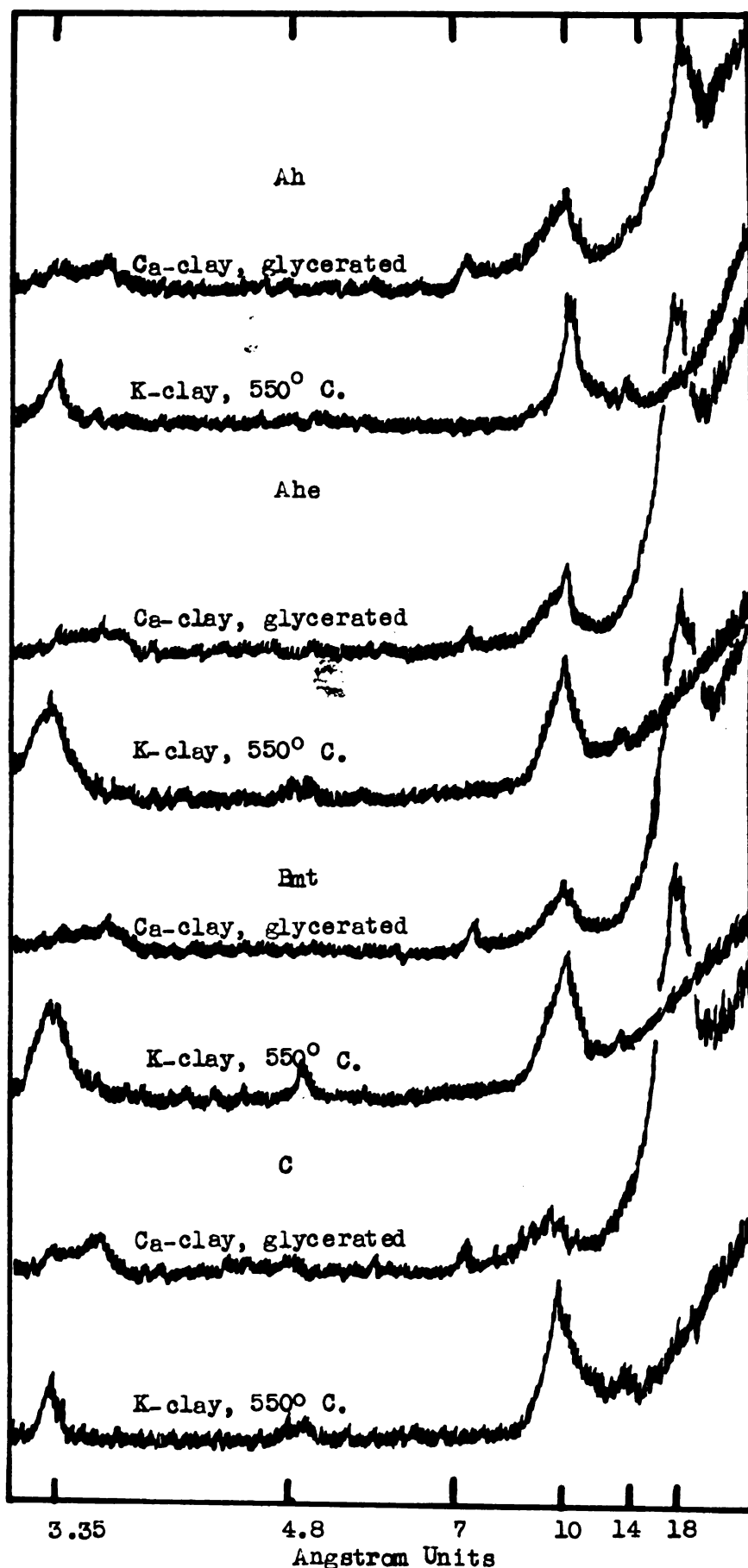


Figure 8 . X-ray diffraction patterns of the fine clay ($< 0.2 \mu$) from the major horizons of the Orthic Dark Grey profile, subjected to glycerol, cation and heat treatments.

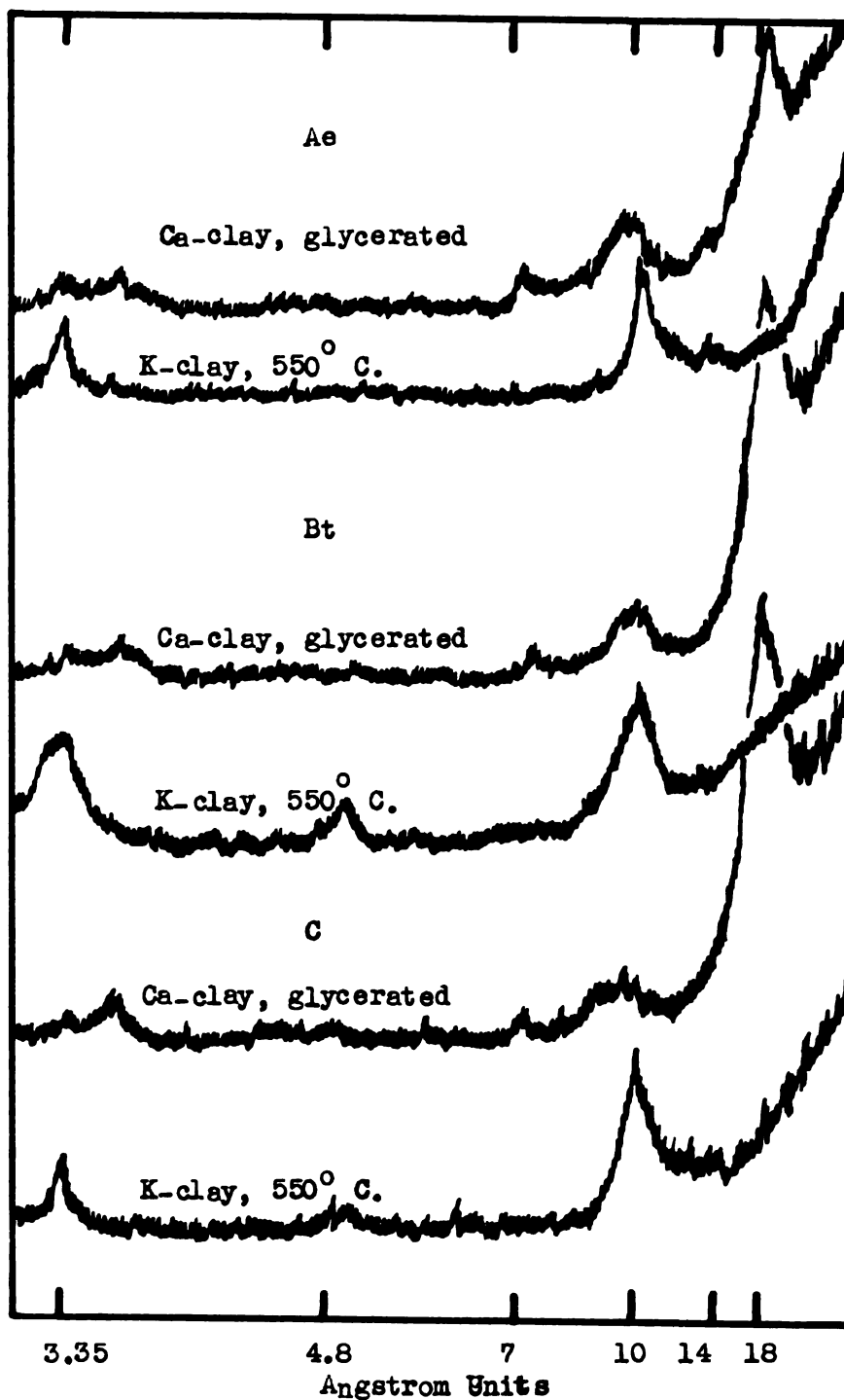


Figure 9. X-ray diffraction patterns of the fine clay ($< 0.2 \mu$) from the major horizons of the Dark Gray Wooded profile, subjected to glycerol, cation and heat treatments.

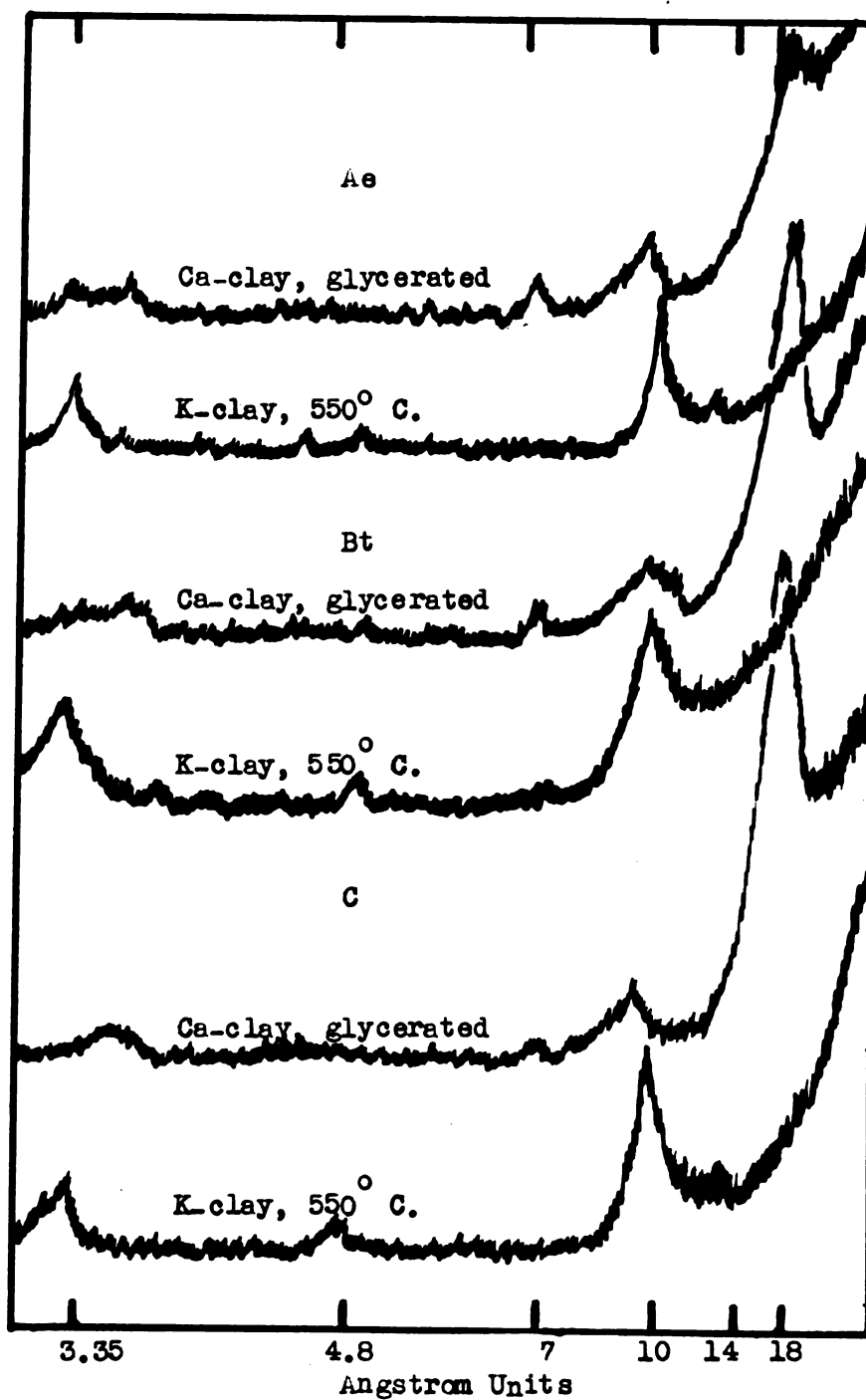


Figure 10. X-ray diffraction patterns of the fine clay ($< 0.2 \mu$) from the major horizons of the Orthic Grey Wooded profile, subjected to glycerol, cation and heat treatments.

The following relationships and conclusions are indicated from the X-ray data:

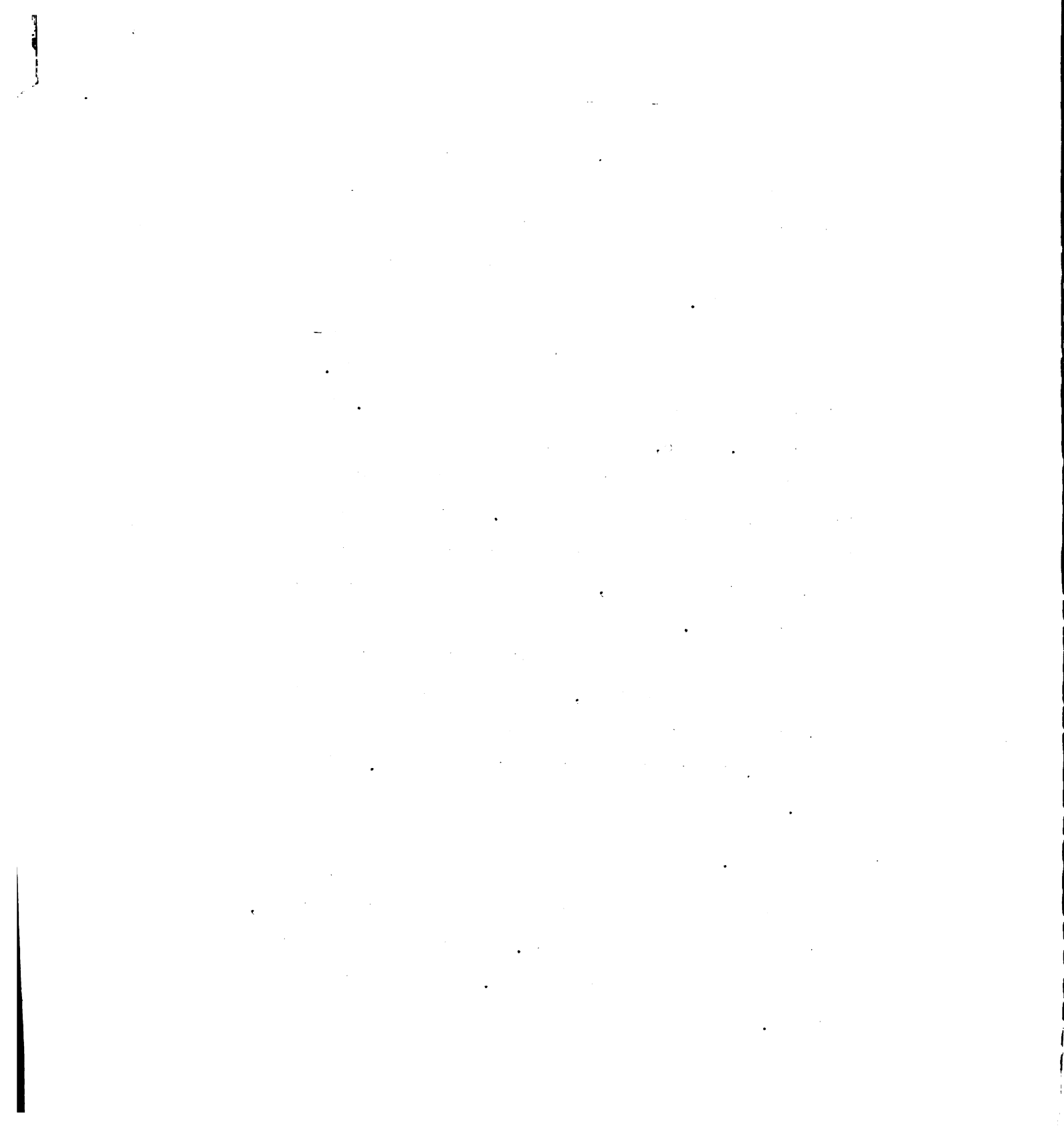
1) Coarse Clays (2.0-0.2 μ):

- a) Illite and montmorillonite are the dominant minerals in all the horizons of the four profiles. Kaolinite, chlorite and quartz are present in small amounts.
- b) Illite is more abundant in the Ah and Ae horizons than in the other horizons.
- c) The 18 $\overset{\circ}{\text{\AA}}$ peaks for montmorillonite are most pronounced in the C₁₋₁ horizons, less in the B's and least in the A's.
- d) Kaolinite is present in all horizons of the four profiles in small and about equal amounts.
- e) Chlorite is present both in the parent material and within the solum of all profiles, but only in small amounts.
- f) In the Orthic Black profile, chlorite is present only in the Ah and C horizons, and not in the Bt. (The reason for the absence of chlorite in the coarse clay fraction of the Bt horizon is made evident from analysis of the fine clays, and will be discussed later.)
Second and third order chlorite lines do not appear or at least are poorly defined.

- g) As degradation increases, there is a greater loss of chlorite from the A horizons than from the B, indicating more intense weathering in the surface horizons of the Podzolic profiles as compared to the Chernozemic.
- h) The quartz content of the A horizons increases progressively from the Black to the Grey Wooded soil. This can be observed by the intensity of the 3.35 \AA reflections. Also, the quartz content increases markedly from the C horizon to the surface horizon in the Orthic Grey Wooded profile. This same trend is evident for both the Orthic Dark Grey and Dark Grey Wooded profiles as well, although the differences are less pronounced.
- i) The quartz content of the B horizons is relatively constant for all profiles, but these horizons contain approximately twice as much quartz as the parent materials, judging by the intensity of the 3.35 \AA peaks.

2) Fine Clays ($< 0.2 \mu$):

- a) Montmorillonite is the dominant mineral in all horizons, illite being next in abundance. Kaolinite and chlorite are present in only trace amounts. No quartz is evident.



- b) The intensity and sharpness of the $18 \overset{\circ}{\text{\AA}}$ peak for montmorillonite decreases progressively from the C to the B to the A horizon in all profiles.
- c) Small and approximately equal amounts of kaolinite are present in all horizons of the four profiles.
- d) Only trace amounts of chlorite appear in the fine clays. In the Orthic Black profile appreciably more chlorite is present in the fine clay fraction of the Bmt horizon whereas it is almost absent in the fine clays of the A and C layers. It appears that chlorite has undergone weathering (as denoted by its absence in the coarse clay) and is showing up in the finer fraction. Second and third order chlorite lines do not appear, or at least are poorly defined.
- e) Most of the fine clays collapse to $10 \overset{\circ}{\text{\AA}}$ after the 550° C. heating, but the $10 \overset{\circ}{\text{\AA}}$ line trails off towards $14 \overset{\circ}{\text{\AA}}$, indicating possible interstratification of chlorite. This effect is most pronounced in the Ah horizons, and particularly in the Ah of the Black profile.

Differential Thermal Analysis

The differential thermograms for clays of the two sizes separated are presented in Figure 11. The curves are strikingly similar for all horizons of the four profiles.

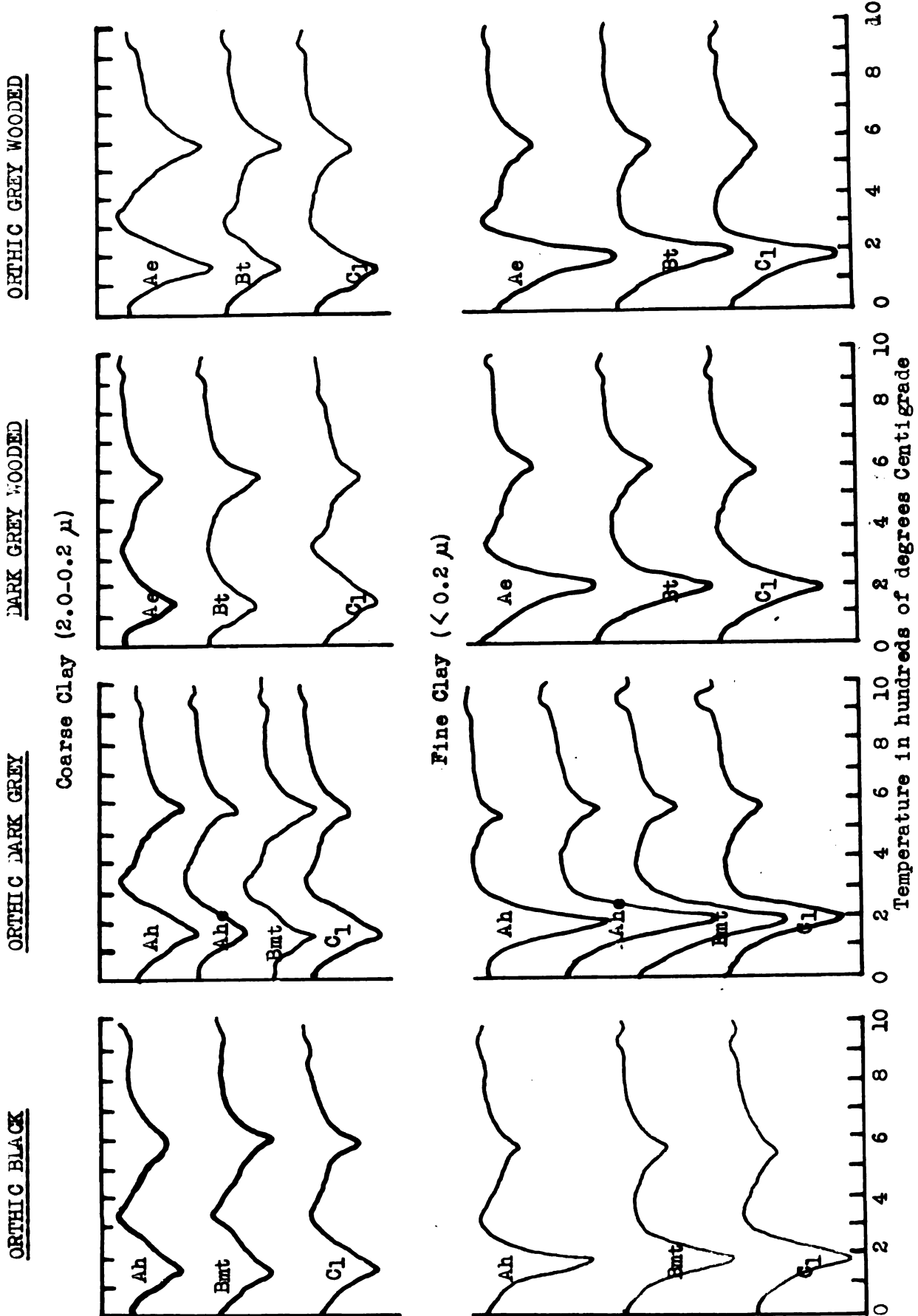


Figure 11. Differential thermograms of the coarse and fine clays from the major horizons of the four profiles.

The coarse clays show an endothermic peak between 138° C. and 152° C., a broad exothermic peak between 300° C. and 500° C., and a characteristic endotherm at 560° - 590° C. For the fine clays the first endotherm, associated with the loss of adsorbed water, ranges between 175° - 195° C., this being higher than the corresponding peak for the coarse clays. For both clays the exothermic reaction occurring between 300° and 500° C. is probably due to the burning of organic matter associated with the clay. Although the soils were subjected to a hydrogen peroxide treatment, organic matter within the clay fraction was probably not all removed. Lutwick (87) reported similar peaks for soil clays but noted that after further peroxidation of the clay fractions, their intensity was markedly reduced.

The hydroxyl endotherm for the fine clays is in the same range as for the coarse clays, between 560° - 590° C. A slight exothermic reaction is evident in the regions just above 900° C. for both the coarse and fine clays. These thermograms, having their characteristic endotherm peak temperatures in the range of 560° - 590° C., are typical of illitic minerals. However, "abnormal" montmorillonites (17, 41, 90) could also show peaks in the same range. The substitution of Mg^{++} for Al^{+++} or Fe^{+++} for Al^{+++} causes this peak in montmorillonite to shift below the normal 720° C. generally recorded for this mineral. The thermograms thus indicate the presence of illite or montmorillonite, or both, and substantiate the results obtained from X-ray analyses.

Chemical and Physical Properties of the Clay Fraction

The chemical and physical characteristics of the coarse and fine clay fractions from the four profiles are given in Table 6. The results and interpretations can be summarized as follows:

- 1) The total iron content of the coarse clay fraction within the Orthic Black profile is relatively constant. In contrast there is a decrease in the iron content of this fraction in the A and B horizons of the other three profiles, relative to that of the parent material. In all profiles, the total iron content of the fine clay fraction is higher than that of the coarse clay. In the fine clay fractions only slight variations in iron content occur between the different horizons. This relative uniformity in iron content suggests that the fine clay fraction is dominated by iron-bearing clays, and that these minerals have been little affected by weathering. If this is so, it is unlikely that much alteration could have occurred in similar clay minerals, if they were present, in the coarse clay fraction. This indicates that the changes in iron content of the coarse clays within the solum may be due to accumulation of minerals containing little or no iron. For example, the quartz analysis (to be discussed later) indicates an increase in the quartz content of the

**TABLE 6. SOME CHEMICAL AND PHYSICAL PROPERTIES OF THE CLAY FRACTIONS
FROM THE FOUR PROFILES (expressed on an oven-dry basis)**

Soil	Horizon	Coarse Clay (2-0.2 μ)			Fine Clay (<0.2 μ)			Surface Area M ² /g.	Surface Area M ² /g.
		% Fe ₂ O ₃	% K ₂ O	C.E.C. me/100 g.	% Fe ₂ O ₃	% K ₂ O	C.E.C. me/100 g.		
ORTHIC BLACK	Ah	7.52	4.01	20.5	12.24	2.79	70.9	345	535
	Bmt	7.85	4.37	19.0	12.61	2.19	72.7	207	567
	C1-1	7.22	2.74	24.8	12.23	2.00	72.2	266	607
ORTHIC DARK	Ah	5.83	3.90	26.2	13.12	2.60	75.1	233	606
	Ahe	5.38	3.90	22.3	13.26	2.42	75.0	192	612
GREY	Bmt	6.30	3.79	22.5	12.32	2.02	76.5	222	645
	C1-1	7.45	3.26	29.3	12.42	1.94	76.6	296	648
DARK GREY	Ae	6.00	3.98	17.7	12.85	2.39	74.1	158	520
	Bt	5.88	3.61	17.0	12.90	2.38	75.2	188	611
WOODED	C1-1	7.36	3.27	28.9	12.32	2.19	72.4	285	595
ORTHIC GREY	Ae	5.70	3.86	11.9	11.74	2.32	71.8	141	545
	Bt	7.16	4.03	19.7	12.51	2.14	76.6	250	603
WOODED	C1-1	7.55	3.27	31.6	12.50	2.03	75.4	314	618

coarse clay fractions of the solum as compared to those of the parent materials. The accumulation of quartz and other minerals low in iron within the coarse clay fraction would have a diluting effect and would tend to lower the percentage of iron-bearing minerals within this fraction. The close correlation obtained between total iron and total clay contents of the various horizons (Figure 2) can, in large part, be attributed to the uniform iron content of the fine clay fraction.

- 2) For both the coarse and fine clay fractions, the potassium content invariably increases in the solum as compared to the parent materials, and this increase is generally greatest in the A horizons. This increase in potassium content suggests a higher proportion of illitic clay within the solum relative to the C horizon. Such an increase in illite content could result from the weathering of other clay minerals with complete removal of the weathering products from the profile, or could be due to a process of illitization whereby montmorillonite present in the soils is subjected to potassification and reverts to an illite-type of mineral. A possibility which has also been suggested is that expanding type clays are more readily dispersed and hence are probably translocated in preference to non-expanding types (19, 63). Movement or translocation of montmorillonite from the A horizon

to the B would have the effect of concentrating illite in the clay fraction of the A horizon and hence of raising the potassium content of this horizon. However, the movement of montmorillonite into the B horizon would cause a reduction in the percentage of both illite and potassium in the clay fractions of the B relative to those of the C horizon. Since this has not occurred there is no evidence to suggest that preferential translocation of this nature has taken place. It is also unlikely that only minerals other than illite would be weathered and completely removed from the soil. This means that, in all likelihood, illitization has occurred and does account for the increased potassium content of the clays within the solum. Bourne (19) has reported similar results and claims that potassium has been fixed by expanding type soil clays in the surface horizon of a medial Chernozem developed in loess. In addition, preferential translocation of montmorillonite had occurred within the profile.

The increase in illite content of clays in the A and B horizons should be reflected to some extent in the cation exchange capacity of the clays. The exchange capacities in most cases do show a decrease in the A and B horizons, relative to the C, suggesting that they may contain more illite. However, the decrease in exchange

capacity of the clays, and particularly of the coarse clays of the solum relative to the C, becomes greater in going from the Black to the Grey Wooded profile. This, in part, can be attributed to the more intensive weathering as degradation progresses, with a resulting accumulation of quartz and other resistant primary minerals. Similar though less marked decreases in surface area values are observed for clays from the solum relative to those from the parent material.

The inverse relationship between percentage K_2O and the surface area of the clays is shown graphically in Figure 12. Since the illite content of the clays can be assumed to be directly proportional to the potassium content, the same relationship can be said to exist between illite content and the surface area of the clays. Although this relationship appears to be linear within the range of values for the clays studied, it is expected that the line would curve sharply and flatten out as the potassium content increased above 4.0 percent, since true micas which contain around 12 percent K_2O have a surface area of about 10 square meters per gram. Thus, it would seem that the straight line relationship would not in fact be valid beyond the values plotted, at least not for the clays having a K_2O content greater than 4 percent.

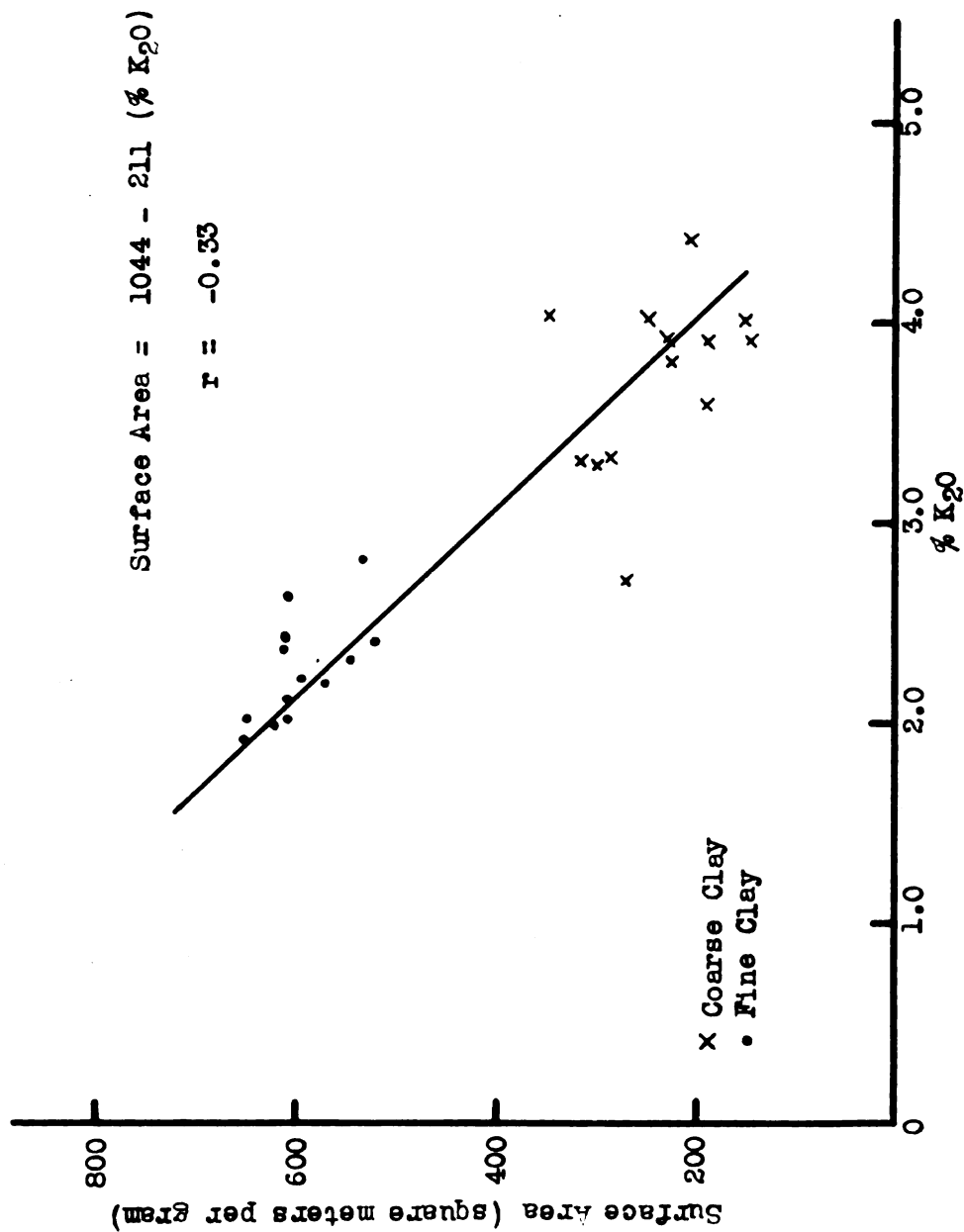


Figure 12. Relation of percentage K₂O to the surface area of the fine and coarse clay fractions.

The relationship between percentage K_2O and the surface area of only the fine clay fraction is shown in Figure 13. The best fitting line has less slope than the line drawn for both the coarse and fine clays (Figure 12). Also, the correlation between percentage K_2O and surface area is much higher ($r = -0.61$) when only the fine clays are considered than when both clay sizes are included ($r = -0.33$). Extrapolation of the line in Figure 13 provides a value of 800 square meters per gram for clay with 0 percent K_2O , a value which happens to coincide exactly with the theoretical value calculated for montmorillonites (62) and which agrees with values reported for soil montmorillonites by Sawhney and Jackson (126).

The relationship between cation exchange capacity and surface area of the clay fractions is shown graphically in Figure 14. Although there appears to be a linear relationship, there is a tendency for the points to curve slightly downward at the lower end of the plotted line. It will be seen that if the line is extrapolated upwards to a surface area value of 800 square meters per gram (assumed to be that of montmorillonite, from Figure 13) a cation exchange capacity value of 104 me/100 g. is obtained. This value falls within the 80-150 me. range reported by Grim (62) and compares closely to the values

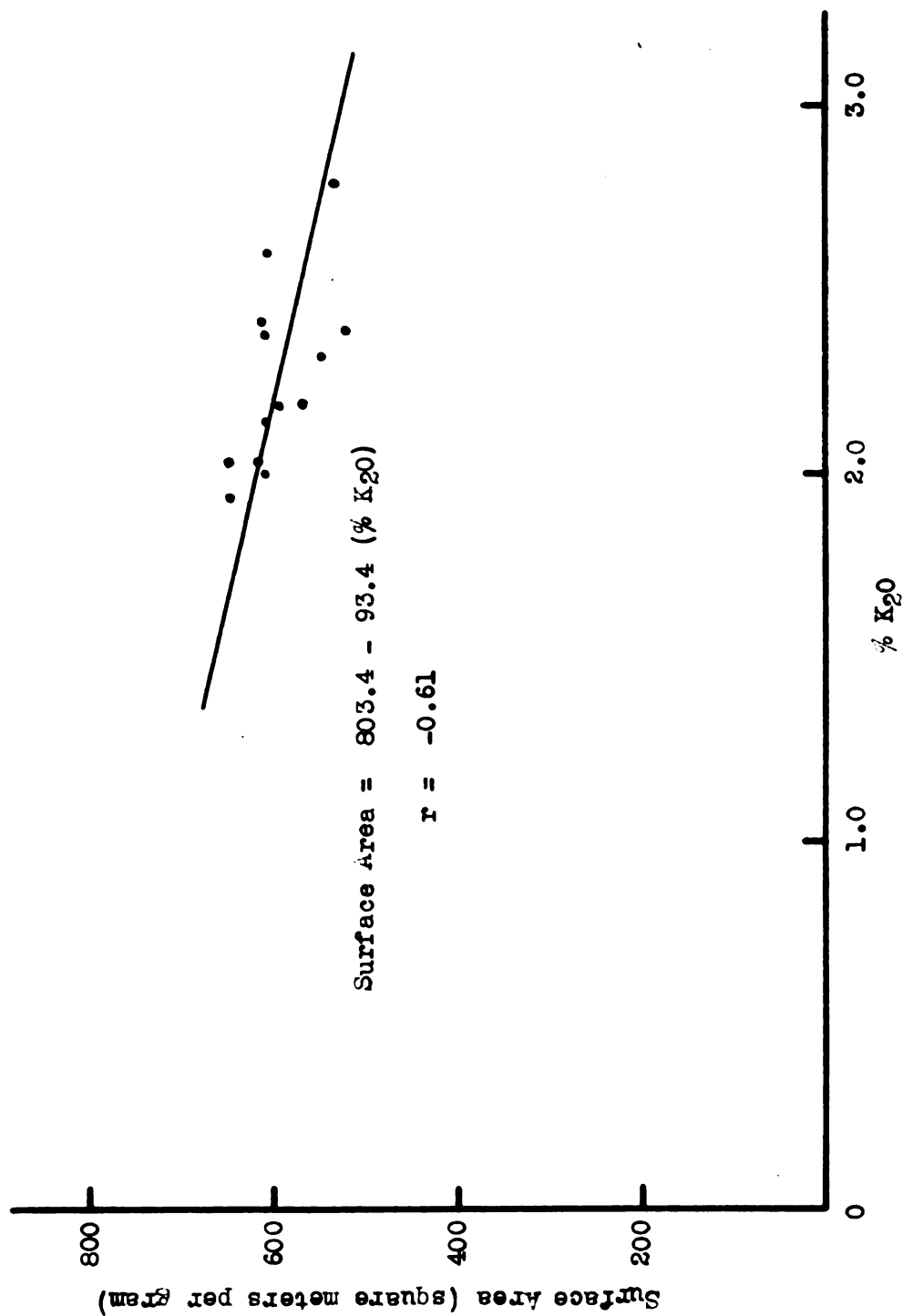


Figure 13. Relation of percentage K₂O to the surface area of the fine clay fraction.

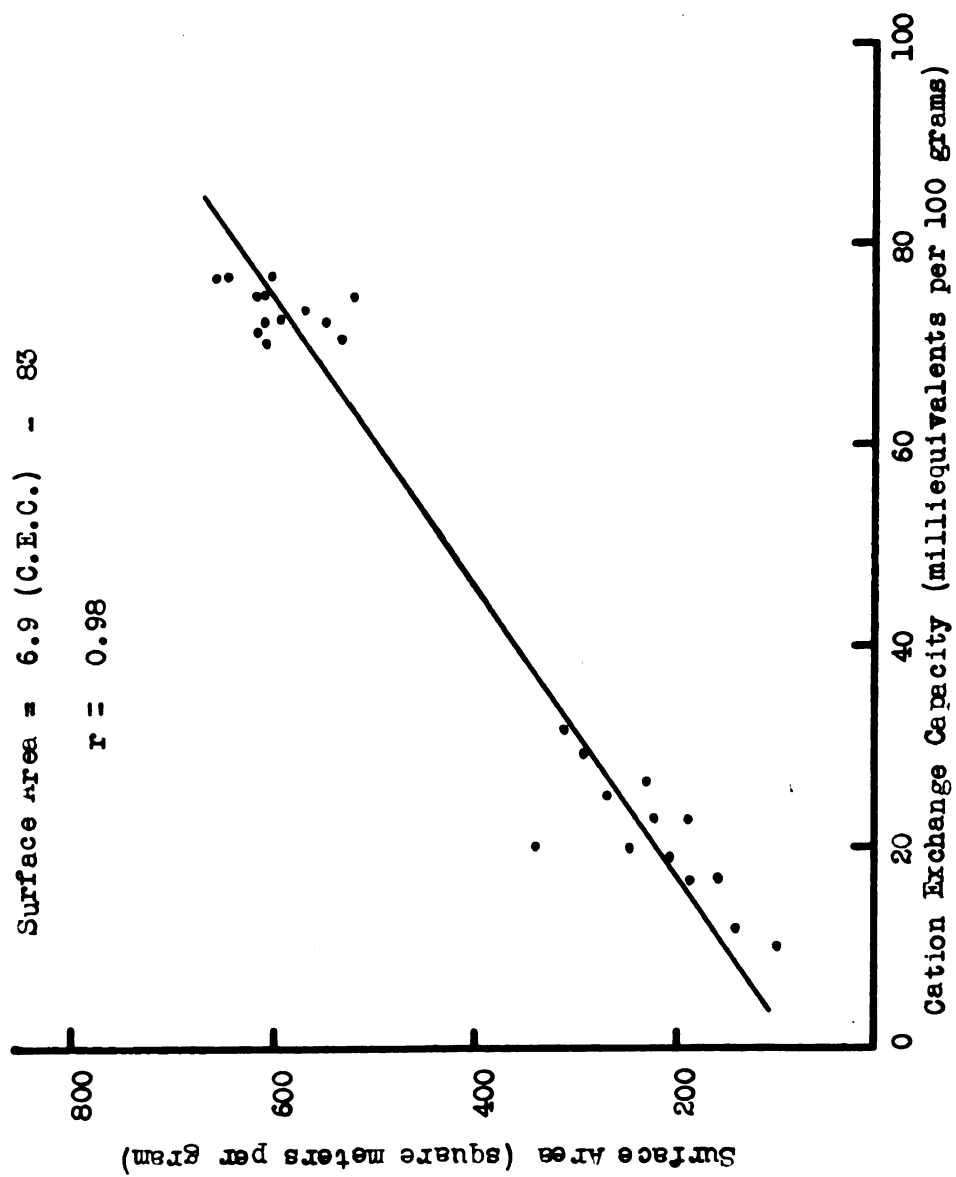


Figure 14. Relation of cation exchange capacity to the surface area of the clay.

reported for soil montmorillonites by Sawhney and Jackson (126). It would appear that the montmorillonite-type clays within the soils studied are characterized by a specific surface of about 800 square meters per gram and a cation exchange capacity near 100 me/100 g.

- 3) X-ray and differential thermal analyses of the coarse and fine clay fractions from the four profiles under study have indicated a predominance of montmorillonite and illite types of minerals. On this basis, estimates of the proportions of these two minerals can be made for the clay fractions.

Estimates of the amounts of illite and montmorillonite present in the two clay sizes were calculated on the basis of K_2O content, cation exchange capacities and surface area determinations. The illite content was determined by assigning all the potassium to illite and assuming illite to have a K_2O content of 10 percent (103). Once the amount of illite present had been calculated, it was possible to assign a certain proportion of the exchange capacity or surface area to it, and thus estimate the montmorillonite on the basis of the remaining portions of the exchange capacities or surface areas. The illite was assumed to have a cation exchange capacity of 10 me/100 g. and a surface area of $10 \text{ m}^2/\text{g}$. These values were based upon values reported for micas by Barshad (6) and

Jackson (68). A cation exchange capacity of 100 me/100 g. and total surface area of 800 m²/g. were assigned to montmorillonite and are based upon the values obtained from data for the clays under study as mentioned previously. It was possible, by using the above values, to calculate the montmorillonite content of the soil clays by two methods, one based on cation exchange capacity, the other based on surface area data.

Values obtained from the calculations made for the major horizons of the four profiles studied are presented in Table 7. From these values it is seen that, for the coarse clays, marked variations are obtained for montmorillonite values calculated by the two methods. This is no doubt due to the fact that illite and montmorillonite make up only a portion of the coarse clay fraction. The presence of quartz and other primary minerals, as well as the greater proportion of kaolinite and chlorite as compared to the fine clay fraction tend to make the calculations quite variable. The presence of potassium-bearing primary minerals such as orthoclase and microcline could very well reduce the accuracy of the assumed illite values. X-ray diffraction patterns of the coarse clays do indicate the presence of some quartz which, in part at least, would invalidate the assumptions made in making such calculations.

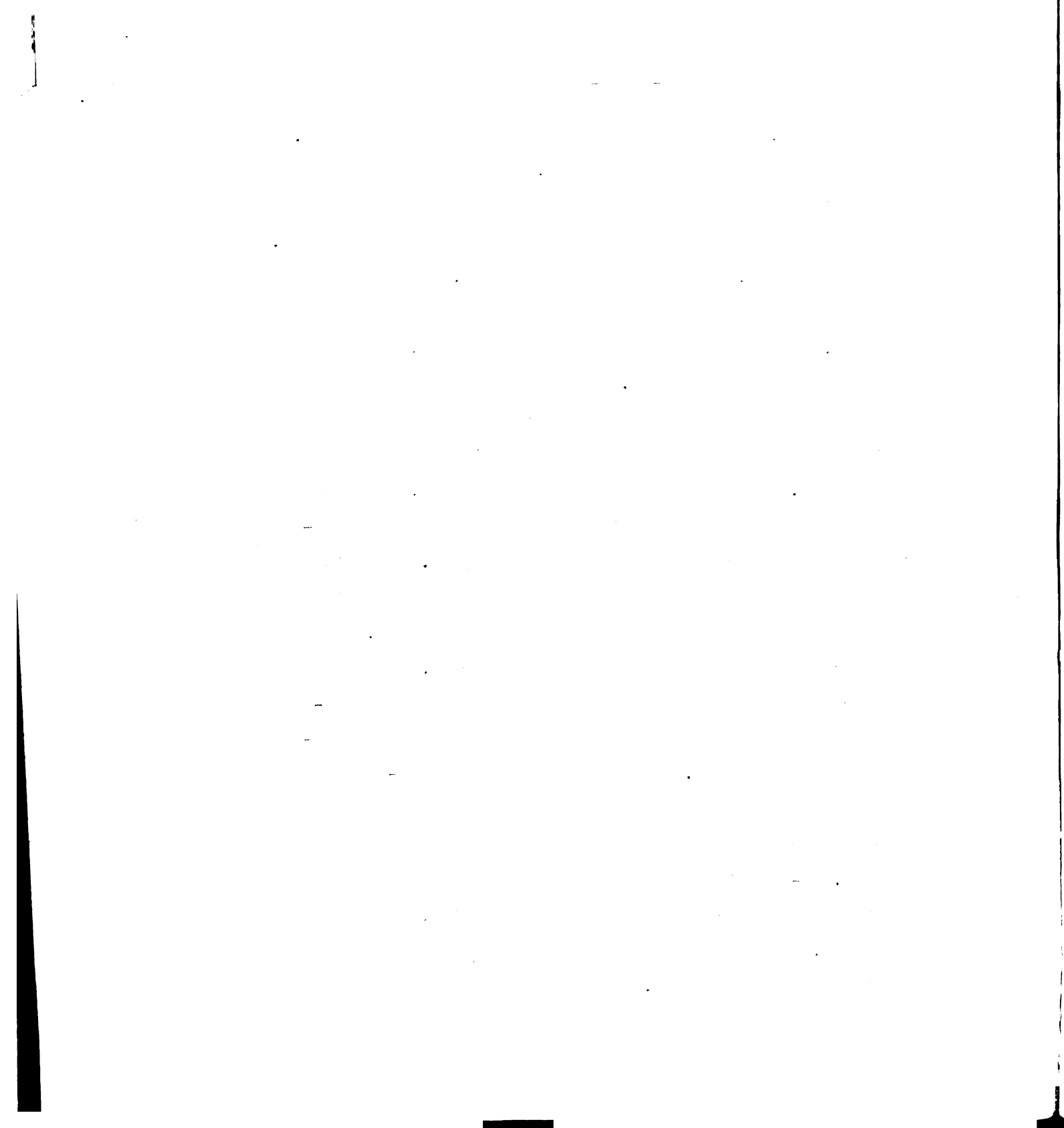


TABLE 7. CALCULATED ILLITE AND MONTMORILLONITE CONTENT OF CLAY-SIZED FRACTIONS FROM THE MAJOR HORIZONS OF THE FOUR PROFILES STUDIED (percentage by weight)

Profile and Horizon	Coarse Clay (2-0.2 μ)			Fine Clay (<0.2 μ)					
	Illite	Mont. (S.A.)* (C.E.C.)**	Diff.***	Illite	Mont. (S.A.)* (C.E.C.)**	Diff.***			
ORTHIC BLACK	Ah	40	43	17	26	28	66	68	-2
	Bmt	44	26	15	11	22	71	70	1
	C1-1	27	33	22	11	20	76	70	6
ORTHIC DARK GREY	Ah	39	29	22	7	26	75	73	2
	Ahe	39	24	18	6	24	76	73	3
	Bmt	38	27	19	6	20	80	75	5
C1-1	33	37	26	11	16	81	75	6	
DARK GREY WOODED	Ae	40	19	14	5	24	74	72	2
	Bt	36	23	13	10	24	76	73	3
	C1-1	33	35	26	9	22	74	70	4
ORTHIC GREY WOODED	Ae	39	17	8	9	23	68	70	-2
	Bt	40	31	16	15	21	75	76	-1
	C1-1	33	39	28	11	20	77	73	4

* Mont. (S.A.) = Montmorillonite values based on surface area data.
 **Mont. (C.E.C.) = Montmorillonite values based on cation exchange capacity data.
 *** Diff. = Mont. (S.A.) - Mont. (C.E.C.)

Fairly good agreement is obtained for montmorillonite values calculated by the two methods for the fine clay fractions. It is seen that the sum of illite and montmorillonite also approach 100 percent. In spite of the inherent errors in trying to quantitatively assess mineral percentages in soil clays, it would appear that the fine clay fractions from the four soils are composed almost entirely of montmorillonite and illite, and presumably in the proportions indicated.

The previously discussed differences in potassium content of the clay fractions were taken to denote variations in the illite content within the profiles. The calculated illite values given in Table 7 will therefore show these same differences, since the illite percentages are calculated directly from the potassium content of the clays. However, the values are interesting since they give actual calculated illite percentages which make comparisons between the horizons more readily perceptible. Although the illite percentages for the coarse clays may be in error due to contamination by other potassium-bearing minerals, the differences in illite contents reported will again reflect the general order of magnitude of differences in illite content if it is assumed that the "contamination" in the coarse clays is about the same for all horizons.

On the basis of the above determinations and additional evidence provided by X-ray analysis, it seems that illitization has occurred in the four soils studied. The highest illite content is noted in clays from the A horizon of the Orthic Black profile. This may be anticipated, since under grassland vegetation the more rapid buildup and decomposition of organic matter supplied by the dense fibrous root system would result in a more rapid recycling of potassium within the soil system. Potassium released from decomposing organic residues would be subjected to fixation by expanding-type clays more rapidly in the grassland soil, due to the more extreme and more frequent drying conditions which occur, than in the more humid forest soils. Experiments of Wear and White (145) and Mortland et al. (109) as well as Bourne's work (19) indicate that such a process can and does occur.

Quartz Analysis

Mineralogical studies of the Orthic Black, Orthic Dark Grey, Dark Grey Wooded and Orthic Grey Wooded profiles included the determination of quartz content of the different sized fractions from the major horizons. It was believed that the quartz content of the various fractions might indicate

some of the mineralogical changes occurring in the various profiles and might also be useful in determining whether or not some of the coarser fractions could be used in quantitatively estimating changes occurring within the profiles, as suggested by Marshall and Haseman (95) and others (5, 7, 118). Since preliminary work indicated that the fine clay fraction ($<0.2 \mu$) contained no detectable amounts of quartz, no quartz values for this fraction are reported. Quartz was determined by the X-ray diffraction technique described under Laboratory Procedures.

Particle Size Distribution of Quartz

The quartz values for the soil separates from the major horizons of the four profiles are given in Table 8. The values are expressed as percentage of the oven-dry weight of acid treated fractions as well as of total untreated fractions. It was realized that quartz percentages reported for the untreated fractions were not all comparable since variable amounts of dolomite (and possibly calcite) were present in the different sized fractions. In separating the sands, silts and clays from the soils, the pretreatment consisted of adjusting the pH to 3.8 to 4.5 with dilute HCl prior to the removal of organic matter with hydrogen peroxide.

TABLE 8. QUARTZ CONTENT OF THE SOIL SEPARATES FROM THE MAJOR HORIZONS OF THE FOUR PROFILES. (Expressed as percentage of HCl-insoluble oven-dry weight of the fraction)*

Fraction	Horizon	Orthic Black	Orthic Dark Grey	Dark Grey Wooded	Orthic Grey Wooded
Coarse Clay	Ah	12 (10)	17 (16)	-	-
	Ahe, Ae	-	17 (16)	23 (21)	26 (24)
	Bmt, Bt	13 (12)	16 (15)	17 (15)	16 (14)
	C1-1	7 (6)	6 (5)	7 (6)	7 (6)
Fine Silt	Ah	38 (33)	32 (31)	-	-
	Ahe, Ae	-	35 (34)	42 (40)	45 (43)
	Bmt, Bt	41 (40)	33 (31)	40 (37)	38 (36)
	C1-1	32 (28)	33 (28)	37 (31)	34 (31)
Medium Silt	Ah	46 (42)	43 (42)	-	-
	Ahe, Ae	-	45 (44)	55 (54)	51 (50)
	Bmt, Bt	53 (51)	50 (49)	52 (50)	48 (46)
	C1-1	46 (42)	41 (35)	52 (43)	46 (42)
Coarse Silt	Ah	60 (59)	54 (53)	-	-
	Ahe, Ae	-	61 (60)	62 (61)	59 (58)
	Bmt, Bt	64 (63)	53 (52)	61 (60)	57 (56)
	C1-1	55 (50)	58 (50)	59 (50)	55 (50)
Very Fine Sand	Ah	60 (59)	61 (59)	-	-
	Ahe, Ae	-	60 (59)	65 (62)	61 (61)
	Bmt, Bt	64 (62)	62 (60)	64 (62)	65 (64)
	C1-1	60 (56)	60 (55)	61 (53)	63 (58)
Fine Sand	Ah	68 (66)	71 (69)	-	-
	Ahe, Ae	-	71 (70)	72 (70)	62 (60)
	Bmt, Bt	72 (71)	69 (68)	74 (72)	71 (69)
	C1-1	66 (63)	70 (67)	69 (64)	67 (62)
Coarse & Medium Sand	Ah	60 (58)	70 (69)	-	-
	Ahe, Ae	-	67 (66)	67 (65)	67 (65)
	Bmt, Bt	57 (56)	65 (64)	66 (64)	68 (66)
	C1-1	61 (54)	65 (56)	66 (55)	62 (52)

* Values in brackets are percentages based on the oven-dry weight of the fraction without acid treatment.

Since the samples were not heated with HCl, the dolomite was relatively unaffected. Heating with acid (to destroy dolomite) was avoided because chlorites are also destroyed by treating with warm HCl(29). As a consequence the C horizons contained significant amounts of dolomite; smaller and more variable quantities of dolomite remained within the solum fractions following its removal by natural weathering processes. In order to make the values comparable, it was necessary to treat the fractions with warm dilute HCl to destroy dolomite and thus correct for its presence by reporting the quartz percentages on a dolomite-free basis or, actually, an HCl-insoluble basis. Thus, both methods of reporting the quartz values were used in compiling the data for Table 8.

In observing the values for the HCl-treated fractions given in Table 8, it is seen that there are pronounced increases in the quartz content of the fine fractions of the A and B horizons of all profiles relative to the parent material, whereas the differences are smaller in the coarser fractions. In comparing values for the acid-treated and untreated fractions, it is seen that the acid treatment brought quartz values for the C horizons much closer to those of the A and B horizons, particularly in the coarser fractions. However, the general trend is still evident since the fractions from the A and B horizons are nearly always higher in quartz than those from the parent materials.

For any given size fraction, an increase in quartz content in the acid-insoluble fractions of the A and B horizons over the C could result from:

- 1) the weathering and removal of minerals other than quartz in that particular fraction (this would increase the relative proportion of quartz in the fraction), and
- 2) the weathering of quartz or quartz-bearing rock material in coarser fractions resulting in the weathered quartz product thus showing up in the finer fractions. (This could increase the actual quartz content of all but the coarsest fraction.)

From our present knowledge of chemical weathering, it would be most probable that such weathering would be more pronounced in the finer fractions than in coarse ones and that quartz would be less affected than most other minerals. One could readily expect the loss of feldspars and non-resistant heavy minerals from the silt and coarse clay fractions, leaving a predominance of quartz in these fractions. The weathered products would presumably appear in the clay fraction, or would be removed from the solum. It is recognized that few or no primary minerals such as quartz and feldspars exist in the clay fraction below 0.2 μ size (68, 72, 73); X-ray and other data substantiate this in the case of the four soils in this study.

If chemical weathering occurred to some degree in all size ranges, it would be plausible to assume that non-quartz minerals weathering in the coarsest size fraction would end up in the next smaller size fraction. Such a process would tend to decrease the quartz percentage in the smaller sized fraction and increase it in the coarser one. A similar effect would result throughout the entire range of particle sizes. This general tendency might not be detected, however, if the rate of non-quartz mineral weathering increases as particle size decreases. Due to differential rate of weathering, the quartz content of all fractions could increase in comparison with the presumably unweathered parent material. This could explain why the fractions in the A and B horizons are nearly always higher in quartz than in the parent material.

A second process by which the quartz content of acid-insoluble fractions from the solum could increase relative to the C horizon was suggested above. This required the breakdown of quartz or quartz-bearing rock material in the coarser fractions, resulting in the weathered quartz product showing up in the finer fractions. Such a process could presumably increase the quartz content of all but the coarsest fraction. Presumably, a decrease in quartz would result in the coarsest fraction. The data in Table 8 show that for the four profiles under study, the fine and coarse

sand fractions of the A and B horizons have quartz values very similar to those of the corresponding fractions in the parent materials. Although slight decreases in quartz are observed in some cases, slight increases show up in others. The data would seem to indicate that redistribution such as that suggested is, therefore, not occurring or at least not to any great extent. On the basis of the results thus reported, it would appear that the first explanation can more satisfactorily account for the observed trends in quartz content of the various fractions.

The above considerations may be open to question since particle size distribution itself could markedly affect the total quartz percentage in any fraction. It is entirely possible that rock fragments whose composition, as far as quartz is concerned, closely approximates the composition of the coarse sand fraction, could break down into finer sizes with little or no resulting change in the quartz percentage of the coarse sand fraction itself. For example, a piece of granite of coarse sand size having a quartz content of about 60% could break down so that all the fragments fell into a smaller size range without affecting the quartz percentage of the coarse sand fraction from which it weathered, if the latter also contained about 60% quartz by weight. Even a small amount of breakdown such as this in fractions high in quartz would not show up in the quartz percentage of

the coarser fractions but could significantly increase the quartz percentage of the finer fractions which are much lower in quartz. If, on the other hand, changes in quartz percentages resulted only from the weathering of non-quartz material from the various fractions, with little or no effect on the quartz present in them, a uniform particle size distribution of quartz should result for all horizons. A non-uniform distribution of quartz would naturally result if the breakdown of quartz-bearing rock material had occurred. The same effect could be realized if quartz itself were to break down into smaller particles simultaneously with non-quartz minerals, even though to a lesser degree. With this possibility in mind, it was therefore desirable to calculate the quartz size distribution for all the horizons concerned.

The total weight of quartz in any fraction within a given horizon was obtained by multiplying the quartz percentage by the percentage of each fraction in the horizon concerned. Thus, if a sample contained 10% fine silt having a quartz content of 50%, the sample contained 5 grams of quartz in the fine silt size per 100 grams of soil (50% of 10% of 100 g.). By calculating the total quartz in all fractions (excluding the fine clay which has negligible quantities of quartz) it was possible to obtain a value for total quartz in a given soil horizon and to express the quartz in each fraction as a percentage of the total quartz

in that soil horizon. Values, calculated for the major horizons of the four profiles, are given in Table 16, Appendix. The same data are presented graphically in Figure 15.

In observing the graphs shown in Figure 15, it will be noted that in all four profiles, a greater percentage of the quartz is present in the coarser fractions of the C horizons than in the A and B horizons, the depression generally being greatest in the A horizons. The decrease in quartz in the medium plus coarse and fine sand fractions of the A and B horizons has resulted in an increase of quartz in the intermediate fractions, notably the medium silt, coarse silt and very fine sand fractions. Observation of the various fractions under a microscope revealed that many rock fragments and badly fractured quartz and other mineral grains are present in the coarse and medium sands. In the smaller sizes, the grains are predominantly individual minerals and fewer of them show signs of fracture. Also, the rock fragments and badly fractured quartz grains are much more abundant in the parent material coarse plus medium and fine sand fractions, as compared to the same sizes in the A and B horizons. A purely physical breakdown of such particles with the resulting release of quartz as discrete smaller quartz grains would favor the accumulation of quartz in the finer sizes. Non-quartz material would also break down to smaller sizes but since quartz is much more abundant, the effect of the quartz would be dominant.

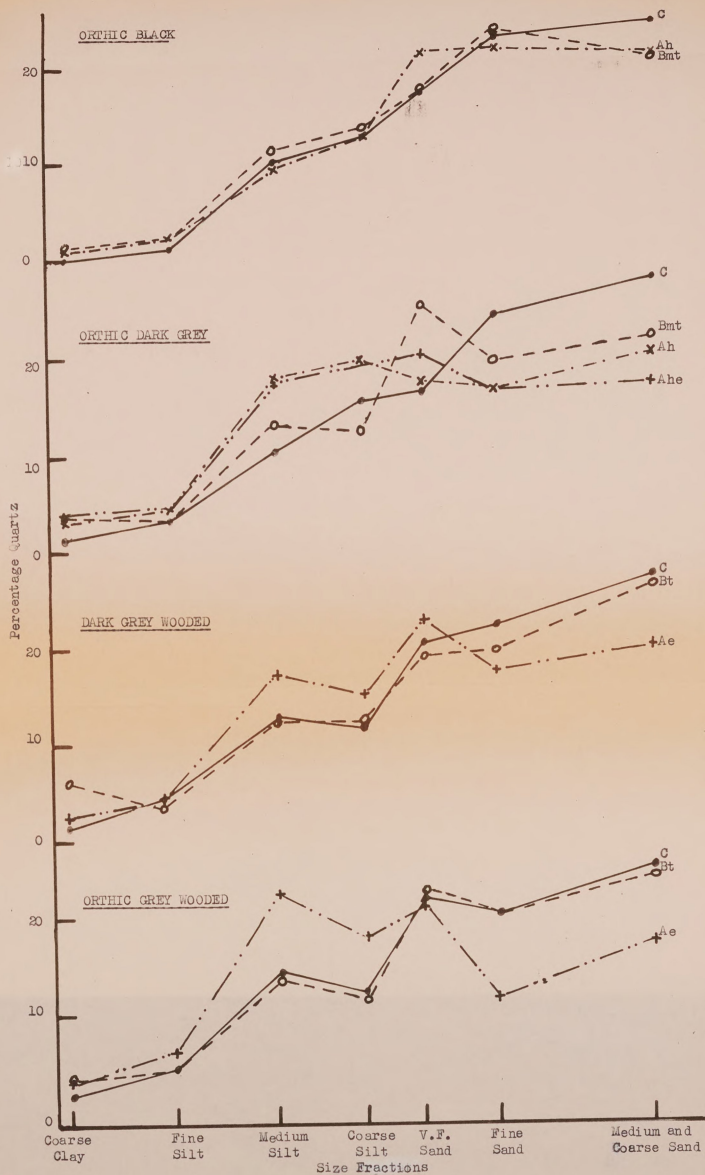


Figure 15. Particle size distribution of quartz within the major horizons of the four soil profiles, expressed as percentage of total quartz.

Variations in quartz distribution are observed both within and between the four profiles. In all cases, there is less quartz in the coarser fractions of the A horizons than of the B horizons. For the Orthic Black profile, differences in quartz distribution between the solum fractions and those of the C horizon are relatively small. However, marked differences appear in comparing the A horizons of the other three profiles to the parent materials. In going from the Orthic Dark Grey profile to the Grey Wooded soil, the curves for the B and C horizons, while quite dissimilar in the first, approach one another and almost become coincident in the latter profile. If these trends do in fact indicate a physical breakdown of coarser material, it is evident that in all cases such breakdown is most pronounced in the surface horizon, with the chernozemic Black soil undergoing the least decomposition of this type. Also, appreciable breakdown occurs in the B horizons, but this decreases in going from the Orthic Dark Grey to the Grey Wooded soil.

The median particle size of quartz as determined from cumulative percentage curves for quartz of the various horizons provides an additional measure of the quartz distribution within the soils. A comparison of median diameters of quartz in the major horizons of the four profiles indicates that there is a decrease in quartz size within the solum horizons relative to the parent material and that this decrease

in size is least pronounced in the Black soil. Also, there appears to be a relationship between median quartz diameters and depth of the respective horizons. This relationship for the four profiles is shown graphically in Figure 16. It is apparent that breakdown of quartz decreases with depth. Despite the apparent correlation between size and depth ($r = 0.75$), the scatter of points indicates that other factors may be affecting the degree of breakdown within the four profiles. This point merits further attention and will be dealt with more fully in subsequent discussions.

Particle Size Distribution Within the Total Soil

Quartz distribution within the different fractions of the major horizons of the four profiles studied has indicated the possibility and likelihood of physical weathering having taken place in the coarser fractions. If this has occurred, similar trends to those demonstrated in the quartz distribution should show up in the particle size distribution of horizons of each profile. In fact, this is the case; the mechanical distribution of the soil separates does show that more coarse, medium and fine sand are present in the C horizons than in the upper horizons of the profiles (Table 2). This general trend holds for all four profiles. It will be noted that corresponding increases in the proportions of some of the intermediate fractions in the A and B horizons (relative

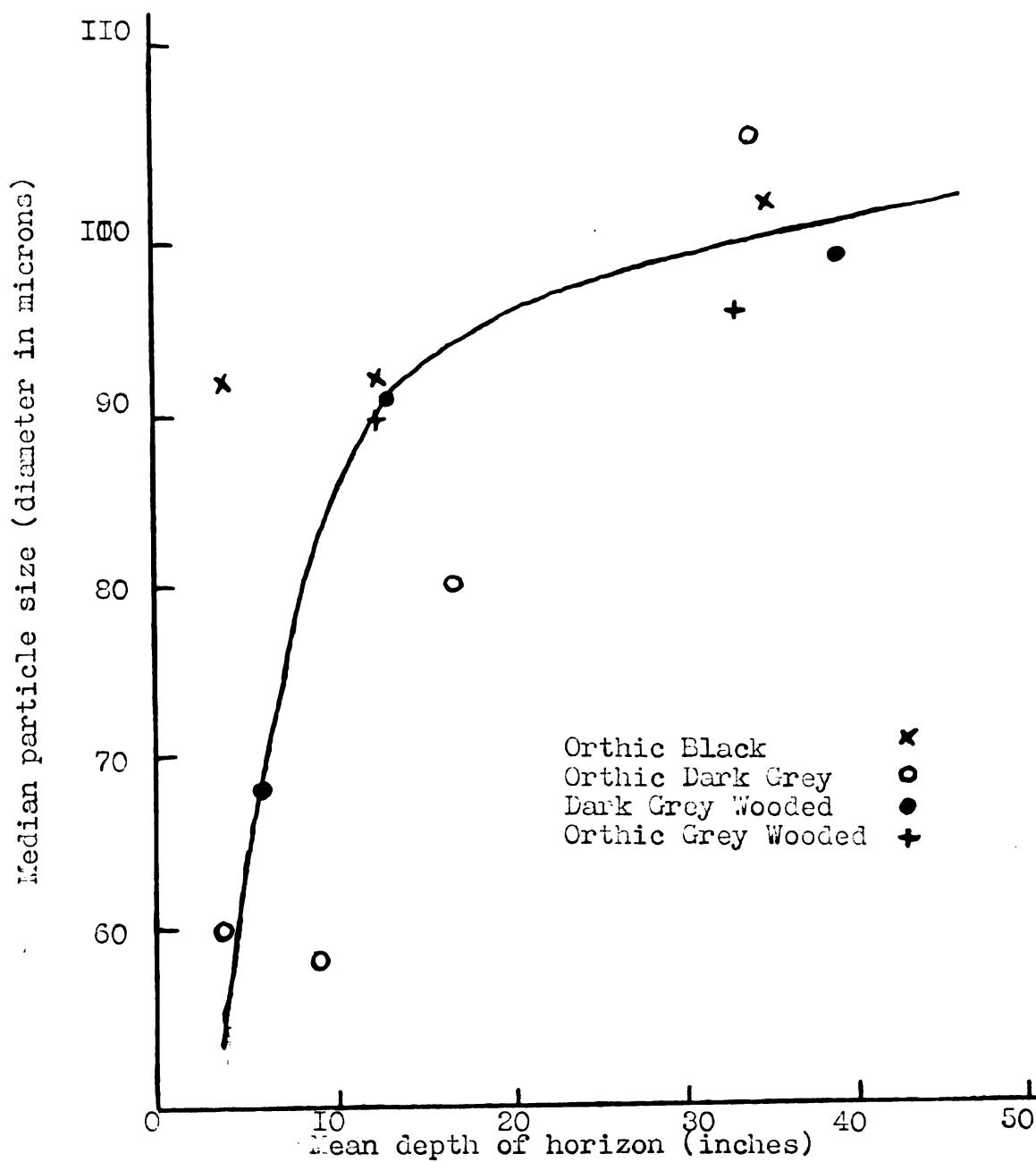
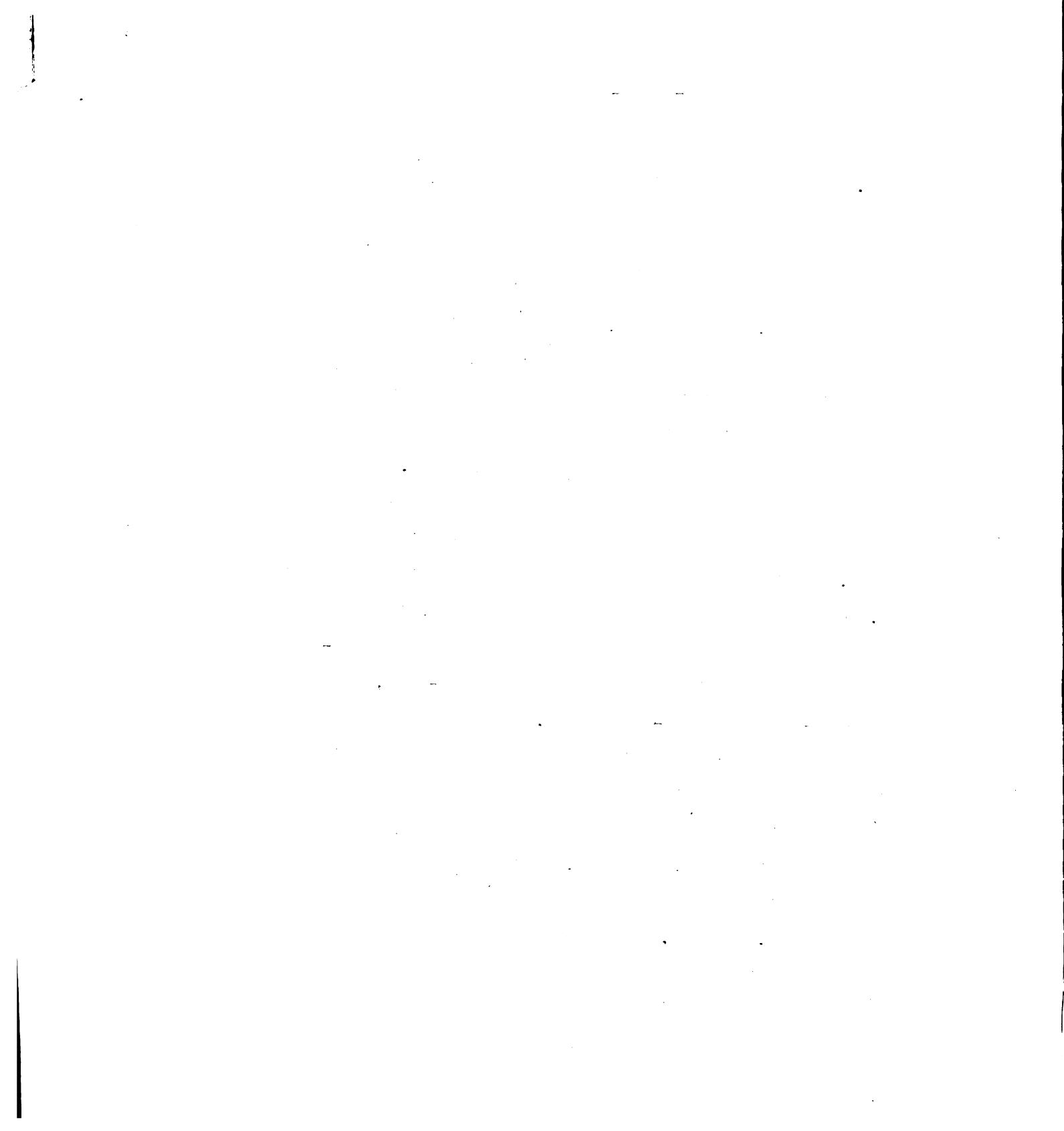


Figure 13. Relation of the median particle size of the fine earth quartz to the mean depth of the horizon in the four profiles studied.

to the C horizon) accompany the decreases in the coarser fractions. Although these differences do show up, the values are not really comparable for two reasons:

- 1) The translocation of clay from the A to the B horizon will have a concentrating and diluting effect for the two horizons, respectively, and thereby distort the particle size distribution picture; and,
- 2) Appreciable quantities of calcite and/or dolomite in the C horizon with smaller and variable amounts in the solum tend to invalidate comparisons made. It is known that calcite and dolomite will weather out of the solum much more readily than other soil minerals (73). If it can be assumed that only clay finer than 0.2μ is likely to move to any great extent, it is possible to make particle size distribution data comparable by reporting values on a fine clay-free, calcite- and dolomite-free basis. The assumption that only fine clay is likely to undergo translocation in soils is not strictly valid since particles as large as fine silt size have been reported to have moved in soils (66). However, it is likely that the major portion of translocated particles will be below the 0.2μ size. The mechanical analyses data (Table 2) indicate that the clay accumulation in the



B horizons results almost entirely from fine clay indicating that the movement of coarse clay is not very significant. Also, the relatively low (less than 6 percent) fine silt content of these soils and its relatively uniform distribution within the profiles seem to indicate that particles within this range do not readily move, and that if they do, the small amounts moved will not seriously affect the calculations being suggested. On this basis, the assumption that only clay less than 0.2μ in size has moved seems warranted.

With this in mind, mechanical analysis values based on the total mineral soil were corrected for loss by acid treatment, all fractions but the fine clay were added for each horizon, and the fraction percentages reported on a fine clay-free, HCl-insoluble basis. It must be noted that the acid treatment possibly removed materials other than carbonates but that at least all fractions were treated similarly. By making the necessary corrections to exclude fine clay and carbonates, the results presented in Table 17, Appendix, were obtained. The data from this table are shown graphically in Figure 17. The similarity between the particle size distribution of all the soil minerals (Figure 17) and the quartz (Figure 15) is very evident. There is a decrease in the amounts of coarse and fine sands in the selum as compared to the C, with corresponding increases in the

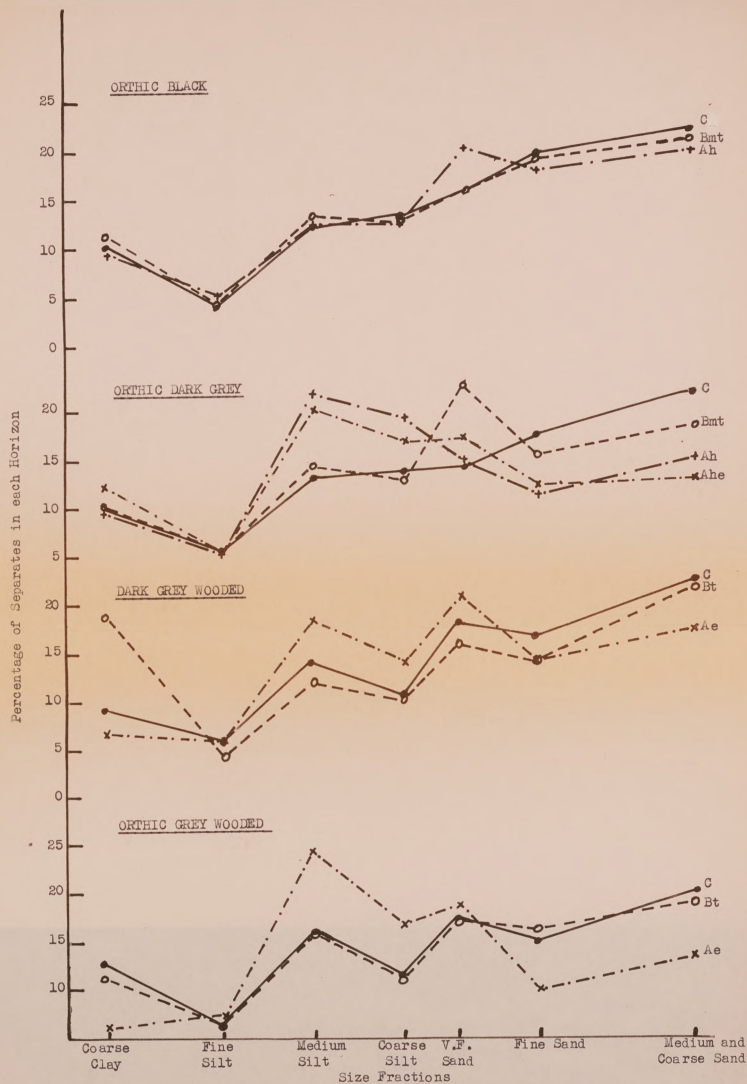


Figure 17. Particle size distribution within the major horizons of the four profiles.
(Soil separates expressed as percentage of HCl-treated, fine clay free fine earth, on an oven dry basis.)

intermediate fractions. Again, as in the quartz distribution, the B and C horizon values for the Grey Wooded soil are very similar and the curves almost coincide. The particle size distributions thus calculated seem to confirm the possibility of physical breakdown in the solum of the four profiles, or at least they indicate a physical redistribution of separates which could result from physical or chemical weathering or both.

Temperature differences and frost action may largely account for the physical breakdown which occurs in the four soils studied. It is known that daily and seasonal variations in temperature cause expansion and contraction of rocks and, since the component minerals have different rates of expansion, tension is set up within the mass so that the rock gradually crumbles (119, 120, 124). There is no reason why this should fail to apply just as well to rock fragments present in soils. Frost could also be instrumental in such breakdown by the action of expanding water as it freezes in fissures or cleavages of rocks or minerals. It is likely that frost action would be most effective under wet soil conditions and least under dry conditions.

In soils which have dense impermeable B horizons, there may be times when such layers restrict downward move-

ment of water to such an extent as to produce a temporary water-logging (a perched water table) in the surface horizons immediately above them. If this was immediately followed by freezing temperatures, frost action could have a very destructive action on rock fragments or fractured minerals in the saturated layer. Repeated freezing and thawing such as occurs under Saskatchewan conditions in the fall and early spring would accentuate any such breakdown. Ice lenses have actually been observed in surface layers of soils in the early spring. Their presence invariably results under conditions of high moisture in the soils.

Following the above considerations, it is suggested that differences in the degree of physical disintegration may be related to differences in water content of the horizons during certain times of the year when frost action would be at its maximum. Although all four of the profiles under study show an accumulation of clay in the B horizons, this accumulation is much more pronounced in the Dark Grey Wooded and Grey Wooded profiles. In addition, there is a progressive increase in bulk density (Table 3) of the B layers in going from the Black to the Grey Wooded soils. This means that the permeability of the B horizon of the Orthic Black profile will likely be much better than for the other three profiles. The Orthic Black soil, having developed under grassland vegetation is generally recognized

as having good structure and provides suitable internal drainage. The degraded Black and Grey Wooded soils all possess heavier, more dense B horizons which restrict internal water movement to a more marked degree. Due to these differences in drainage within the profiles, it is understandable that the Black soil shows the least physical breakdown since drainage is adequate and water-logging may seldom occur. In other words, conditions favoring frost action are rarely at their optimum in this profile, while they will more often be so in the other profiles. Another factor which brings this trend about is the generally higher moisture content of the soils in going from the grassland to the forested soil. Moisture losses due to evaporation are greatest in the Black soil and least in the Grey Wooded. This would tend to accentuate the possibility of excessive moisture being present more often in the Grey Wooded than in the Black soil.

It is not suggested here that water-logging must occur before frost action can cause physical breakdown of particles in soils, although such a condition may enhance such a process. Colloidal material present in fissures or cracks of coarse fragments in a soil will hold water and even if no free water is present freezing of such material will exert pressures due to the freezing of water held by it.

It is suggested, therefore, that physical breakdown is more likely to occur in soil horizons which are more often wet than dry when fluctuating temperatures occur near the freezing temperature of water, and that soils with impervious subsurface horizons are more likely to become saturated with water under conditions of excessive precipitation.

The frequency of freezing and thawing in a soil will no doubt have a direct bearing on the degree of physical breakdown of particles; the higher the frequency, the greater will be the possibility of breakdown. It is known that soil temperatures can vary markedly from day to day and from season to season. It is also recognized that the greatest temperature fluctuations occur in the surface soil. The insulating qualities of different types of vegetation and leaf litters have been discussed and reported on by many (77, 124, 125). From existing evidence, one would expect that of the four profiles studied here, the greatest variations in temperature would occur in the Orthic Black profile. The presence of L-H layers in the other three soils would serve as insulation so that temperature changes might not be as pronounced and would not be effective to as great a depth as in the Orthic Black soil. The impervious nature of the Bt horizon of the Grey Wooded soil, plus limited temperature fluctuations at the lower levels may explain the marked breakdown occurring in the Ae horizon and its absence in the

Bt horizon of that soil. Even though the greatest changes in temperature may occur in the Black soil, its good drainage and resulting generally drier condition would reduce the effectiveness of frost action. Thus, even though there appears to be a direct relationship between breakdown (as indicated by the median size of quartz) and mean depth of the horizons (Figure 16) the presence of impervious subsurface horizons, the soil moisture conditions, and the insulation afforded by L-H layers in the profiles all have a controlling effect on the extent to which such breakdown will occur.

Other factors, such as the prying action of roots within cracks in rocks and minerals must not be overlooked. It has been recognized that disintegration of rock material has resulted from such action. The extent to which it occurs in soils, however, is not known. Also, sudden changes in temperature such as often occurs when cold rain hits warm rock material may be another factor leading to disintegration.

Freezing and Thawing Experiment

Quartz analyses and particle size distribution data have provided evidence that a redistribution of particle sizes has occurred within the sola of the four soils under study. The breakdown or disintegration of the coarse-sized fractions in these soils with attendant accumulation of particles of

finer size, has been suggested. The possibility of such breakdown being due, in part at least, to frost action has also been suggested. In order to determine whether frost action could account for the breakdown of coarse-sized fractions, an experiment was set up to determine the effect of repeated freezing and thawing on sand grains separated from the Ae horizon and parent material of the Grey Wooded soil. In addition, samples of crushed quartz, Ottawa (silica) sand, and a single piece of granite were subjected to similar treatment.

Duplicate samples (previously sieved to exclude grains < 0.5 mm. in size) were weighed, and placed in beakers. Sufficient water was added to completely cover them. The beakers were placed in a freezer, the temperature of which was maintained at -16° C., and the samples allowed to freeze. The samples were left in the freezer for two hours and then kept at room temperature for two hours in order to complete the cycle of freezing and thawing. Four or five such cycles per day were thus possible, the samples being left in the freezer overnight. After 100 cycles, the samples were dried at 45° C., cooled, sieved and the material finer than 0.5 mm. in diameter was weighed. The data from this experiment are recorded in Table 9, losses to sizes smaller than 0.5 mm. resulting from breakdown being expressed as percentages of the original weights of materials used.

TABLE 9. THE EFFECT OF REPEATED FREEZING AND THAWING ON THE BREAKDOWN OF MINERAL GRAINS

Material	Sample No.	Size Range (mm.)	Original Weight	% Loss		Total
				First 100 Cycles	Second 100 Cycles	
Sands from Ae of Grey Wooded Soil	1	0.5-2.0	17.64	1.30	0.64	1.92
	2	0.5-2.0	17.01	1.93	0.44	2.35
	3	2.0-10	43.92	0.61	0.44	1.02
	4	2.0-10	45.61	1.58	0.32	1.79
Sands from Cl-1 of Grey Wooded Soil	5	0.5-2.0	15.25	3.49	0.32	3.80
	6	0.5-2.0	14.82	2.84	0.35	3.16
	7	2.0-10	66.60	1.68	1.40	3.03
	8	2.0-10	71.42	0.66	0.60	1.20
Crushed Quartz	9	1.0-2.0	42.56	0.16		
	10	2.0-10	38.52	0.13		
	11	2.0-10	38.22	0.18		
Ottawa Sand	12	0.5-1.0	27.76	0.08		
Granite	13	1.5" Cube	37.61	0.48		

The values reported are corrected for losses which would have resulted had the samples simply been immersed in water for the same length of time. The control samples, which consisted of similar materials (immersed in water) but which were kept at room temperature during the entire experiment rather than being subjected to the freezing and thawing treatments, provided values to make such corrections. Disintegration

within the control sample varied from 0.1 to 0.4 percent for the first run and occurred only in the sands from the parent material of the Grey Wooded soil. No losses occurred during the second run. The breakdown recorded for the control samples in the first run resulted mainly from disintegration of shaly fragments and calcite particles.

The following conclusions can be made regarding the effect of repeated freezing and thawing on the materials used:

- a) Physical breakdown or disintegration has occurred in all samples.
- b) Disintegration was greatest for the sands from the parent material and less for those from the Ae horizon. This is due in part to the presence of appreciable amounts of limestone and a few shaly fragments in the parent material and the low proportion of these in the Ae horizon. Microscopic examination of the fractions recovered confirmed this observation.
- c) The disintegration of the quartz and granite samples was very slow, but breakdown had definitely occurred. The crushed quartz samples (Nos. 9-11 inclusive) had undergone freezing and thawing treatments prior to their use in this experiment. These fractions had been incorporated into a matrix of silty clay, to which water was added, and repeatedly frozen and

thawed approximately 60 times. The moisture content of the soil-quartz mixture was maintained slightly above field capacity. The total recorded breakdown of the quartz amounted to 2.15 percent of the original weight of quartz. The low losses reported for the crushed quartz in Table 9 indicate that the badly fractured grains had probably undergone breakdown during the first experiment, thus diminishing the possibility of additional disintegration during the subsequent treatments. This is substantiated by the decrease in losses resulting from the second 100 cycles as compared to the first 100 cycles of freezing and thawing of the sands from the Grey Wooded soil.

As was anticipated, the Ottawa sand underwent the least breakdown of all the materials used. This sand is a well-rounded quartz sand, the grains of which possess few fractures, thus rendering it less susceptible to destructive action by freezing water.

The amounts of material breaking down to below the 0.5 mm. size may not represent the entire disintegration which has occurred in the sands, especially in the 2.0-10 mm. size, since particles may have broken down to sizes above the 0.5 mm. limit. Thus, the values reported may represent only a portion of the total breakdown which has occurred.

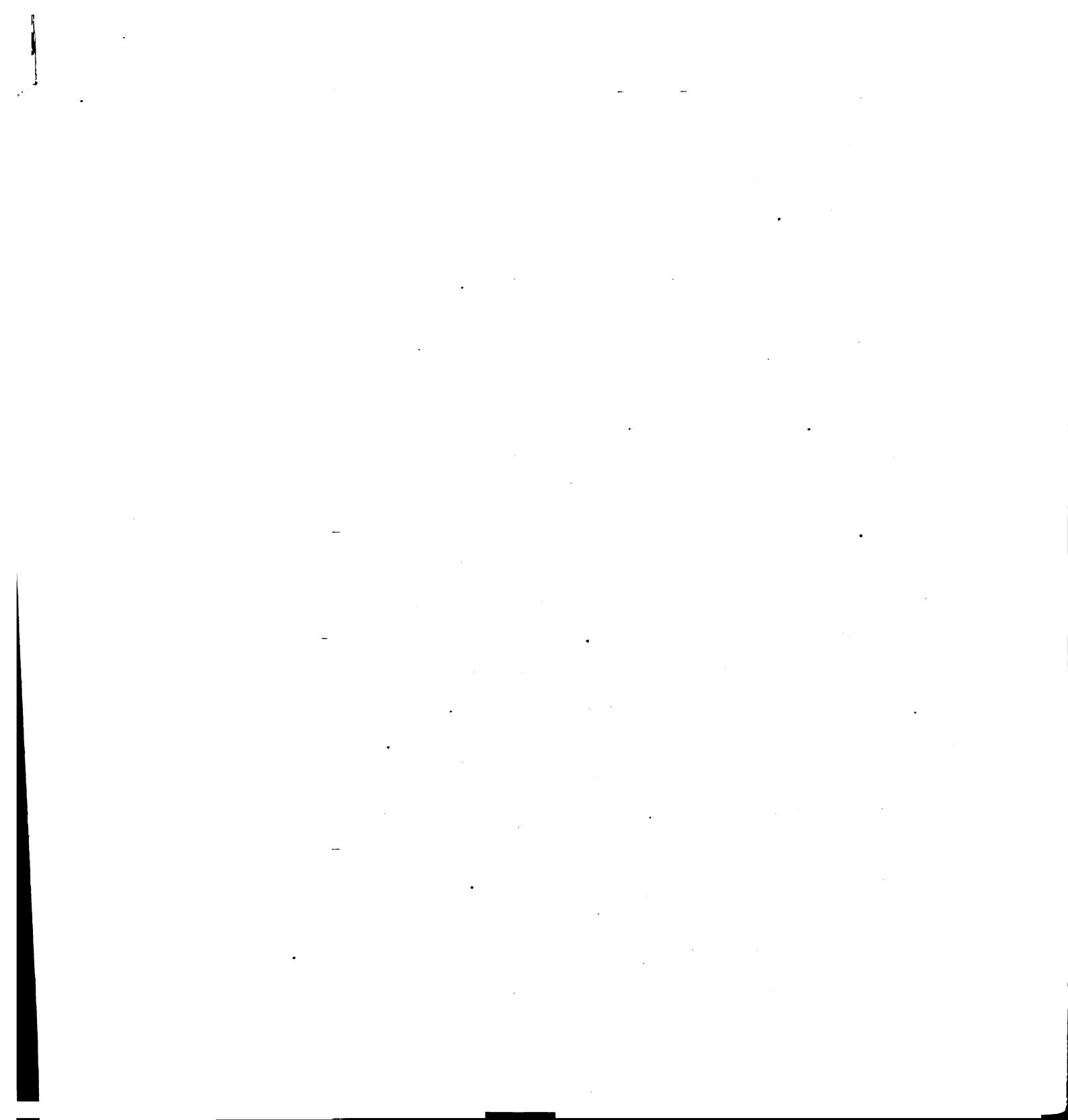
On the basis of the results from these experiments it is evident that coarse-sized fractions in soils could undergo breakdown as a result of the physical forces of freezing water. It appears that disruption of badly fractured grains would occur fairly rapidly so that the amount of disintegration would fall off markedly after freezing and thawing had continued for some time. Thereafter, the amounts of breakdown would possibly depend upon the rate at which chemical factors such as solution effects could bring about the widening of spaces along less pronounced incipient fractures, so as to allow freezing of water within them and cause splitting of grains. Breakdown would possibly be most pronounced in soils at high moisture levels. More detailed work is no doubt required in order to determine the many factors which could affect breakdown such as has occurred in this experiment.

If physical breakdown has occurred in the four soils as suggested, it may be occurring in many other soils of this and other regions. If this is the case, certain implications arise which have a direct bearing upon the interpretation of certain studies in soil genesis. First of all, if physical weathering occurs, quartz can not be considered as an inert mineral, the fractions of which can be used as indicators in assessing changes which occur in soils during their development. However, the total amount, if occurring in sizes not eluviated, could be used if quartz is not dissolved or formed during soil formation. Secondly, uniformity of ratios of

quartz percentages in given size fractions throughout a soil profile does not necessarily indicate that the material was initially uniform. The proportion of quartz in various size fractions of a given horizon may decrease or increase markedly without an apparent change in total composition.

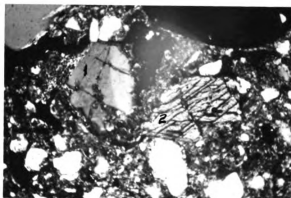
Since quartz distribution may be affected by physical breakdown, it is also likely that the distribution of other minerals present in soils may be affected in a similar manner. If this occurs, the use of mineral ratios in a given size fraction to assess weathering within a soil may not be valid and erroneous conclusions may result from their use. Abnormally high quantities of silt in some horizons of certain Saskatchewan soils (111) (especially the horizons) often can not be accounted for by the concentration effect of clay movement out of them. The production of silt-sized particles resulting from physical breakdown of coarser ones, in addition to the effect of outgoing clay, may more readily explain the high silt content of such horizons.

In the course of the micropedological investigations which will be discussed later, certain observations were made relative to the physical breakdown of rock and mineral fragments within the horizons of the soil profiles. A study of thin sections from the various horizons revealed that fractured sand grains were evident in both the solum and parent materials. In many mineral grains from the C horizons, incipient fracture

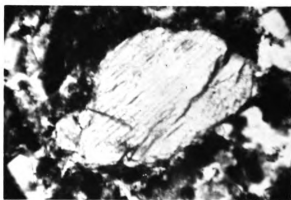


lines were visible, but very little splitting was apparent. Within the solum horizons, however, mineral and rock fragments did show signs of splitting along fractures. These fractures invariably had a stained appearance and in cases where splitting had occurred, the cavities were generally filled with soil matrix material. Examples of physical breakdown in the solum horizons are shown in Plate 2A and 2B. Faint fracture lines, visible throughout a quartz grain in the parent material of the Orthic Black soil are seen in Plate 2C. These are only examples of the many which have been observed in the thin sections.

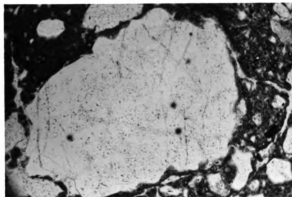
Thin section studies thus provide further evidence that physical breakdown has occurred in situ within the solum horizons of the four profiles studied. The presence of fractured grains throughout the entire profile indicates that fractures were present at the time the glacial till material was deposited. Most of the fracturing probably resulted during transport of the material by glacial action. The splitting of grains, however, has apparently occurred mainly in the solum horizons since deposition. Chemical action has, no doubt, played some part in causing this breakdown, since chemical weathering along the fractures would enlarge the spaces into which water, roots and colloids could penetrate and bring about disruption of the mineral grains. Although



A. Quartz (1) and hornblende (2) undergoing physical breakdown in the Bmt horizon of the Orthic Black soil. (x-nicols)



B. Feldspar grain from the Ae horizon of the Orthic Dark Grey soil showing signs of splitting. (x-nicols)



C. Quartz grain in the parent material of the Orthic Black soil. The faint fracture lines, visible throughout the grain, do not have the stained appearance characteristic of those in grains within the solum.

microscopic examination of the coarse sands indicated that rock fragments are present, there is also much quartz which has undergone straining and fracturing and which is also undergoing disintegration. The presence of splitting in many different minerals indicates that the breakdown is not limited to quartz and rock fragments.

Mineralogical Studies of the Fine Sand Fractions

Consideration of the quartz data and particle size distribution which were discussed previously has led to the suggestion of possible physical breakdown of coarser fractions occurring in the four profiles under study. It was pointed out that since a redistribution in sizes of quartz grains has occurred, similar differences in the distribution of other minerals could also result. If this occurs, the validity of mineralogical studies of the sand fractions and certain interpretations of such studies would be questionable. Studies of the light and heavy minerals in the sand fractions have been a part of many pedogenic investigations (19, 32, 52, 65, 66, 95, 151). As part of the present study, counts were made of minerals present in the fine sand fractions of the major horizons of the four profiles. It was hoped that the mineralogical studies of the fine sand fractions would provide information with respect to chemical weathering and also perhaps indicate whether physical disintegration of minerals and rock material had occurred within the soils under study.

Mineralogical studies of both the light (sp. gr. < 2.80) and heavy (sp. gr. > 2.80) minerals within the fine sand fractions were undertaken. Preliminary mineral counts on duplicate samples indicated that good reproducibility could be obtained. Single samples were therefore used for the mineral counts. No attempt was made to estimate the percentage error involved in the counts, but since a minimum of 600 and 800 grains was counted for the light and heavy minerals respectively, the percent error is considered to be within acceptable limits. Previously established statistical computations (80) indicate that probable error depends largely upon the number of grains counted, and is greatest for the rarer minerals and lowest for the abundant minerals.

Light Mineral Percentages and Ratios

Results of the petrographic analysis of the light fine sand fraction from the major horizons of the profiles under study are given in Table 10. Examination of the data reveals the following points:

- 1) For all four profiles, the quartz content of the light fraction of the fine sands from the A and B horizons is always greater than that of the same sand fraction from the C or parent material. The differences between the solum and C horizon values are most pronounced for the Grey Wooded profile, least for the Black soil.

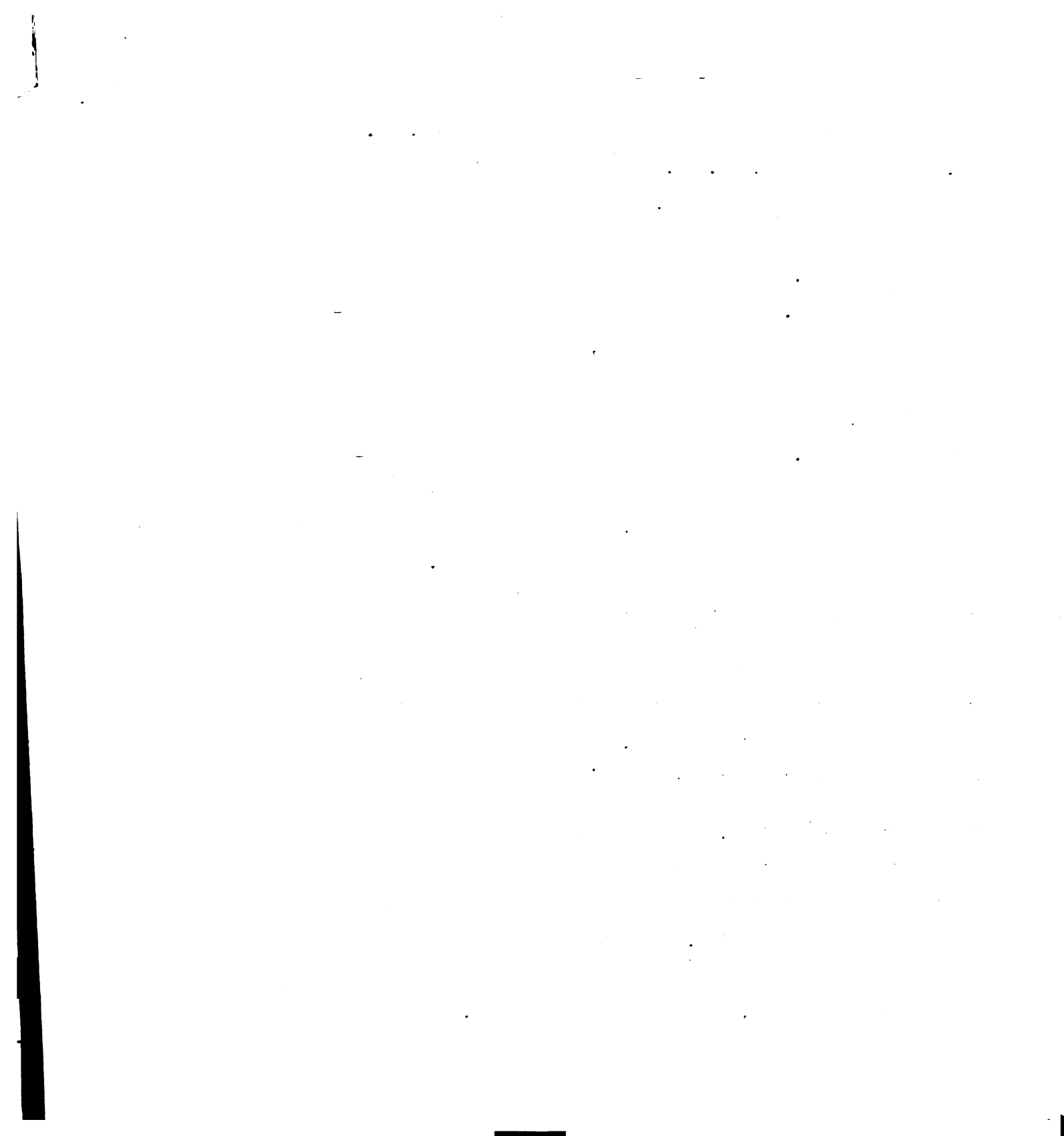


TABLE 10. QUARTZ, POTASSIUM FELDSPAR AND PLAGIOCLASE FELDSPAR CONTENT OF THE LIGHT FRACTION (sp. gr. <2.80) OF THE FINE SAND FROM THE FOUR PROFILES.
(Expressed as percentage of the total grain count.)

Soil	Horizon	Quartz	Plagioclase Feldspar	Potassium Feldspar	Total Grain Count	Quartz/ Plagioclase	Quartz/ K-Feldspar
ORTHIC BLACK	Ab	74.4	13.4	12.2	821	5.6	6.1
	Bmt	76.6	14.5	8.9	798	5.3	8.6
	C1-1	72.8	20.0	7.2	631	3.6	10.1
ORTHIC DARK GREY	Ab	83.8	7.5	8.7	781	11.2	9.6
	Abe	84.3	8.4	7.3	892	10.0	11.4
	B mt	82.8	10.8	6.4	760	7.7	12.8
	C1-1	73.8	19.6	6.6	961	3.8	11.2
DARK GREY WOODED	Ab	82.6	10.6	6.8	880	7.8	12.1
	Bt	85.4	7.6	7.0	1003	11.2	12.2
	C1-1	75.8	17.5	6.7	922	4.3	11.3
ORTHIC GREY WOODED	Ab	86.4	6.7	6.9	961	12.9	12.5
	Bt	85.0	7.0	8.0	852	12.1	10.6
	C1-1	75.4	18.0	6.6	720	4.2	11.4

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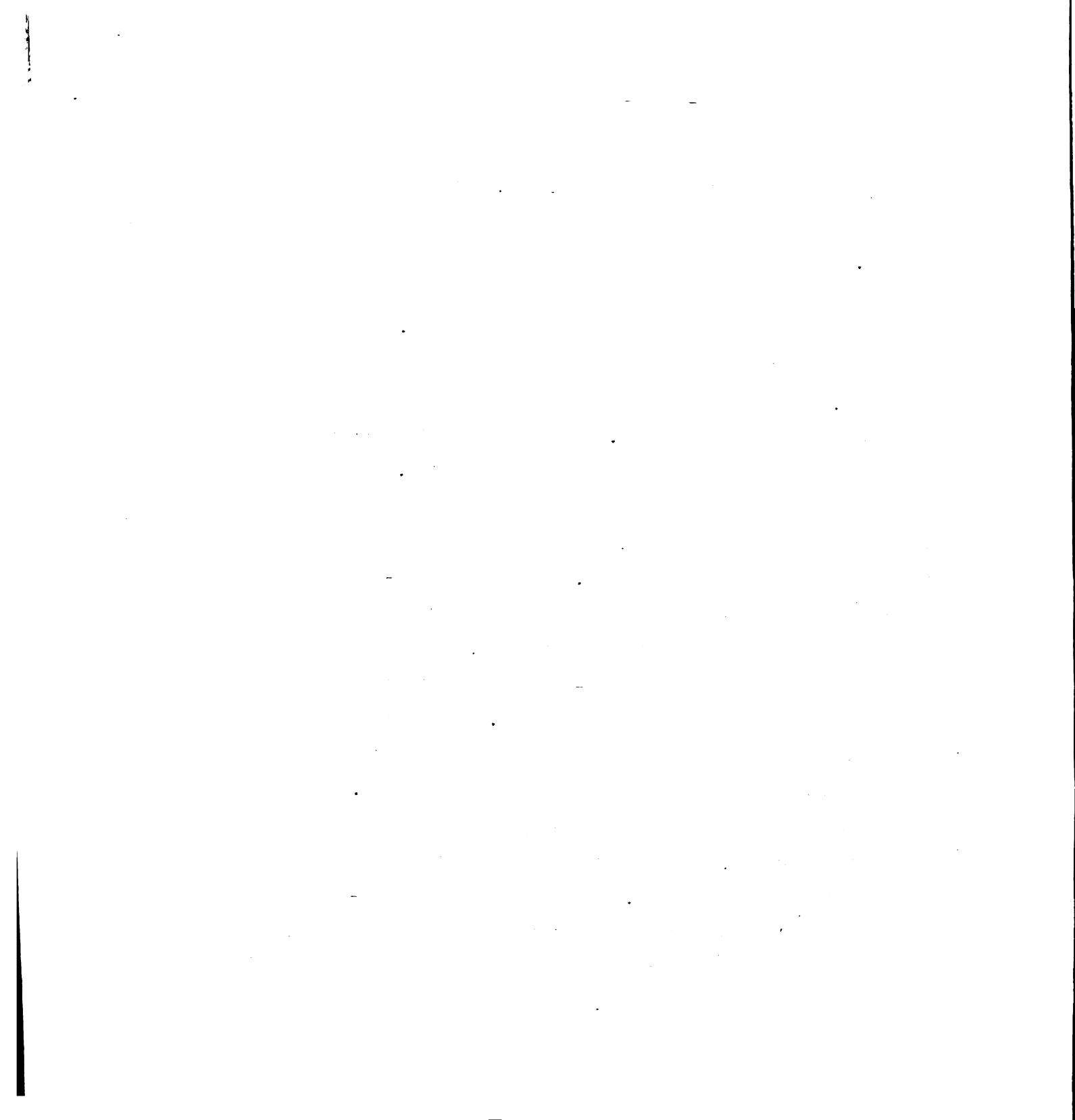
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- 2) For all four profiles the plagioclase content in the solum decreases relative to the C horizon, while the potassium feldspar content increases in all but one horizon.
- 3) The decrease in plagioclase percentage is greatest in the Grey Wooded soil and least in the Orthic Black.
- 4) The quartz/plagioclase feldspar ratios increase within the solum. Such a trend indicates the weathering of plagioclase relative to quartz. The highest ratios occur in the A and B horizons of the Grey Wooded profile.
- 5) The quartz/potassium feldspar ratios are relatively constant within the Dark Grey, Dark Grey Wooded and Grey Wooded profiles respectively. Since potassium-bearing feldspars are considered to be more resistant to weathering than the plagioclase minerals, the above ratios suggest that the potassium-bearing minerals in these profiles are relatively unweathered. The similarity of the ratios should also be an indication of the uniformity of the material from which the profiles have developed.

In the Black profile the quartz/potassium feldspar ratios are variable, being considerably lower in the A and B horizons than in the C. This suggests some variability in the mineralogical composition of the material from which the A and B horizons developed relative to that of the underlying material. Mechanical analyses



data, which were discussed previously, also indicated that possibly the Orthic Black soil had not developed from a uniform material similar to that underlying it.

6) The mineral ratios listed in Table 10 indicate that all four parent materials are similar with regard to quartz, potassium feldspar and plagioclase feldspar contents.

Cursory examination of the results would suggest that quartz may be accumulating as a result of weathering of plagioclase feldspars from the fine sands within the solum. Also, plagioclase would appear to be weathering more rapidly than the potassium feldspars, a trend which agrees with similar results reported by numerous other investigators (7, 32, 77, 102, 117, 144). The increases in potassium feldspars within the solum fractions relative to those from the parent materials could result if these minerals underwent very little weathering in comparison to the plagioclases. Thus, preliminary examination of the data would indicate a normal weathering sequence taking place in these soil fractions. The question as to whether the decrease in plagioclase content can account for the relative increase in quartz and potassium feldspar in the solum fractions immediately arises. If the assumption is made that only plagioclase has been lost from this fraction, it is possible to calculate how the change in plagioclase content will affect the percentages of quartz and potassium feldspar in the various horizons.

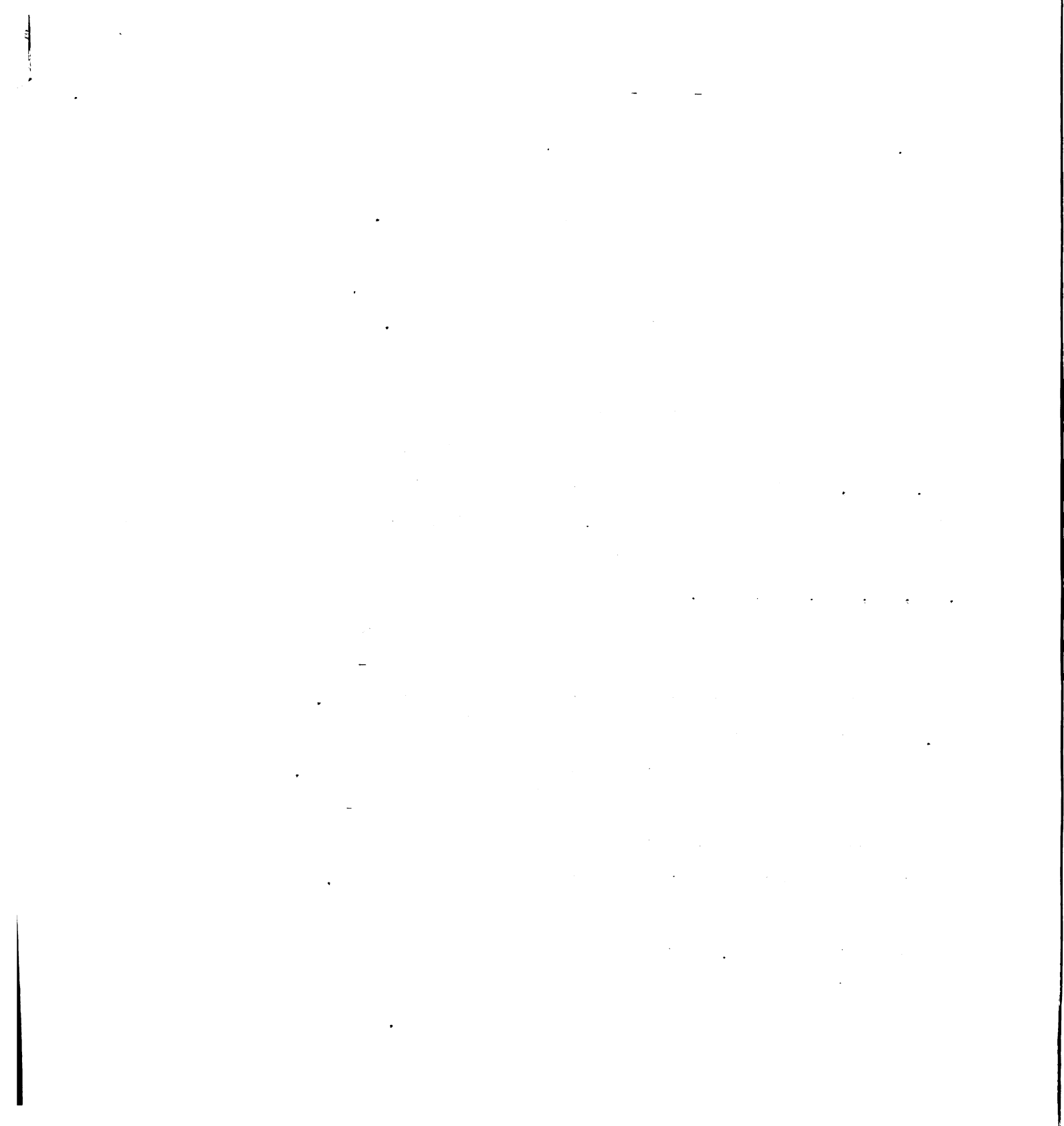


TABLE 11. ACTUAL AND CALCULATED* QUARTZ AND POTASSIUM FELDSPAR PERCENTAGES IN THE LIGHT FRACTION OF THE FINE SAND FROM HORIZONS OF THE FOUR PROFILES.

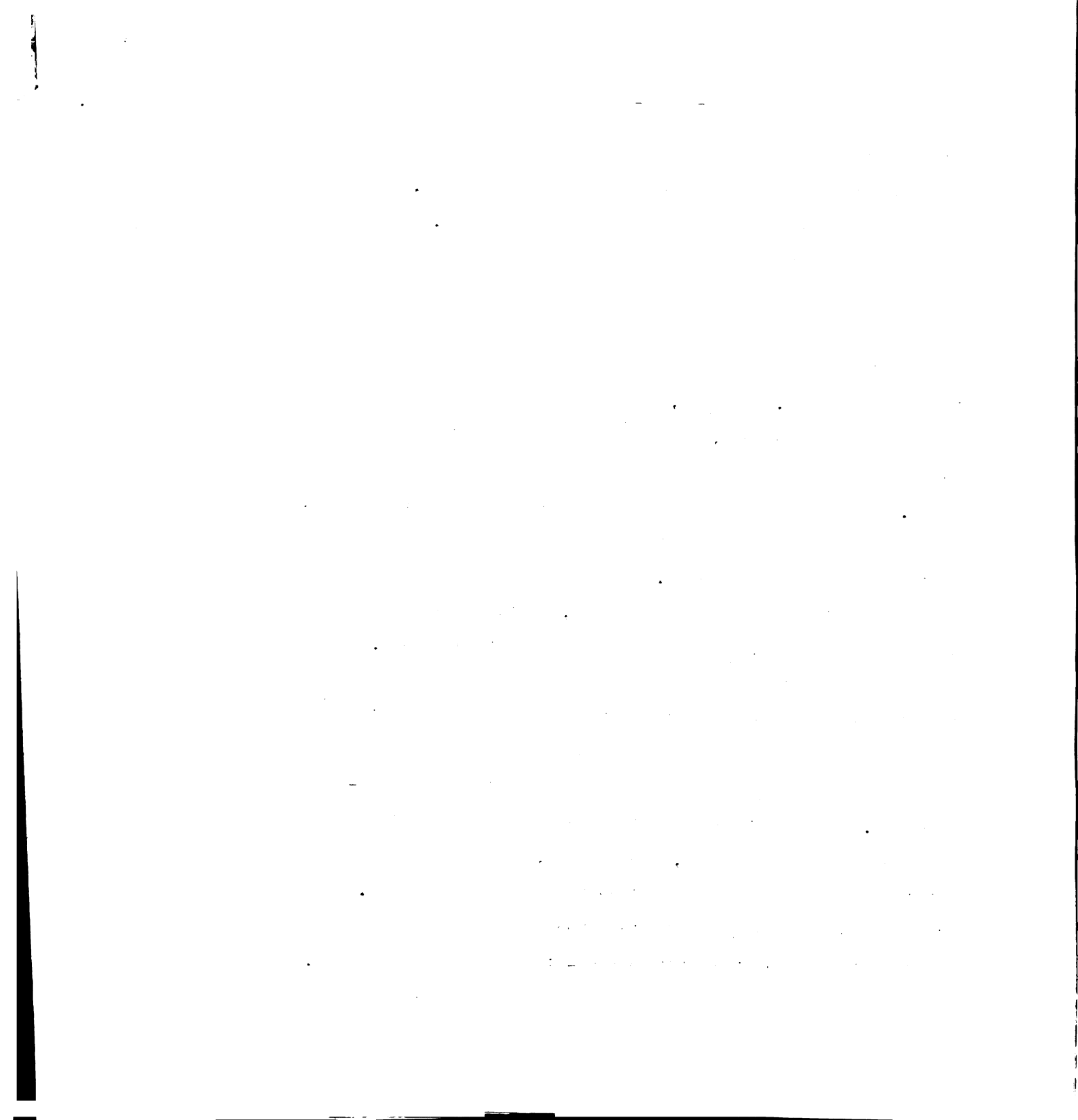
Soil	Horizon	Quartz		Potassium Feldspars	
		Actual	Calculated*	Actual	Calculated*
ORTHIC BLACK	Ah	74.4	78.6	12.2	7.7
	Bmt	76.6	77.6	8.9	7.6
ORTHIC DARK GREY	Ah	83.8	85.0	8.7	7.6
	Ahe	84.3	84.2	7.3	7.5
	Bmt	82.8	81.9	6.4	7.3
DARK GREY WOODED	Ae	82.6	82.2	6.8	7.3
	Bt	85.4	84.9	7.0	7.5
ORTHIC GREY WOODED	Ae	86.4	85.7	6.9	7.5
	Bt	85.0	85.4	8.0	7.5

* Calculated values are those which would result if the only change within this size fraction was the loss of plagioclase by weathering processes.

Table 11 gives the calculated values for quartz and potassium feldspar which result when such an assumption is made. These values are compared to the values actually measured.

The similarity between the actual and calculated quartz percentages given in Table 11 seems to indicate that in most instances the increase in quartz could be explained as resulting from a loss in plagioclase feldspars from the fine sand fraction. However, the potassium feldspar values show greater differences, the actual percentages in most horizons being appreciably lower or higher than the calculated values. When the actual values are lower than those calculated, one might assume that weathering of some of the potassium bearing minerals has occurred. When the actual values are appreciably higher than the calculated, as in the case of the Orthic Black profile, some other explanation is required.

The variability and inconsistency observed in the mineral percentages of the light fine sand fractions indicate that simple loss by solution of plagioclase feldspars from these fractions is not the only factor affecting their distribution. The significantly higher content of potassium feldspars in some fractions, for example, can best be explained by addition of such minerals to these fractions. This could result from the physical breakdown of coarser material with liberation of fine sand-size potassium feldspars.



On the other hand, the loss of quartz as well as of plagioclase from the fine sand fraction would also have the effect of increasing the potassium feldspar percentage in this fraction. This again requires a redistribution process explained only by physical disintegration of quartz or quartz-bearing rock fragments of fine sand size.

If redistribution of particle sizes due to physical breakdown occurred, the losses resulting from chemical weathering or solution effects within a given size fraction would be less readily detected. In the four soils studied, it would appear that the light minerals present in the fine sand fraction are not entirely reliable as a measure of weathering in these soils. However, the percentages of these minerals in the parent materials indicate the uniformity of the glacial till deposit in the area from which the soils were selected.

Heavy Mineral Percentages and Ratios

The heavy mineral content of the fine sand fractions for the major horizons of the selected profiles are given in Table 12. It is seen that the heavy minerals make up only 2.4 to 3.4 percent of the total fraction.

TABLE 12. PERCENTAGE OF HEAVY MINERALS (sp. gr. > 2.80) IN THE FINE SAND FRACTION FROM THE MAJOR HORIZONS OF THE FOUR PROFILES.

Horizon	Orthic Black	Orthic Dark Grey	Dark Grey Wooded	Orthic Grey Wooded
Ah	3.43	2.62	--	--
Ahe, Ae	--	2.57	2.62	2.87
Bmt, Bt	3.36	2.38	2.87	2.93
C ₁ -1	3.12	2.44	2.41	2.74

The above data indicate that for the fine sands, there is an increase in heavy minerals within the solum relative to the parent material. This could occur if: 1) the light minerals, such as feldspars, weather out of the fraction faster than the heavy minerals; or 2) if redistribution of particles due to physical breakdown is causing a more rapid accumulation of heavy than light minerals in this particular fraction; or 3) if a combination of the above two processes is operating. It is not possible to determine from this data alone which of the above factors is responsible for the observed trend.

The proportions of minerals present in the heavy fraction of the fine sands under study are given in Table 13. Percentages are reported to the nearest decimal and, since they are based on grain counts, are a measure of percentages by volume rather than by weight. Calcite and dolomite had previously been removed by acid treatment of the sands.

TABLE 13. HEAVY MINERAL CONTENT OF THE FINE SAND FRACTION
FROM THE MAJOR HORIZONS OF THE FOUR PROFILES.
(Expressed as percentage of total grain counts.)

Horizon	ORTHIC BLACK			ORTHIC DARK GREY			
	Ah	Bmt	C ₁₋₁	Ah	Ahe	Bmt	C ₁₋₁
Actinolite	1.6	1.2	1.2	1.6	1.2	0.8	0.8
Apatite	0.0	0.0	0.0	0.4	0.1	0.2	0.1
Biotite	23.2	11.4	1.4	3.6	3.4	2.4	0.5
Chlorite	0.8	0.3	1.2	0.9	0.4	0.6	0.5
Corundum	0.2	0.0	0.2	0.1	0.1	0.2	0.1
Diopside	2.2	2.0	3.0	1.9	2.9	2.6	1.7
Epidote	1.0	1.6	0.8	1.9	2.0	1.9	1.4
Garnet	12.9	14.9	20.8	21.0	21.0	19.8	23.5
Hornblende	36.3	38.6	50.1	48.5	50.8	50.6	50.8
Hypersthene	1.2	1.7	1.7	1.7	1.6	2.5	3.8
Magnetite	6.5	9.5	7.5	6.3	6.8	7.0	8.0
Muscovite	1.5	0.9	0.8	0.6	0.2	0.5	0.8
Rutile	0.0	0.0	0.1	2.0	0.0	0.1	0.2
Staurolite	1.0	0.0	0.0	0.0	0.1	0.2	0.1
Topaz	0.4	0.4	0.4	1.0	0.8	0.3	0.5
Tourmaline	1.0	0.0	0.4	0.1	1.3	0.2	0.5
Tremolite	4.1	5.8	1.9	3.4	1.9	3.4	3.0
Zircon	0.5	1.2	1.1	1.2	0.9	0.6	0.9
Opakes	5.4	10.4	7.3	3.6	4.3	5.8	2.7
Other	0.2	0.1	0.1	0.2	0.2	0.1	0.1
Total Grain Count	1025	936	907	827	828	879	874

TABLE 13 (Continued)

Horizon	DARK GREY WOODED			ORTHIC GREY WOODED		
	As	Bt	C ₁₋₁	As	Bt	C ₁₋₁
Actinolite	1.0	1.0	1.1	1.2	0.7	1.2
Apatite	0.2	0.6	0.1	0.0	0.0	0.0
Biotite	6.1	9.5	1.5	8.5	10.9	0.8
Chlorite	0.6	0.4	1.3	0.2	0.7	1.0
Corundum	0.0	0.0	0.1	0.0	0.1	0.2
Diopside	2.4	1.6	1.9	3.0	1.8	2.0
Epidote	1.1	1.3	1.9	1.6	1.8	1.3
Garnet	17.4	18.1	20.2	16.5	18.1	23.5
Hornblende	47.5	41.4	48.8	38.9	39.8	48.7
Hypersthene	1.8	2.7	2.5	3.9	2.0	2.5
Magnetite	8.3	7.2	6.9	7.7	8.6	7.5
Muscovite	0.2	1.1	2.3	0.5	0.8	0.6
Rutile	0.1	0.0	0.0	0.0	0.0	0.0
Staurolite	0.0	0.0	0.3	0.3	0.0	0.0
Topaz	0.2	0.7	0.4	0.3	0.5	0.1
Tourmaline	0.6	0.9	0.4	0.0	0.1	0.4
Tremolite	2.8	3.0	2.0	3.7	4.5	1.9
Zircon	0.5	1.1	1.2	1.0	0.7	0.7
Opakes	9.0	8.3	6.9	12.2	8.7	7.6
Other	0.2	1.1	0.2	0.5	0.2	0.0
Total Grain Count	943	899	923	940	975	801

It is seen that, in order of abundance, the main minerals are hornblende, garnet (white and pink to salmon colored variety), magnetite, tremolite, opaques and diopside.

Lesser amounts of other minerals, varying from one or two percent to traces, make up the remainder of the heavy fraction.

The content of biotite is quite variable within the four profiles, and ranges from less than 1.5 percent in the parent materials up to 23 percent in the A horizon of the Black soil. In this regard, it should be mentioned that

some difficulty was encountered in the separation of the various fractions as far as biotite was concerned. Due

possibly to its platy nature, variable quantities appeared in the different sand fractions as a result of the dry

sieving separation. Preliminary counts showed that, aside from biotite, the proportions of other minerals in the fine sands were similar for three replicates of the same sample which were separated individually, whereas the biotite content varied quite markedly. This difficulty occurred only

with the sands from the solum horizons. This may be due to

the breakdown of coarse mica particles into fine sand size due to the action of hydrogen peroxide used in pretreating

the samples. Such a breakdown due to peroxide has been

noted by Dresdoff and Miles (48) and apparently occurs only

in the case of weathered biotite. This would explain why the difficulty of separating biotite was encountered only in the

A and B horizons. Aside from biotite, the separations were quite reproducible. For this reason the discrepancies in biotite content are not considered to indicate actual differences in the fraction composition.

In looking over the percentages of the heavy minerals present in the fine sands of the various horizons, certain trends are observable. For example, it is noted that the contents of hornblende and garnet decrease within the solum fractions relative to the parent material. This could possibly be attributed to the removal of such minerals from the fractions by weathering. Other minerals show similar or opposite trends, some of which are contrary to what might be expected. Where only small amounts of a mineral are present in a fraction, variations might be attributed to the very fact of their low proportions, since the accuracy of determining actual composition is markedly reduced as the content of a mineral in a sample decreases (80). However, the similarity in distribution and amounts of the various minerals in the C_{1-1} horizons of all four profiles, aside from indicating the uniformity of the four parent materials, also indicates that such variations as occur between solum fractions and the parent material can not be dismissed as the result of low degree of accuracy in the determination of mineral percentages. The differences are real and can not be accounted for in terms of general changes

which result from chemical weathering as it is usually interpreted. A closer examination of the results is indicated before any definite conclusions can be drawn.

In using heavy minerals to study weathering within soils, heavy mineral ratios are often employed to better indicate changes in the distribution which result from such weathering. The problem has always been to select some mineral which is believed to be relatively unaffected by chemical or physical processes in the soil and to relate other mineral percentages to the so-called "index mineral". Zircon, tourmaline, garnet and magnetite have been considered suitable index minerals (7, 65, 115) since they are relatively resistant to alteration within soils. In this study, magnetite has been used as the reference mineral to which others are compared. Ratios of several minerals to magnetite are presented in Table 14. The ratio of hornblende to garnet is also given.

In making use of heavy mineral ratios as an indication of weathering in soils, trends in the ratios are interpreted in certain ways. Assuming magnetite to be relatively unaffected by weathering as compared to hornblende, the ratio of hornblende to magnetite can be used to illustrate this point. If the ratio decreases in the solum relative to the C horizon, it indicates that hornblende is weathering out of the fraction. An increased ratio in the solum must signify an increase in the hornblende within the fraction if the

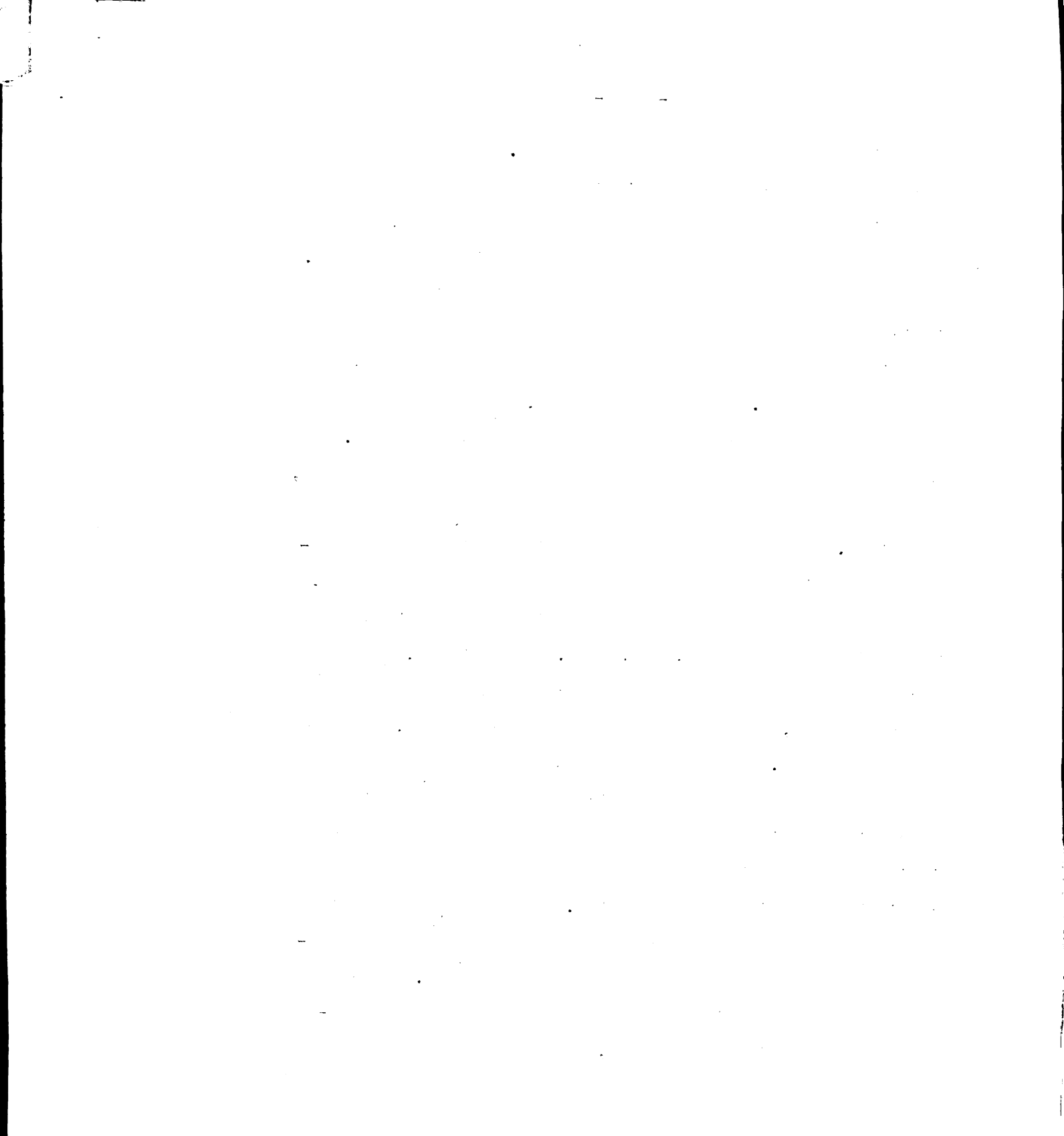
TABLE 14. HEAVY MINERAL RATIOS FOR THE FINE SAND FRACTIONS FROM THE MAJOR HORIZONS OF THE FOUR PROFILES STUDIED.

Soil	Horizon	Hornblende Magnetite	Garnet Magnetite	Opakes Magnetite	Hypersthene Magnetite	Hornblende Garnet
ORTHIC BLACK	Ah	5.6	2.0	0.8	0.2	2.8
	B _{ut}	3.8	1.5	1.0	0.2	2.6
	C1-1	6.9	2.8	1.0	0.2	2.4
ORTHIC DARK GREY	Ah	7.7	3.6	0.6	0.3	2.2
	A _{he}	7.5	3.2	0.6	0.3	2.3
	B _{ut}	7.1	2.8	0.9	0.4	2.5
	C1-1	6.3	2.9	0.3	0.5	2.2
DARK GREY WOODED	A _e	5.7	2.1	1.1	0.2	3.0
	B _t	5.7	2.5	1.2	0.4	2.3
	C1-1	7.0	2.9	1.0	0.4	2.4
ORTHIC GREY WOODED	A _e	5.0	2.1	1.5	0.5	2.4
	B _t	4.5	2.1	1.0	0.2	2.2
	C1-1	6.5	3.1	1.0	0.3	2.1

magnetite content has remained unchanged. A constant ratio throughout the profile would indicate that no weathering of this mineral has occurred within this size fraction, or at least not to the extent that a measurable loss has resulted.

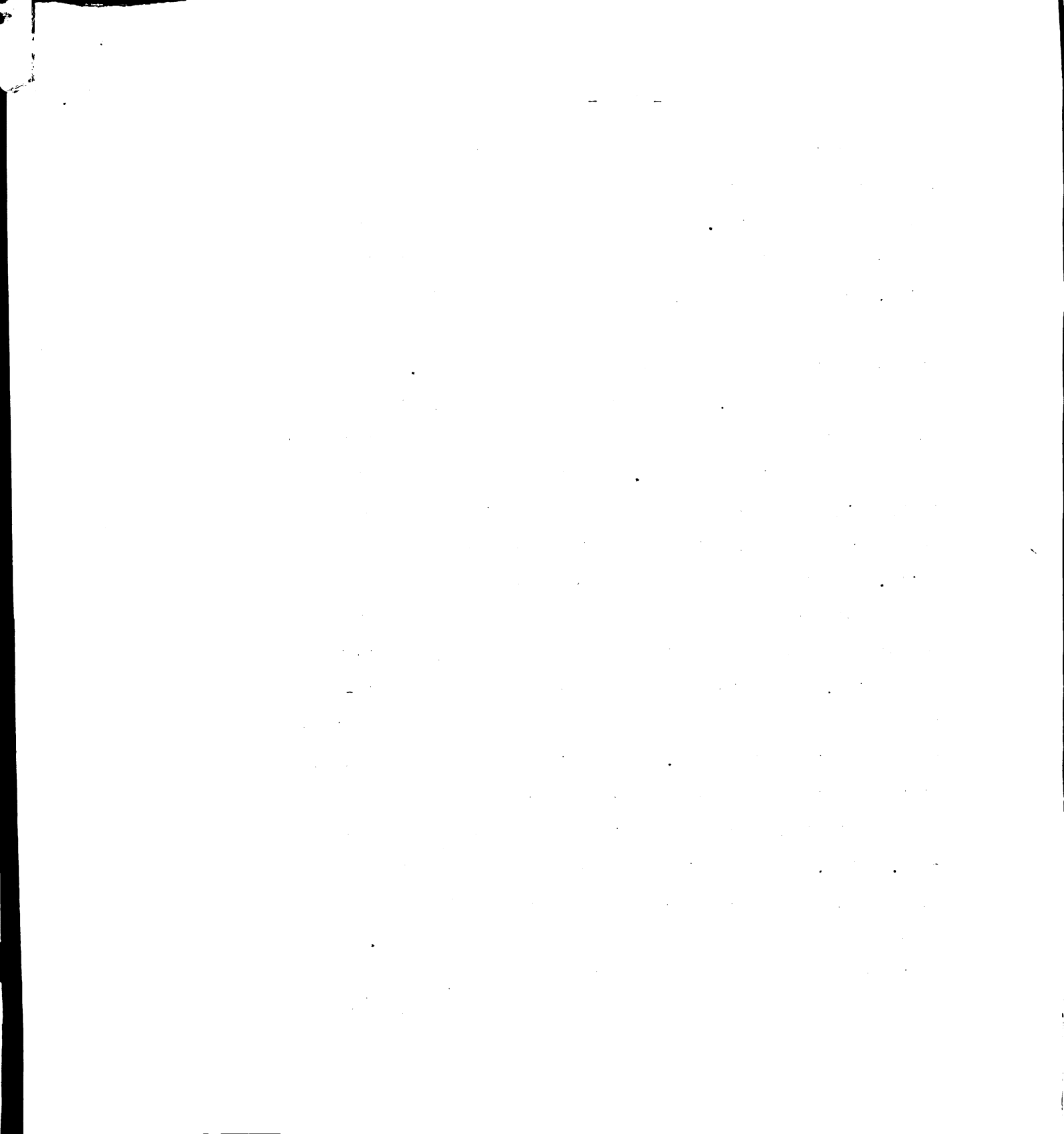
The heavy mineral ratios given in Table 14 would indicate that hornblende and garnet have weathered out of the fine sand of the A and B horizons on all but the Orthic Dark Grey profile. In the latter soil, an accumulation of these minerals has resulted within the solum fine sands. The quantity of opaque minerals varies for the four profiles, some values being higher or lower than those for the parent materials. The hornblende/garnet ratios indicate that hornblende is being weathered at a slower rate than the garnet, a fact that is inconsistent with previously established weathering sequences (60, 117, 141). In addition, the hornblende within solum fractions appeared to be weathered to some extent, whereas the garnets appeared sharp, angular and unweathered.

The above results indicate that the heavy mineral values in the fine sand can not be taken at face value to indicate the normal changes which occur as a result of chemical weathering in these soils. In the Dark Grey soil there appears to be evidence to substantiate physical breakdown of coarser material into the fine sand size. Since the quartz distribution analysis has indicated a redistribution of sizes in all profiles, it is quite possible that



the quantities of heavy minerals in the various fractions could also change with or without a marked effect on mineral percentages or ratios. It is not suggested that normal chemical weathering of minerals is not occurring within these soils, but rather that evidence of such weathering might or might not be affected by redistribution of particles of different sizes resulting from physical breakdown.

In summary, certain facts have become evident from the mineralogical studies of the fine sand fractions of the four profiles studied. The increase of heavy minerals in the fine sand fraction of the solum horizons may or may not be due to a mechanism of physical breakdown in these four soils. The increased potassium feldspar content of the A and B horizons of the Black soil relative to the parent material can not be explained in terms of normal chemical weathering, but indicate that a process of physical disintegration has occurred or that the material was not uniform in composition originally. Heavy mineral data suggest that similar explanations are required to account for mineral changes within the solum fractions of the Orthic Dark Grey soil. Also, it is difficult to accept the indication that garnets have weathered more than hornblendes in the fine sand fraction as suggested by the hornblende/garnet ratios. This again suggests that physical redistribution of sizes may be responsible for the observed content of these minerals in



the fine sand fraction. Thus it appears that although some of the mineralogical data can be interpreted in terms of chemical weathering in soils, there are certain discrepancies which can not be accounted for in the normal sense and which do add strength to the possibility of significant changes resulting from physical breakdown within these soils.

In any pedogenic study, the possibility of unconformities occurring within profiles as a result of depositional differences in the material from which such profiles have developed must not be overlooked. In many cases such unconformities are quite evident and unmistakable; in others the differences between the two adjacent materials may be so slight as to be undetected or overlooked. The possibility of unconformities must necessarily be considered in the present study.

Chemical, physical and mineralogical data for all four profiles indicate that the parent materials in all cases are very similar and that the C₁₋₁ horizons, at least, consist of glacial till of fairly uniform composition. The similarity of mineral suites in both the parent materials and sola of these profiles indicate that the A and B horizons have also developed from similar material. This does not preclude the possibility that the composition of the solum material did differ from that of the parent material to some degree. This appears to be the case for the Orthic Black soil.

It seems inconceivable, however, that the line of demarcation between unlike materials should always occur at the upper boundary of what is designated as the C_{1-1} horizon, especially under the topographical situations from which the four profiles under study were selected. There is no way of definitely establishing the uniformity of the entire profiles in this case, especially if physical breakdown has occurred, but there also is no evidence to indicate that the original material was not uniform before soil formation began. The assumption that at least three of the four, and possibly all four, profiles have developed from a uniform glacial till deposit, therefore, seems to be a valid one. One may therefore be justified in assuming that differences in the composition of horizons within the profiles are due in part to processes of physical breakdown.

Quantitative Pedogenetic Changes

In the absence of evidence of discontinuities of materials in the four profiles, calculations of the net changes in particle size distribution within the major solum horizons seemed warranted and such calculations were made for the Black and Grey Wooded soils. In doing so, the total quartz within the fine earth material of each horizon was assumed to have remained constant, and served as the resistant index mineral upon which the calculations were

based. The calculations were essentially the same as those described in detail by Barshad (7) and Bourne (19). The present total quartz content of each horizon was used as a basis for calculating the original weight of soil and the original particle size distribution, assuming the original composition of the solum to have been the same as that of the present C horizons. The particle sizes are reported as percentages of the acid-insoluble fine earth material. It is assumed in all cases that the C_{1-1} horizons of each profile underwent no change in mineralogical composition as a result of soil formation. The results are given in Table 15, the recorded weights representing the weight of the fractions per unit cross-section of horizon.

The data presented in Table 15 indicate the differences between present and original particle size distribution within the horizons. It is noted that a net loss of only 1.0 percent sand occurred in the Ah of the Black soil, whereas there was a loss of 7.3 percent from the sand fraction of the Bmt horizon. In the Grey Wooded soil, the loss from the sand fraction amounted to 26.6 percent in the Ae horizon and 7.9 percent in the Bt horizon. These figures indicate that the disintegration of the sand fraction is much more pronounced in the surface horizon of the Grey Wooded soil than of the Black soil, while the amount of breakdown in the B horizons of both soils is similar.

TABLE 15. QUANTITATIVE CHANGES IN PARTICLE SIZE DISTRIBUTION IN THE
MAJOR HORIZONS OF THE ORTHIC BLACK AND ORTHIC GREY WOODED SOILS

Orthic Black					Orthic Grey Wooded				
	Original Weight(g)	Present Weight(g)	Loss or Gain(g)	Loss or [*] Gain(%)		Original Weight(g)	Present Weight(g)	Loss or Gain(g)	Loss or [*] Gain(%)
Ah Fine Clay	1.26	1.77	+0.51	+40.1	As	2.29	0.43	-1.86	-81.2
Coarse Clay	1.57	1.39	-0.18	-11.5		2.17	0.93	-1.24	-57.1
Fine Silt	0.64	0.77	+0.13	+20.3		1.02	1.13	+0.11	+10.8
Med. Silt	1.97	1.86	-0.11	- 5.6		2.64	3.79	+1.15	+43.6
Coarse Silt	2.02	1.88	-0.14	- 6.9		1.86	2.56	+0.70	+37.6
Very fine Sand	2.40	3.02	+0.62	+25.8		3.09	2.82	-0.27	- 8.7
Fine Sand	2.97	2.72	-0.25	- 8.4		2.50	1.56	-0.94	-37.6
Coarse Sands	3.47	3.01	-0.46	-13.2		3.36	2.19	-1.17	-34.8
Total Sand	8.84	8.75	-0.09	- 1.0		8.95	6.57	-2.38	-26.6
Total	16.30	16.42	+0.12	+ 0.7		18.93	15.41	-3.52	-18.5
Bmt Fine Clay	1.76	4.39	+2.63	+149	Bt	5.06	10.10	+5.04	+99.6
Coarse Clay	2.18	2.28	+0.10	+ 4.6		4.79	3.67	-1.12	-23.4
Fine Silt	0.89	0.95	+0.06	+ 6.7		2.25	2.07	-0.18	- 8.0
Med. Silt	2.75	2.67	-0.08	- 2.9		5.81	5.29	-0.52	- 8.9
Coarse Silt	2.83	2.58	-0.25	- 8.8		4.10	3.77	-0.33	- 8.0
Very fine Sand	3.35	3.24	-0.11	- 3.2		6.80	6.28	-0.52	- 7.6
Fine Sand	4.14	3.87	-0.27	- 6.5		5.50	5.38	-0.12	- 2.2
Coarse Sands	4.84	4.32	-0.52	- 10.7		7.40	6.49	-0.91	-12.3
Total Sand	12.33	11.43	-0.90	- 7.3		19.70	18.15	-1.55	- 7.9
Total	22.74	24.30	+1.56	+ 6.9		41.71	43.05	+1.33	+ 3.2

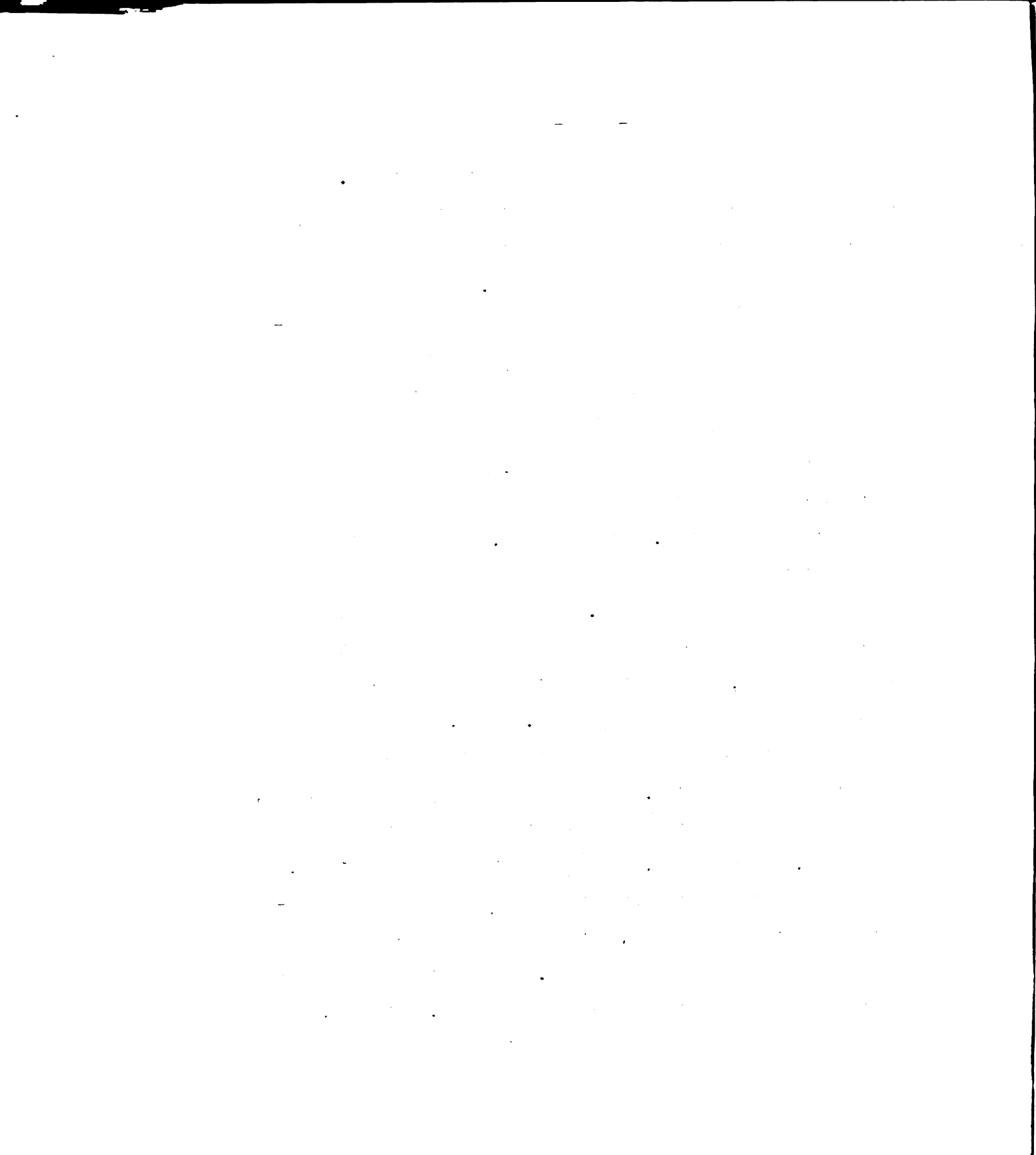
* Expressed as percentage of original weight of fraction.

It is of interest to compare the net gains and losses of the total clay fraction per unit cross-section within the two profiles. The Ah of the Black soil gained 0.33 grams of clay, whereas the Bmt showed a gain of 2.73 grams of clay. Since, according to the calculations there was no net loss from the Ah horizon as a whole, the increase of clay in the Bmt horizon can not be said to be due to illuviation from above. The A-B horizon, two inches in thickness, does not show a decrease in clay relative to the Ah horizon (Table 1) so that if the loss and gain values are accepted as being valid, the clay can only be accounted for by assuming in situ formation of clay in the Bmt horizon.

In the Grey Wooded profile, the Ae horizon underwent a net loss of 3.10 grams of clay whereas the Bt gained 3.92 grams of clay. Since the A-B and the Bmt horizons also increased in clay content relative to the parent material, it appears that the loss of clay from the Ae horizon does not account for the entire increase in the underlying horizons. The values suggest that clay has formed within this profile as well, although to a less marked degree than in the Black soil. The total decrease in weight of the Ae (3.52 g.) is not fully accounted for by the net increase of 1.33 g. in the Bt horizon. Although a gain in the A-B and Bmt horizons could be expected (as indicated by their higher clay content than the C horizon) the entire loss from the Ae

probably exceeds the gain in the underlying horizons. The dissolution of minerals in the Ae horizon with subsequent leaching of the dissolved components in solution may account for some of the losses recorded.

Before accepting the thesis that the clay accumulation in the Orthic Black profile is due mainly to in situ formation whereas translocation (as well as in situ formation to a minor extent) accounts for most of the accumulation in the B horizon of the Grey Wooded soil, it is necessary to consider some of the inherent errors and limitations of the calculations undertaken. First of all, complete uniformity of the original material from which the profiles developed was taken as an accepted fact. Although the analytical data indicated that the profiles have developed from relatively uniform material, some variations in composition could affect the results obtained to some degree. Also, it was assumed that the quartz content of the horizons did not change as a result of soil formation. Although theoretically acceptable, there are no data available to confirm the validity of this assumption. In addition, the application of bulk density, quartz and particle size distribution values to such computations may introduce errors since some values can not be determined as accurately as others. The reliability of bulk density measurements is particularly suspect. Finally, it



is probably unwise to attempt to evaluate the significance of losses and gains unless data are available for the entire soil profile. Unfortunately, in the present study, only the major horizons were subjected to the necessary analyses so that a quantitative estimate of changes within the entire solum of the soils was not possible.

A few discrepancies in the data presented in Table 15 tend to invalidate the results to some degree. For example, it is difficult to explain a net gain in the Bmt horizon of the Black soil when there has been no apparent loss from the Ah horizon. Likewise, even though the net loss of clay from the Ae of the Grey Wooded soil could account for a major portion of the accumulation in the Bt horizon, the lower net gain of the Bt horizon itself suggests that much of the increase in clay was not due to illuviation.

In spite of the limitations attached to the calculated data, they do tend to confirm the fact that little translocation of the mineral fractions has occurred in the Orthic Black soil and that clay formation in situ has probably occurred. The weathering of chlorite in the coarse clay fraction to fine clay size in the Bmt horizon had been indicated previously from the X-ray analyses. The data also confirm the translocation of clay from the Ae to the Bt horizon of the Grey Wooded soil. In situ formation of clay may also have occurred to a limited degree in this soil.

Micropedological Studies

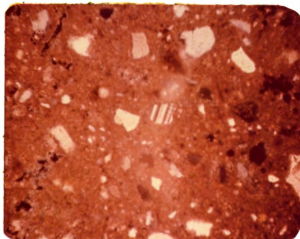
Thin sections of oriented clods taken from the major horizons of the four soils under study were examined with the aid of a petrographic microscope. The micromorphological characteristics of the various horizons are described below, the A, B and C horizons being discussed as separate groups. Photomicrographs of pertinent features serve to illustrate the points under discussion. Prior to the discussion of the micro-characteristics of the major horizons, reference is made to relevant macro-structural features.

The sola of the four soils are underlain by glacial till which represents the parent material from which they have developed. Mechanical analysis and mineralogical data have indicated that the solum of the Orthic Black soil may have developed from till of slightly different composition. Such variations are common in deposits as heterogeneous as glacial till. In the Black soil, since these differences are minor and are mainly ones of proportions rather than of types of components, it is not likely that they will have affected the morphological features of the soil to any great extent. It is possible, for comparative purposes, to assume that all four soils have developed from similar material, bearing in mind, of course, that some features could possibly be affected by the different composition of the Orthic Black soil, if such a difference did originally exist.

The C Horizons

As previously indicated, the C horizons of all four profiles consist of calcareous, medium-textured, glacial till material. The parent material is mostly massive, but occasionally displays a tendency towards faint coarse platiness and the material crushes readily to a weak granular structure.

In this section, the most striking feature is the uniform fabric of the parent material. This results from the relatively uniform distribution of skeletal grains in a homogeneous light brownish-gray to buff colored matrix of finer materials. Fabric which is typical of the C horizons is demonstrated in the photomicrograph of the C_{1-1} horizon of the Orthic Black soil (Plate 3). The only accumulations which occur consist of organic matter, in various stages of decomposition, along root channels, and concentrations of lime carbonate which line some of the voids.



0.2
mm.

Plate 3. Photomicrograph of the C_{1-1} horizon of the Orthic Black profile (x-nicols)

Carbonate accumulations lining pore spaces are apparent in the lower left hand corner of the photograph. Such concentrations have resulted from the movement of lime from the upper portions of the soil with subsequent deposition in the parent material.

Another noticeable feature of the parent material is the relatively fresh appearance of the skeletal mineral grains. Although quartz and feldspar are the dominant minerals, hornblendes and other heavy minerals are also observed. Grains of calcite and dolomite are common. Occasionally, ferruginous concretions and shaly fragments are seen, the former often showing some evidence of iron having diffused outward from them. These iron concretions were no doubt present in the material prior to deposition.

A striking feature of the parent material is the lack of concentrations along cleavages and cracks. Aside from the previously mentioned local accumulations of organic matter and lime there is no evidence of any illuviated colloidal materials in the parent material. This is significant in the light of pronounced accumulations which show up in the B horizons of some of the soils studied.

The A Horizons

Marked differences in the characteristics of the A horizons occur in the four soils under study. The entire A horizon of the Orthic Black profile is designated as an

Ah, whereas in the other three soils the A is divided into the Ah and Ahe or Ae subhorizons. The thickness of the Ah horizon decreases in going from the Orthic Black to the Grey Wooded profile. The Orthic Dark Grey eluviated zone is represented by the Ahe, while in the Dark Grey Wooded and Orthic Grey Wooded, well developed Ae horizons occur. In order to facilitate comparisons, the Ah horizons and the Ae and Ahe horizons will be considered separately.

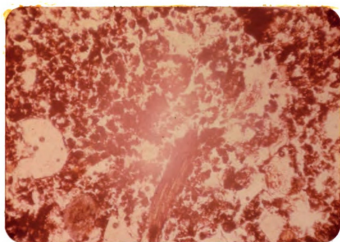
The Ah Horizons:

Macroscopically, the Ah horizons of the Orthic Black, Orthic Dark Grey and Dark Grey Wooded soils are characterized by medium to coarse blocky structure which crushes readily to a fine granular condition. Very faint platiness is observed in the Ah of the Dark Grey Wooded profile. The structure of the Grey Wooded Ah is fine granular to weakly platy, the absence of blocky structure possibly resulting from the relative thinness (one inch) of the horizon. Thus, the structure of all the Ah layers are somewhat similar, except that the blocky structure tends to become weaker as degradation increases.

Microscopic examination reveals much more pronounced differences between the Ah horizons of the four soils than are observed with the unaided eye. Thin section studies of the Orthic Black Ah layer indicate that it is composed of small,

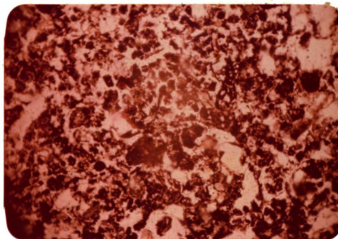
irregularly-shaped, organic-rich aggregates, generally less than 0.2 mm. in diameter, surrounded by an abundance of irregularly-shaped voids (see Plate 4-1). Skeleton grains, undecomposed organic matter and large voids appear throughout the apparently highly flocculated and well aggregated mass. The aggregates are dark brown to dark reddish-brown in color and impart a dark color to the horizon in general. There is rarely any evidence of the buff-colored matrix of silt- and clay-size material which was so apparent in the parent material. All of the inorganic plasmic materials have become closely surrounded and bound together into structural aggregates by the organic fraction of the soil. The mineral grains are no longer embedded in a continuous matrix, but rather are surrounded by inter-connected irregularly-shaped aggregates. Slight coatings, possibly of humic substances, cover a few of the sand grains. In most respects, the fabric of the Orthic Black Ah horizon closely resembles that described by Kubiena (81) as inter-textic, or more specifically as Chernozemic fabric.

The Ah horizon of the Orthic Dark Grey soil (Plate 4-2) is, in most respects, similar to that of the Orthic Black. The same well-aggregated appearance persists except that the organic-rich aggregates do not appear to dominate the fabric to the same extent that they do in the Orthic Black Ah. In contrast, more of the silty clay matrix



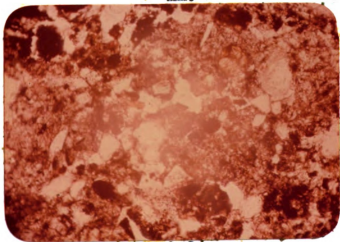
1. Orthic
Black

0.2
mm.



2. Orthic
Dark Grey

0.2
mm.



3. Dark Grey
Wooded

0.2
mm.

Plate 4. Photomicrographs of the Ah horizons of the Orthic Black, Orthic Dark Grey and Dark Grey Wooded soils. (Plane polarized light).

is evident, with local accumulations of organic matter interdispersed throughout. Consequently, larger structural units, consisting mainly of inorganic plasmic material and skeleton grains, appear bordered with clusters of organic colloids or organic-rich aggregates. Again, as for the Orthic Black Ah, the organic matter gives a dark brownish to greyish-black color to the horizon as a whole.

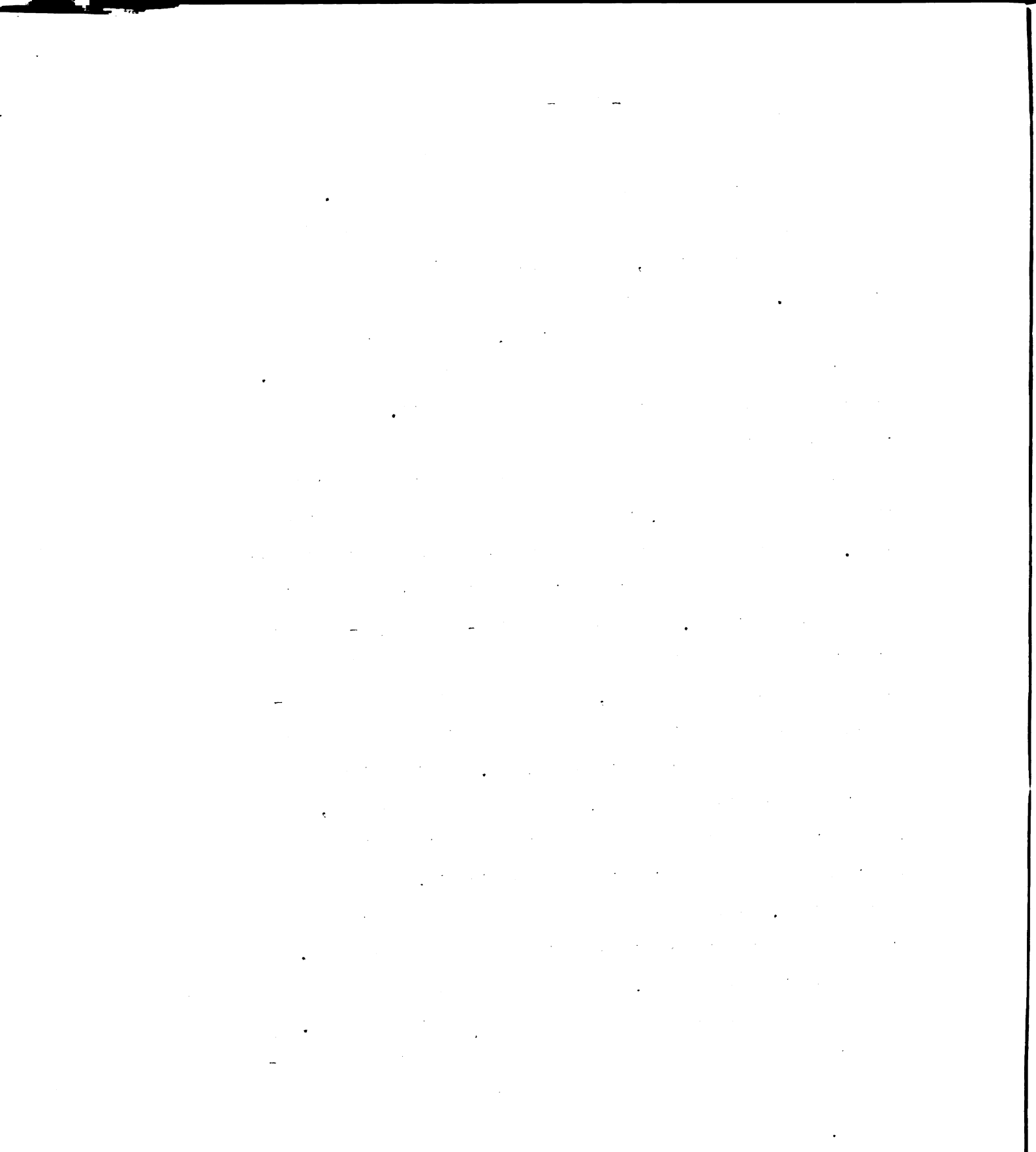
Macroscopically, the Ah horizons of the Dark Grey Wooded and Grey Wooded profiles appear almost as dark in color as the corresponding horizons in the Orthic Black and Dark Grey soils. In thin section, they appear quite different. The fabric of the Dark Grey Wooded Ah horizon is seen in Plate 4-3. As evidenced in the photograph, the predominance of organic-rich aggregates is no longer evident. Instead, a matrix very similar to that of the parent material is observed. Being depleted of lime, this material appears slightly darker than the buff color of the parent material. Local accumulations of organic matter appear as clusters unevenly distributed throughout the soil material and along the surfaces of peds. The peds vary from 1.0 to 2.0 mm. in diameter. As a result, much more of the silty clay matrix, often incompletely surrounded by dark organic accumulations, form aggregates which are much lighter in color and larger in size than those of the Ah horizons from the other profiles.

It is apparent that less intermixing has occurred between the organic and inorganic fractions of the soil material. In addition, faint platiness is evidenced within the soil mass of both the Dark Grey Wooded and Grey Wooded Ah horizons.

The variations in fabric observed among the Ah horizons of the four profiles are undoubtedly caused by differences in vegetation and consequently in the nature and quantity of organic residues and products of decomposition which are associated with the different soils. Visualizing the original surface layer as having a fabric similar to that of the present C horizon (Plate 3), it appears that modifications to this fabric result as plants and rooting systems develop. In the early stages of soil development, very local accumulations of organic residues and humic substances would occur throughout the soil material. Aggregates high in organic matter would, therefore, appear only in such local sites. Under grassland vegetation, the dense, fibrous root system and the rapid incorporation of above-ground plant remains would cause a rapid build-up of organic matter throughout the entire soil mass. The accumulation of these residues and the permeation of humic substances within the entire soil material would eventually lead to the development of a well-aggregated, dark brownish-grey Ah such as seen in the Orthic Black soil. The only visible evidence

of the former parent material at this stage is the presence of skeletal grains scattered throughout the soil mass. Although the organic matter makes up only a small fraction of the total soil weight, it appears to dominate the entire soil fabric.

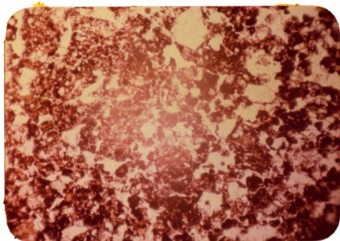
In the other three profiles, the fabric of the Ah horizons somewhat resembles a Chernozemic type of fabric. This is less pronounced in the Grey Wooded soil. The differences which are noted undoubtedly result from the fact that grasses are not the only vegetative species associated with these latter soils, inasmuch as shrubs and trees also occur. The differences in vegetative cover result in different types and amounts of organic residues being incorporated into the surface horizons. The gradual build-up of an L-H layer which increases in thickness in going from the Orthic Dark Grey to the Grey Wooded soil, also attests to the less pronounced degree of mixing between the organic and inorganic components of the surface mineral layer. It is evident that in the Orthic Black soil, developed under grasses, the rate of incorporation of organic substances is rapid and continuous enough to maintain a layer rich in, and apparently dominated by, organic matter to the extent that much of the silt and clay is tied up in relatively stable aggregates. As degradation progresses, proportionately smaller amounts of organic matter are incorporated into the mineral soil. The significance of this trend will become evident in later discussions pertaining to clay translocation within the soils studied.



The Ahe and Ae Horizons:

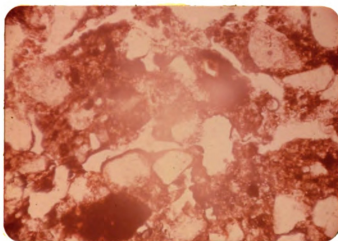
Of the four soils under study, all but the Orthic Black are characterized by the presence of an eluviated Ahe or Ae horizon. In the Orthic Dark Grey soil, the Ahe has a medium to coarse blocky structure in which there is slight evidence of platiness and which crushes to a powdery state. The Ae horizons of the Dark Grey Wooded and Grey Wooded soils exhibit platy structure, the plates being much thinner in the latter soil. The material from the Ae horizons is readily crushed to a fine powder. A significant feature of these eluviated layers lies in their color. The Ahe of the Orthic Dark Grey soil is dark greyish-brown in color whereas in the other two soils, the Ae layers are much lighter in color, ranging from a light greyish-brown in the Dark Grey Wooded to a light grey in the Grey Wooded soil.

In thin section, the Ahe horizon of the Orthic Dark Grey soil appears similar to the Ah horizon of the same profile except that the fabric shows some evidence of faint platiness. The well-aggregated appearance as well as the faint horizontal cleavages which occur discontinuously throughout the soil mass are seen in Plate 5-1. These cleavages are usually 1.5 to 2.0 mm. apart. The overall appearance of the soil fabric of this horizon indicates the leaching of a material possessing a chernozemic fabric.



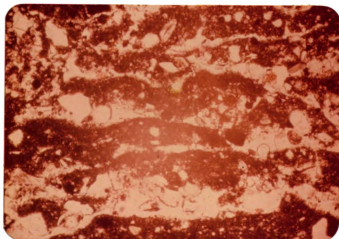
1. Orthic Dark Grey (Ahs)

0.2
mm.



2. Dark Grey Wooded (Ae)

0.2
mm.



3. Orthic Grey Wooded (Ae)

0.2
mm.

Plate 5. Photomicrographs of the eluviated horizons of the Orthic Dark Grey, Dark Grey Wooded and Orthic Grey Wooded soils. (Plane-polarized light)

The Ah and Ae horizons of the Dark Grey Wooded soil show less similarity than that exhibited by the Ah and the Ahe of the Orthic Dark Grey profile. In the Dark Grey Wooded soil, the striking feature of the Ae horizon is the presence of platy or banded fabric (see Plate 5-2). This horizon is much lower in organic matter content than the overlying Ah. The matrix is light brown in color and in many respects is similar to that of the parent material except that it contains a lower proportion of clay. The removal of lime and soluble compounds as well as the presence of some organic matter no doubt impart the darker color to the matrix of the Ae horizon. The plates within the Ae vary in thickness, but average between 0.65 and 1.5 mm. There is no marked difference in concentration of plasmic material within the bands. Occasional accumulations of organic matter and iron concretions are interspersed within the matrix.

The platy or banded fabric is much more pronounced in the Ae horizon of the Grey Wooded soil (see Plate 5-3). The plates, which generally vary between 0.3 and 0.5 mm. in thickness, tend to have a rolling form which imparts a wavy appearance to the bands within the microfabric. As can be seen in the photograph, each band shows a gradation in plasma content, with the highest content of fine material occurring near the top of the plate. This type of banded fabric is similar to that described by Kubiena (81) and McMillan (100). The over-all appearance of the soil

material indicates that much of the clay-sized fraction has been lost from this horizon. This is substantiated by mechanical analysis data (Table 2).

In comparing the Ahe and Ae horizons of the three soils, it is immediately evident that they all have undergone leaching and that such leaching is most pronounced in the Grey Wooded soil. The platy structure associated with these eluviated horizons becomes more pronounced, the plates become thinner and gradations in particle size distribution within the bands more striking, in passing from the Orthic Dark Grey to the Grey Wooded soil. It appears that in the Orthic Dark Grey soil, leaching of a humic horizon has occurred, whereas in the other two profiles there is no evidence to indicate that the Ae horizons have ever been humified.

The B Horizons

In discussing the B horizons of the profiles studied, reference is made only to the major sub-horizon of each soil. The major sub-horizons are represented by the Bmt in the Orthic Black and Orthic Dark Grey soils, whereas the Bt horizons represent the major zones of accumulation within the other two soils. Although other sub-horizons occur within the B of each profile, they reflect to a lesser degree the changes which have occurred in the illuviated zone.

The most significant change in macro-structure which can be observed in the B horizons of the soils studied is associated with the degree of expression of prismatic structure. The Bmt of the Orthic Black soil is characterized by well developed, medium prismatic structure which breaks down to medium, blocky aggregates. Similar structure occurs in the Bmt of the Orthic Dark Grey profile except that the nut-like peds which result upon dismembering the prisms often display slight and discontinuous coatings which are not apparent in the Orthic Black soil. The Dark Grey Wooded soil displays coarse, irregular prismatic structure. In the Grey Wooded soil the prismatic structure is completely lacking, the structure consisting of strong, fine angular to subangular blocky aggregates. These display coatings of colloidal material which are more pronounced than the coatings in the B horizons of the Dark Grey and Grey Wooded soils. Thus, in going from the Black to the Grey Wooded soil, the prismatic structure decreases in expression, becoming first larger and more irregular and finally disappearing. In addition, the ultimate peds of the B horizons decrease in size in going from the Black to the Grey Wooded soil.

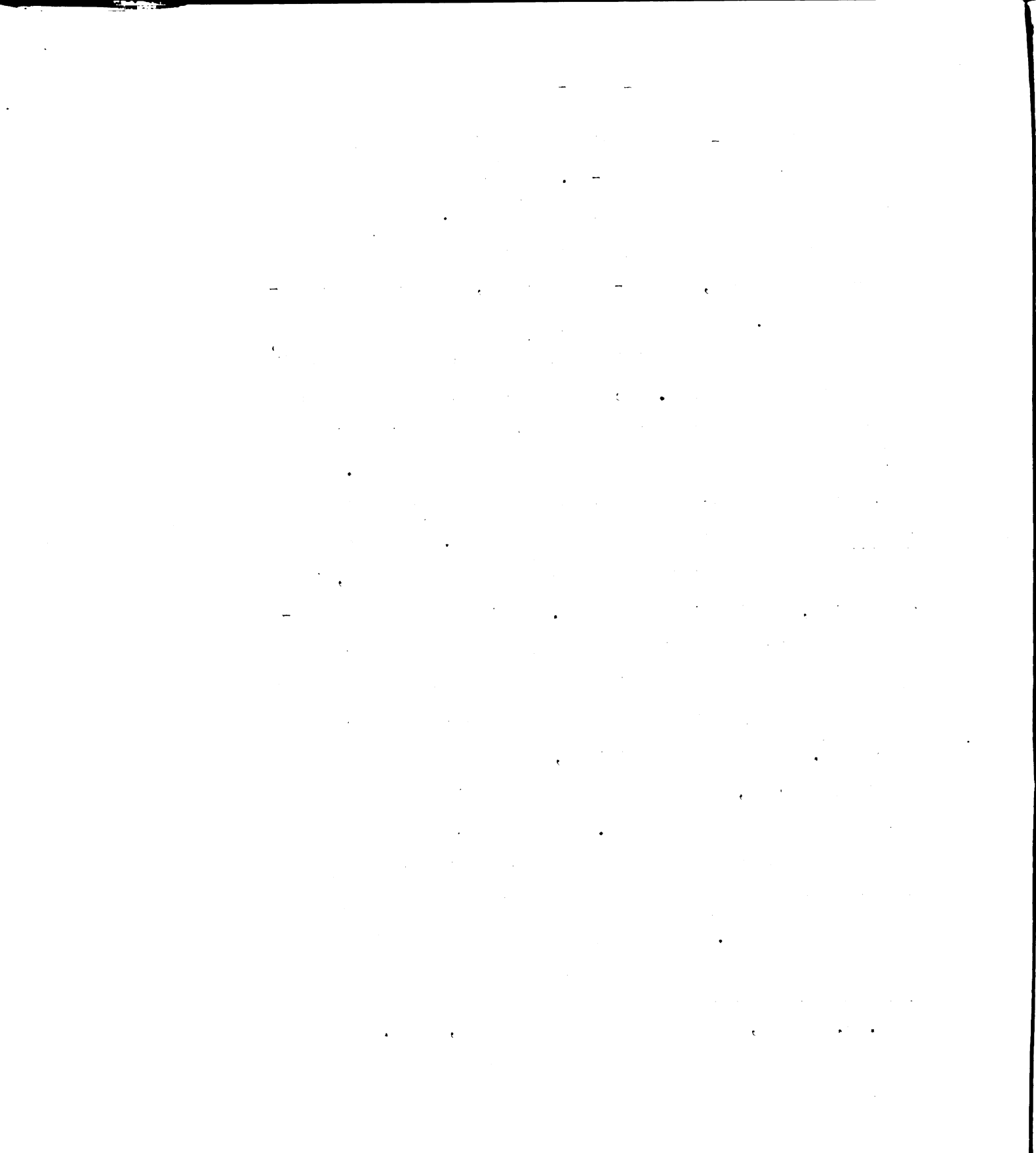
In thin section, the Bmt horizon of the Orthic Black soil is characterized by a dense, uniform, medium

brown to yellowish-brown matrix surrounding skeletal grains of varying sizes (see Plate 6-1). Numerous pore spaces are evident throughout the interior of the peds. Examination of the sections under crossed nicols reveals the presence of very fine flecks, orange-red in color, dispersed throughout the matrix. These minute accumulations appear to consist of oriented clays and exhibit uneven extinction upon rotation of the microscope stage. Acton* has reported the presence of similar accumulations in the B horizons of soils within a catena of the Dark Brown soil zone of Saskatchewan. He attributed their presence to reorientation of clay minerals in situ due to wetting and drying processes. He also suggested the possibility that such accumulations may, in some soils, be illuvial in nature. Their presence throughout the matrix of a soil would indicate that they were transported before the soil had a well developed system of cleavages and channels through which water could percolate downwards. Under such conditions, water would move as a continuous front, carrying dispersed colloids into all portions of the soil material.

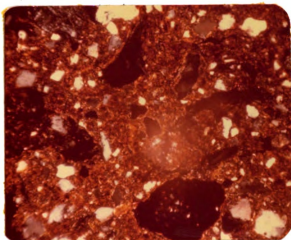
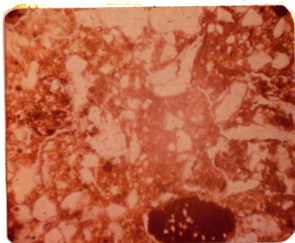
There is very little evidence to indicate that the clays in the B horizon of the Orthic Black profile are illuvial in nature. The accumulations of colloidal material along cleavages and pore walls are discontinuous and rare in

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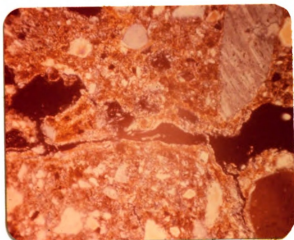
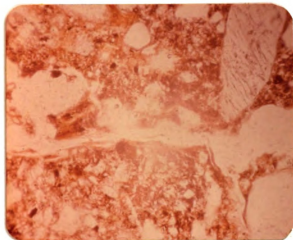
M.Sc. Thesis, University of Saskatchewan, 1961.



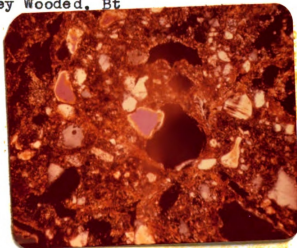
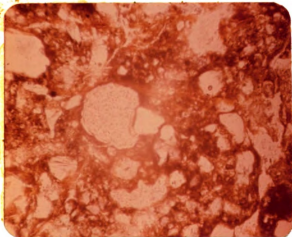
1. Orthic Black, Bmt



2. Dark Grey Wooded, Bt



3. Orthic Grey Wooded, Bt



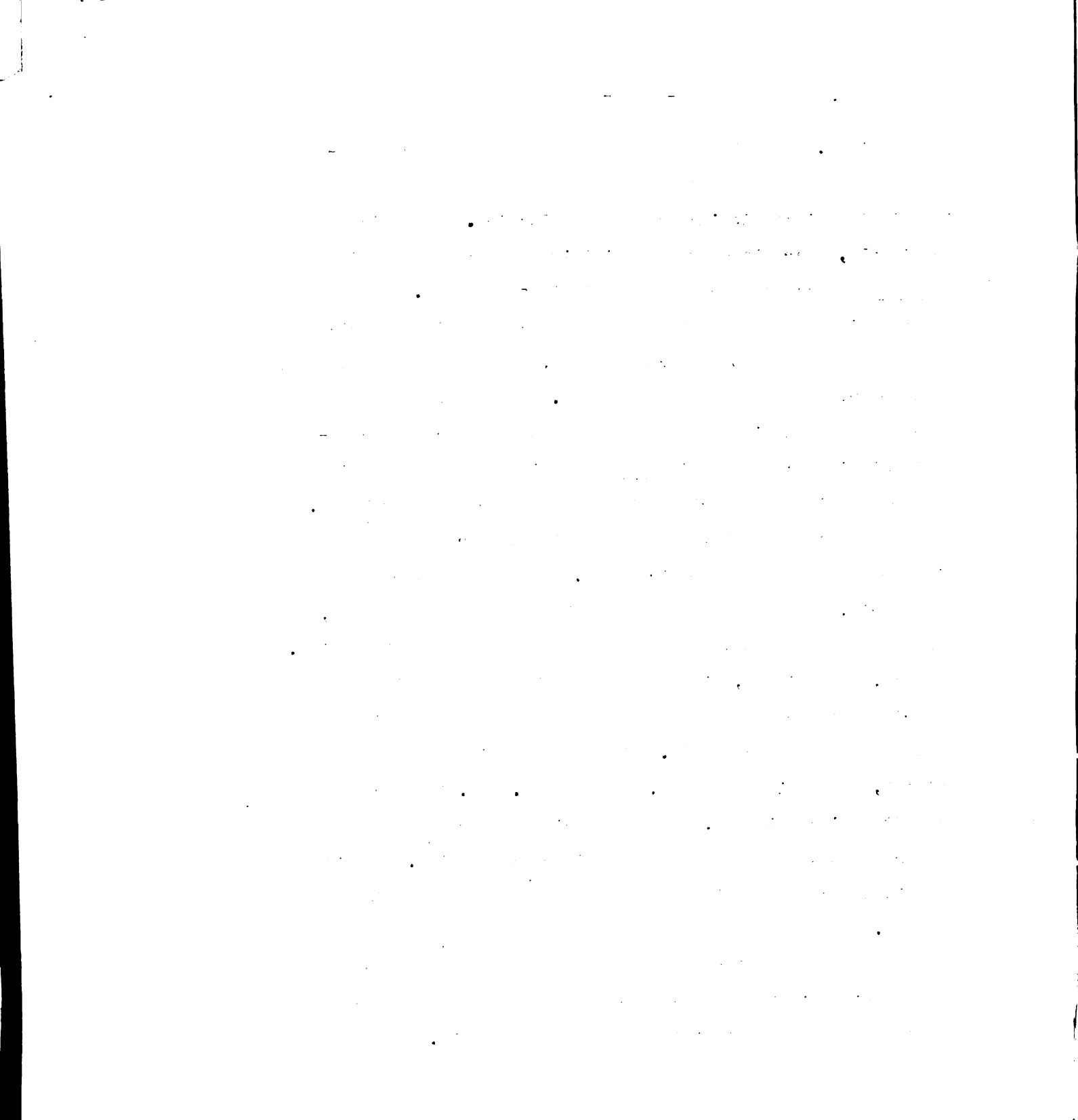
0.2
mm.

Plate 6. Photomicrographs of the Bmt and Bt horizons of the Orthic Black, Dark Grey Wooded and Orthic Grey Wooded soils. (Photo to the left, plane polarized light; right, x-nicols.)

this horizon. The higher clay content of the B in comparison to the A and C horizons does not appear to be due to illuviation since distinct cutans are lacking. As indicated previously, there is a good possibility that clay formation in situ may account for the accumulations observed. The quantitative assessment of changes in particle size distribution based upon total quartz content, although subject to some error, appeared to indicate this. Additional work would be required to definitely establish whether the clay accumulation is in fact due to in situ formation or due to original differences in the material from which the profile developed.

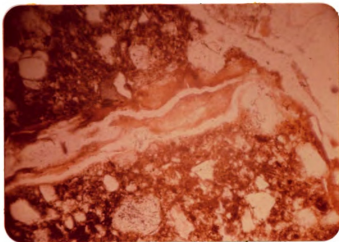
The Bmt horizon of the Orthic Dark Grey soil is similar to that of the Orthic Black. The dense nature of the matrix, the abundance of skeletal grains embedded in it, and the high proportion of voids all attest to this similarity. However, in addition, diffuse accumulations of brownish materials appear along the surfaces of peds and bordering cleavages and root channels. Although no orientation is evident, these diffuse bands, less than 0.1 mm. in thickness and often discontinuous, give the horizon a more dense appearance than the Bmt of the Orthic Black profile. Flecks of oriented clays within the matrix still persist in this horizon.

The Bt horizons of the Dark Grey Wooded and Grey Wooded soils display high clay contents and more pronounced coatings which cover individual peds and channels. All of



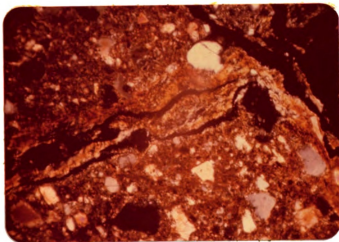
the ped surfaces are covered with plasmic material, the concentration of which decreases towards the centre of the peds. As seen by comparing Plates 6-2 and 6-3, the coatings are much more pronounced in the Grey Wooded soil, although they are strongly expressed in both soils. Under crossed nicols, these coatings are dark orange-brown in color and appear streaky, indicating orientation parallel to the ped surfaces. The cutanic material shows uneven extinction when the clay skin is oriented parallel to the direction of vibration of the polarizer. Oriented colloids within the matrix of these horizons are also present, as they were in the two grassland profiles.

The accumulation of colloidal materials along the faces of the peds and along root channels and other voids strongly suggest that illuviation of clays has occurred within the Bt horizons. The very marked concentrations of cutanic material seen in Plate 7-1 and 7-2 occur in the Bt of the Grey Wooded profile. The streakiness of these coatings, which is evident in these photographs, becomes much more apparent at high power. The flow pattern seen at high power (Plate 7-3) leaves little doubt that materials have moved down in suspension into this horizon. The translocated clays display orientation parallel to the direction of flow. The flow structure, occurring in fabric referred to as channel fabric by Kubiena (81), is ample evidence that illuviation has occurred.



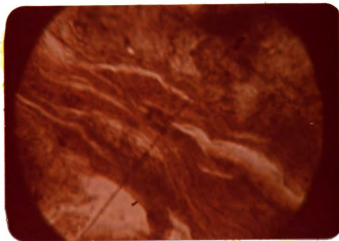
1. Orthic Grey Wooded,
Channel fabric,
(plane polarized
light).

0.2
mm.



2. Orthic Grey Wooded,
Channel fabric
(x-nicols).

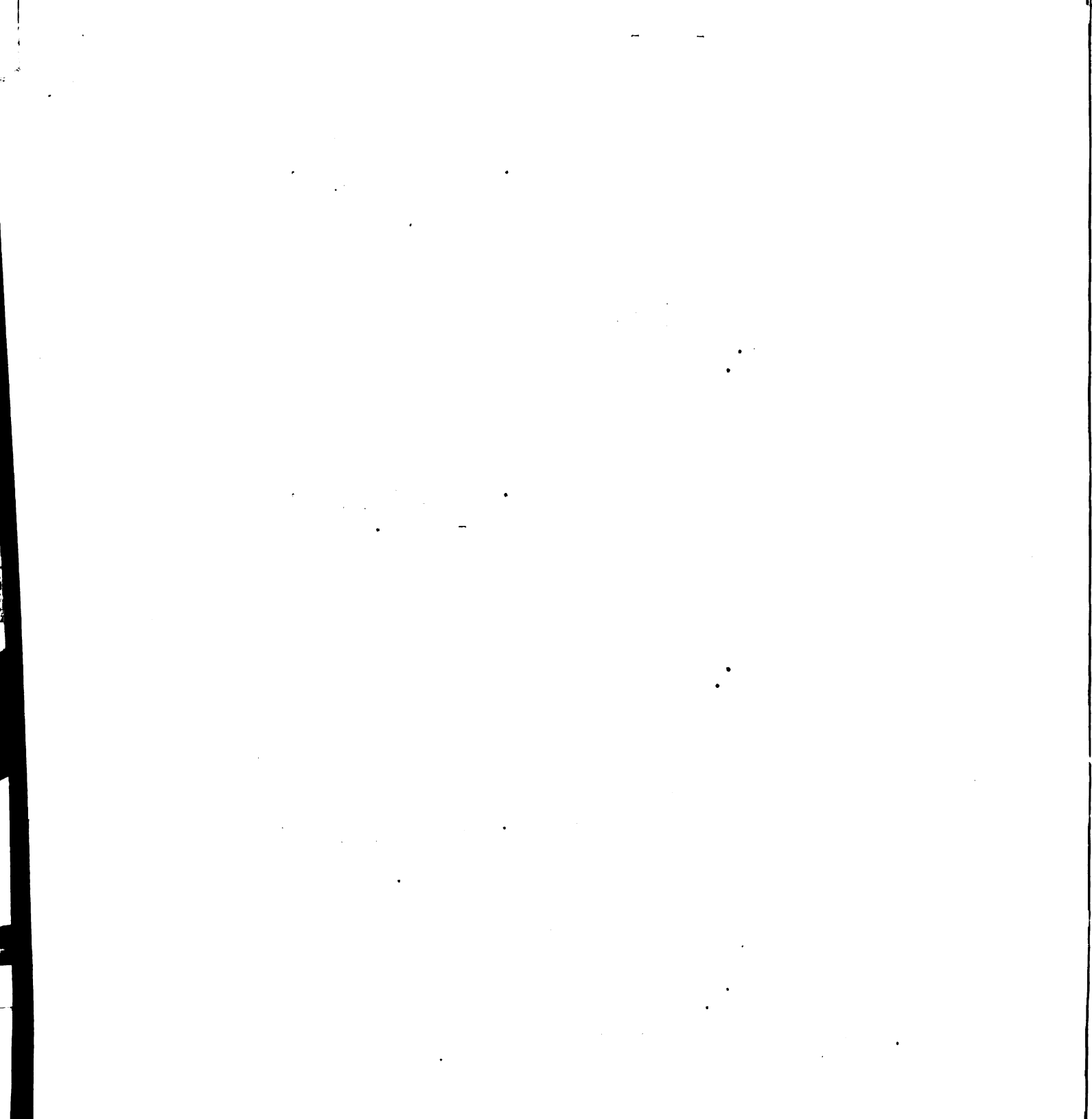
0.2
mm.



3. Orthic Grey Wooded,
Flow structure
(plane polarized
light).

0.05
mm.

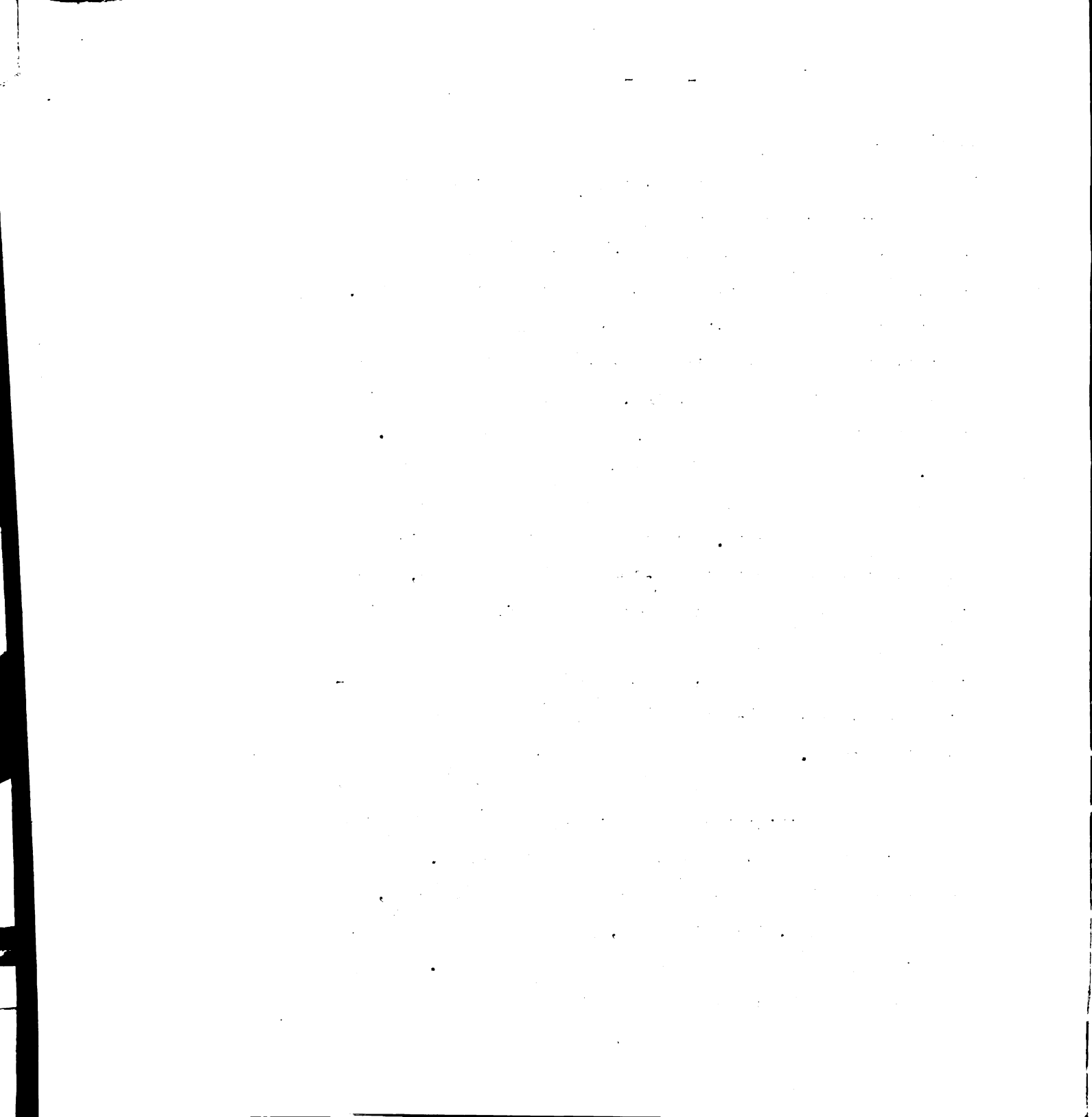
Plate 7. Photomicrographs showing channel fabric and flow structure in the Orthic Grey Wooded soil.



Discussion

The study of thin sections of the major horizons of the soils being investigated has provided valuable information as to the nature and intensity of some of the important processes which have resulted in their formation. Examination of the A horizons indicates that processes of humification and aggregation are very active in the Orthic Black and Orthic Dark Grey soils, whereas they decrease in intensity in the two soils developed under forest cover. Also, it is apparent that the degree of leaching within the A becomes more pronounced in going from the Black grassland to the Grey Wooded soil. Eluviation within the Orthic Dark Grey profile occurs within an already humified layer, whereas in the Dark Grey Wooded and Grey Wooded soils the material being leached is very similar to the original parent material inasmuch as the silt and clay fractions have not been stabilized by organic matter to the extent that they have in the grassland soils.

The effect of organic matter in causing aggregation and thereby stabilization of the soil components most subject to peptization and translocation is very important. In the development of a soil from a calcareous parent material, the soluble salts, including lime, are among the first constituents to be removed from the surface layers. When the duration of leaching has been sufficient to remove most

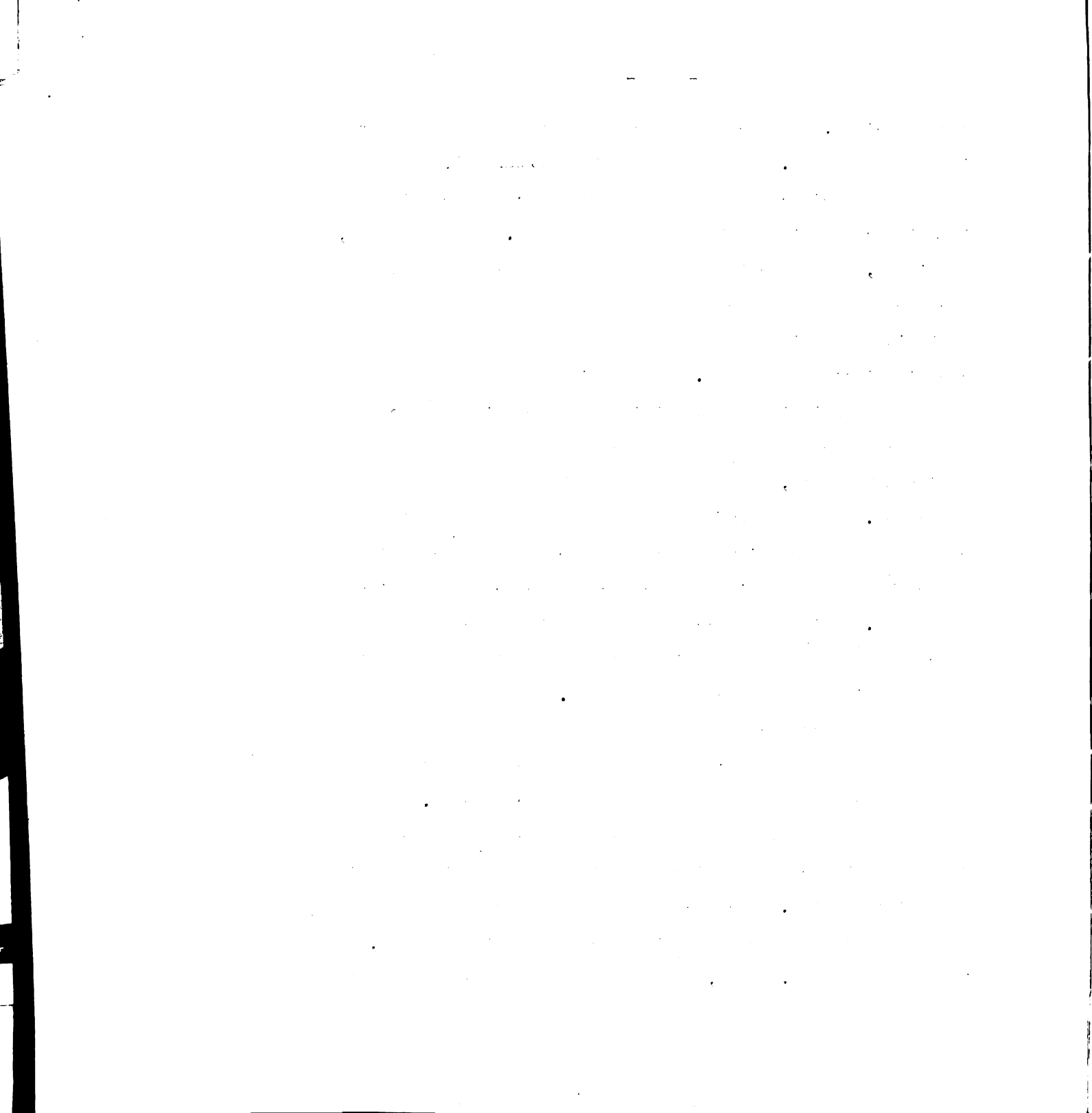


of the flocculating ions such as calcium, dispersion of the colloidal fraction will occur and the finer particles may be moved down in suspension. Thus, even assuming that the degree of leaching was the same for all four soils and that their surface layers were freed of soluble salts at about the same time, the amount of clay which would be likely to move would be much lower in the well aggregated grassland soils as compared to the forested soils. This provides an explanation for the more marked removal of clay from the A horizons of the Dark Grey Wooded and Grey Wooded soils as compared to the other two. The development of heavy, impervious B horizons showing the signs of marked illuviation processes in the form of coatings of oriented clays and flow structures occur in the two forested soils. The B horizons of the grassland profiles, on the other hand, remain more permeable and maintain conditions of good internal drainage within the profile. The differences in the nature of the B horizons indirectly result from differences in the corresponding A horizons.

The differences in internal drainage within the four soils have, as indicated, resulted largely from variations in the amounts of clay material translocated and accumulated within the profiles. The formation of platy structure in the eluviated A horizons appears to be closely associated with the permeability of the B horizons; the more impermeable

the B horizon, the more pronounced the degree of platiness in the Ae horizon. As indicated by Czeratzki (42), platy or banded fabric can be formed by the effect of freezing in soils containing a high content of water. As previously, mentioned, the impervious nature of the B horizons in the Dark Grey Wooded and Grey Wooded soils may result in periodic saturation of the upper layers with water at certain times of the year. If freezing temperatures occur when the soil is in this condition the formation of ice lenses could result in the fracturing of the soil along horizontal planes, leading to the development of platy structure. The processes outlined by Kubiena (81) which result in the formation of zones of enrichment of colloidal materials at evaporating surfaces could occur as the soils dried out. This would account for the differences in concentration of soil colloids observed within the bands in the Ae horizon of the Grey Wooded soil.

The same conditions which have resulted in the formation of platy structure are very important as far as physical breakdown of soil components is concerned. Mention has already been made of the apparent destruction of coarse fractions with resultant increases in finer fractions within the soils studied. Such breakdown was observed to be most marked in surface horizons which were underlain by heavy, impervious layers. Thus, it appears that the processes which



have resulted in the formation of these soils have also indirectly been responsible for the processes of physical breakdown, the latter being less evident in the well drained Orthic Black soil than in the other soils which possess more impervious B horizons.

DISCUSSION AND CONCLUSIONS

The present study provides information on the morphology, composition and genesis of four soil profiles which are typical of large areas of Saskatchewan and of other parts of western Canada. The sequence of soils, ranging from the chernozemic Orthic Black to the podzolic Grey Wooded, demonstrate the significant changes which occur as podzolic degradation progresses. In the following discussion, emphasis will be placed upon the characteristics of the Orthic Black and Orthic Grey Wooded soils since these represent the end members of the sequence under study. The other two soils exhibit properties which are intermediate or gradational to those of the two end members and reference to them will be mainly in this regard.

The uniformity of the glacial till material underlying all four soils is evident from the analyses conducted. It consists of medium textured material having a high lime-carbonate content, the CaCO_3 equivalent for the C horizons of the profiles studied approximating 21 percent. The high lime-carbonate content no doubt results in part from the fact that the lime which has moved out of the solum has not entirely accumulated in the upper C or Ck horizons, but has moved down deeper into the subsoil. This is evident from the lack of well-expressed Ck horizons in any of the profiles.

In Saskatchewan, although well-expressed layers of lime accumulation generally occur in the Chernozemic soils developed from calcareous glacial till, in Podzolic soils such zones of accumulation are never as pronounced and often are not discernable. Aside from variations in lime content, the C horizons of these profiles are remarkably uniform in their mechanical composition, in the nature of their component clays, in the distribution of quartz within the different size separates, as well as in the kind and distribution of minerals within the fine sand fractions.

The analyses indicate that at least three of the four profiles have apparently developed from material similar to the underlying till. The Orthic Black profile may have developed from slightly different material but if so, the difference is reflected mainly in proportions rather than in kinds of soil constituents. For comparative purposes, it is assumed that the four soils have formed from similar parent material.

As was indicated earlier, the soils under study were selected from a relatively small area, and the overall climatic conditions can be considered to be fairly uniform. The mean annual temperature (32° F.) and the mean annual precipitation (16.17 inches) reflect only the macro-climatic conditions of the area. Differences in aspect, elevation and vegetative cover markedly affect the actual

soil climate which is reflected in the differences within the soil profiles. Although all four soils have developed on similar topography, the Orthic Black soils occurred on a south-facing slope, whereas the other three soils were located on north-facing slopes. In addition, the Black soil developed under grasses in a mixed grassland-forest area, whereas the Orthic Grey Wooded soil occurred in a heavily forested area, under deciduous trees. The latter site was also 200 feet higher in elevation. Thus, the micro-climatic conditions which influenced the formation of these soils must have varied quite markedly, the Orthic Black soil developing under drier conditions as well as under conditions of more extreme and more variable temperature than the Grey Wooded soil. Climate and vegetation can, therefore, be considered as the main factors affecting the formation of the soils under study.

Two processes have apparently dominated the formation of the chernozemic Black soil: humification and the maintenance of a high base status (calcification). The dense fibrous root system of the grasses and the continued return of plant residues to the mineral soil have contributed to the formation of a well-aggregated, porous, humic horizon in the upper seven inches of the profile. The continual return of nutrient elements to the soil by the recycling of organic matter has maintained a high

proportion of calcium on the exchange complex of the soil and is reflected in the pH levels of the horizons. Repeated wetting and drying cycles, such as occur under grassland conditions in the area, have resulted in the development of strong, prismatic structure in the B horizon. The relatively low degree of leaching and the stabilization of the colloidal fraction of the soil by the organic fraction, as well as the high base status of the soil, has resulted in little translocation of the soil colloids in comparison to the other soils. Although textural B horizons often occur in Chernozemic soils (113, 132) they are generally weakly expressed and are not the main characterizing feature of Chernozemic soils. Although inconclusive, there is some evidence to indicate that clay may have been formed in situ within the Black soil studied.

The processes involved in the formation of the Grey Wooded soil have resulted in the development of an L-H layer above the mineral horizons, a highly leached platy Ae horizon high in silt, and a heavy impervious Bt layer. Although the profile is highly leached, it is characterized by a high base status with calcium dominating the cation exchange system. The lowest pH occurs in the Bt horizon. Although decalcification of the soil material may be occurring to some extent, as evidenced by the solum pH

values and cation exchange data, the process has not reached the stage of high unsaturation typical of Podzol soils.

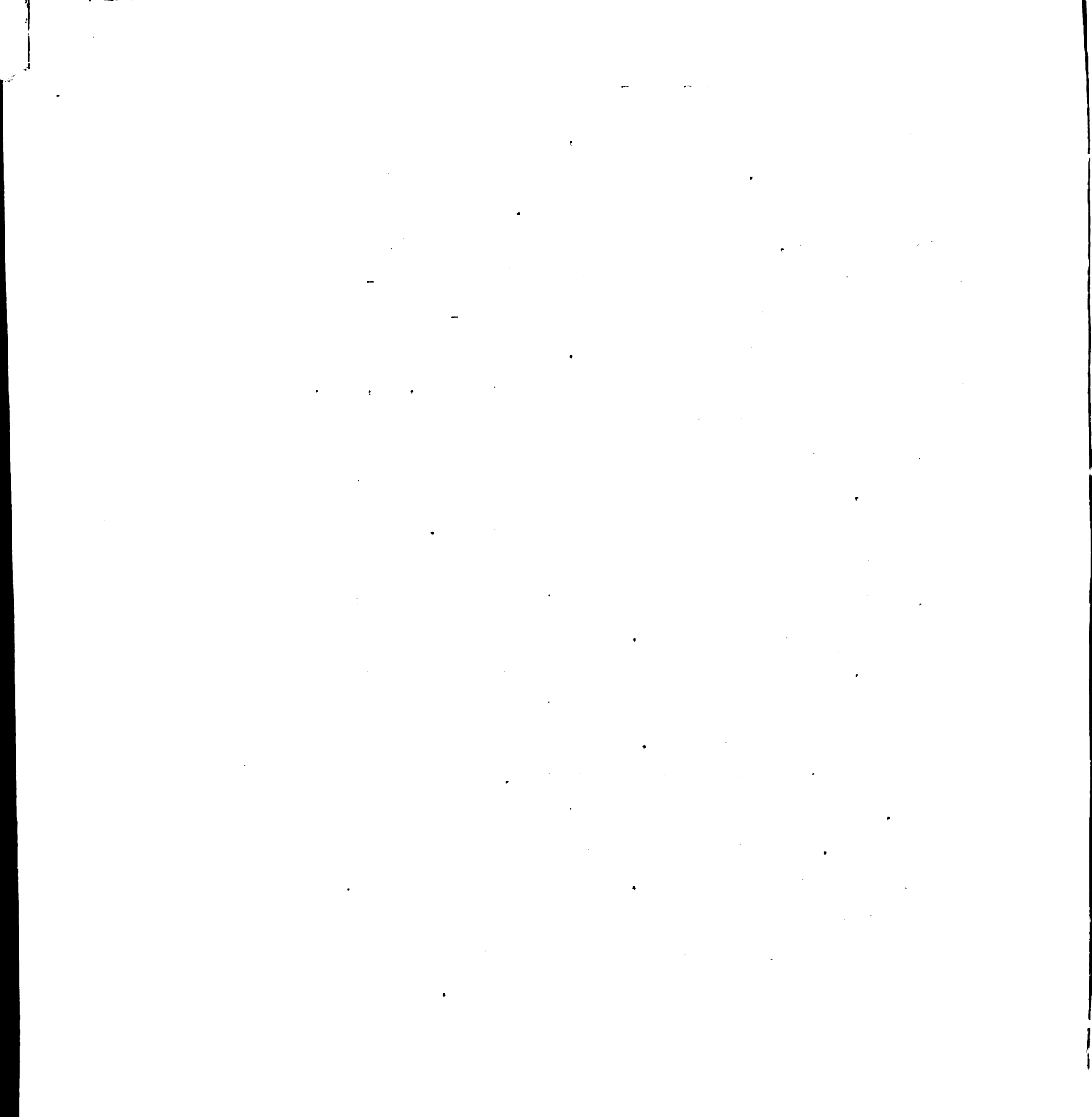
The Orthic Dark Grey and Dark Grey Wooded soils represent intergrades between the Black and Grey Wooded soils. Variations in the thickness of the L-H and Ah horizons, and in degree of development of the Ahe or Ae and textural B horizons illustrate the gradations between the Black and Grey Wooded soils. Although leaching has been largely dependant upon the moisture status within each of the four soils, the amount of translocation of colloidal materials within the profiles has been influenced by the degree of aggregation and the extent to which organic matter and bases have stabilized the mobile constituents in the A horizons. Thin section studies have provided valuable information relative to the translocation of clays and other soil colloids. The degree to which cutans, channel fabric and flow structures occur and are expressed in the B horizons provides ample evidence as to the extent to which illuviation has occurred within the profiles.

The clay fractions of the soils have undergone small but significant changes as a result of pedogenic processes. Montmorillonite and illite are the dominant clay minerals in both the fine ($<0.2 \mu$) and coarse ($2.0-0.2 \mu$) clay fractions of the four soils. However, more illite is present in both the fine and coarse clays of the A and B horizons than in the underlying C horizons. A process of

illitization seems to be taking place, particularly within the surface horizons. The highest illite content occurs in the Ah horizon of the Orthic Black profile. This may be anticipated since, as discussed previously (page 121), conditions in the drier grassland soil are much more conducive to the fixation of potassium by expanding-type clays than in the more humid forested soils. Previous work has indicated that such a process can and does occur (19,109,145).

While chlorite is present in only small amounts in the clay fractions of both the solum and C horizons of the four soils, the chlorite content has decreased within the solum horizons as a result of weathering processes. The decrease is greatest in the A horizon of the Grey Wooded soil, indicating more intensive weathering in the Podzolic than in the Chernozemic profile. In the B horizon of the Black soil, chlorite appears to have weathered to a finer size as indicated by the relative chlorite contents of the fine and coarse clay fractions.

The translocation of sesquioxides, and especially of iron, has always been associated with the process of podzolization. Organic compounds are thought to play an important role in such movement. In the soils under study, the translocation of iron appears to be closely associated with clay movement, inasmuch as the distribution of total iron and clay within the profiles is very similar. The



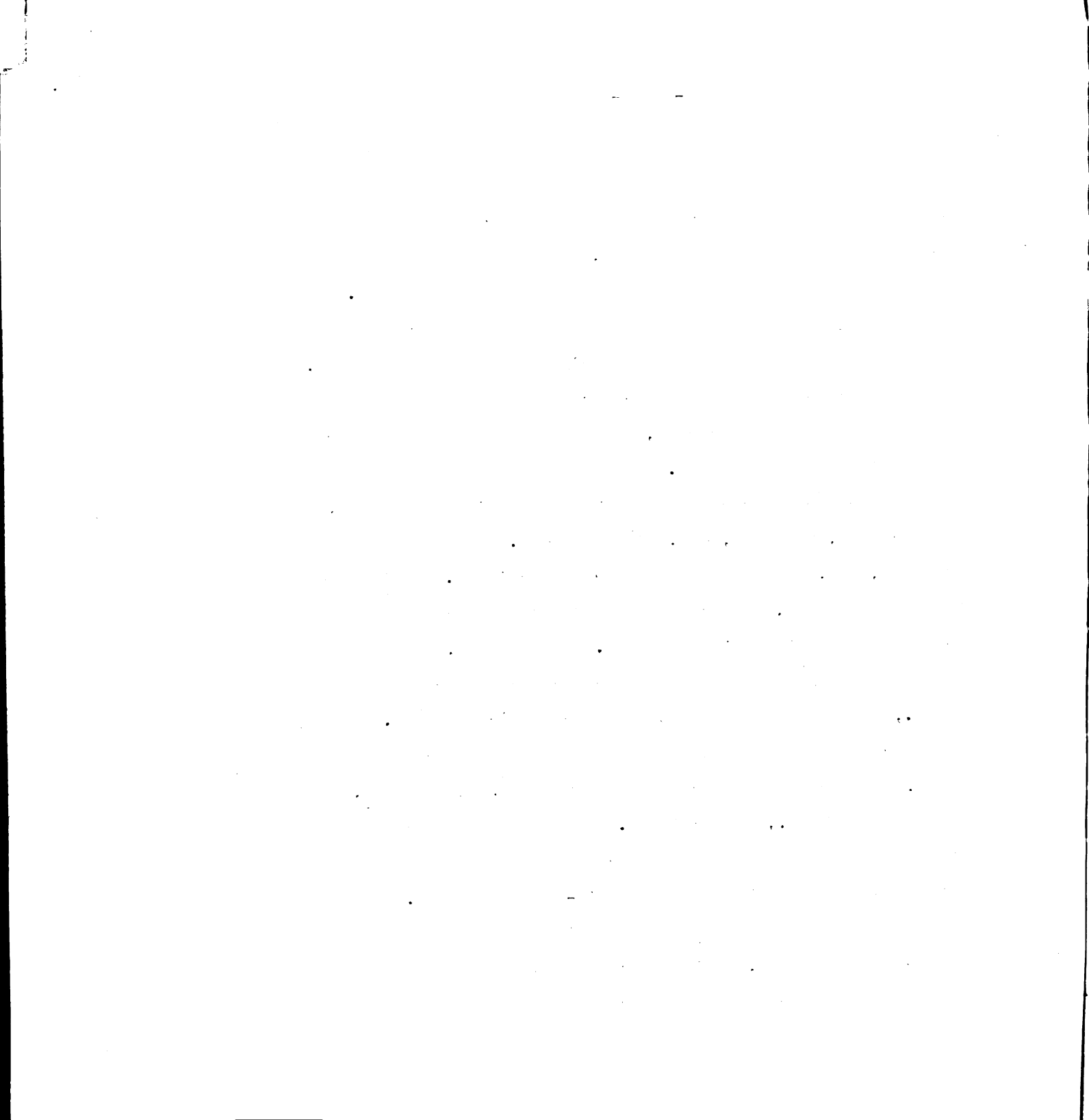
relatively uniform iron content of the fine clay fraction of all horizons of the four profiles indicates that iron may occur as an integral part of the clay minerals, and that the latter have suffered little change as a result of soil formation. The variation in iron content of the coarse clay fractions within the solum is attributed to a dilution effect produced by the accumulation of primary minerals within the coarse clay fractions. Evidence presented indicates a closer correlation between total iron and clay than between free iron and clay content. If free iron is a measure of iron that is regarded as being mobile in the soil, the data presented indicate that the horizon of maximum accumulation of free iron may not always coincide with the horizon of maximum accumulation of total iron and of clay.

It is difficult to determine whether the soil organic fraction has played any part in affecting the mobility of iron since no significant increases in organic carbon or nitrogen occur in the horizons of maximum iron accumulation. Also, calculations indicate that 60 to 85 percent of the total iron in these soils occurs in the clay fraction. If the bulk of this is present as an integral part of clay mineral structures and has not been affected by weathering (and indications are that this is so), only a small portion of the total iron occurring in the soil may be present in forms readily affected by organic compounds

which could effect its translocation. The movement of iron-rich clays accounts for most of the iron moved within the soils studied.

The preceding discussion of the pertinent differences between the four soils under study have provided information relative to the formation of Grey Wooded soils. The effect of micro-climate and vegetation have been stressed. The differences resulting from these effects are reflected in the types of A and B horizons formed. The development of a heavy impervious B horizon in the Grey Wooded soil is in a large degree responsible for the development of platy structure in the Ae horizon. As was previously indicated, the presence of an impervious B horizon leads to periodic conditions of saturation in the overlying horizon. The freezing of free water was suggested as being largely responsible for the development of platy structure in the Ae horizon. Such views agree with those held by Czeratzki (42). Saturated conditions also increase the possibility of physical breakdown of rock fragments and minerals within the surface layer. As indicated by the quartz and particle size distribution studies, such breakdown is evidenced in the solum of all soils but is much more pronounced in horizons underlain by impervious horizons. The increase in the restriction of drainage in going from the chernozemic Black soil to the Grey Wooded soil represents another significant factor affecting the formation of these soils.

In suggesting that the freezing action of water may be largely responsible for the process of physical breakdown and the formation of platy structure in the Ae horizon of the Grey Wooded profile, the question of temperature variations becomes of considerable importance. It was indicated earlier (page 139) that repeated frost action would be most effective in bringing about such changes. Some evidence relevant to the frequency of freezing and thawing in the area concerned, is provided from meteorological data available for the area. The monthly averages of daily mean temperatures recorded over a 20 year period at Hubbard, Saskatchewan, were 15° , 34° , 36° and 21° F. for the months of April, May, October and November respectively. During these four months, air temperatures fluctuate markedly around the freezing point of water. For example, the monthly average of daily maximum temperatures recorded for March was 29° F., whereas the minimum temperatures averaged 5° F. The average of daily maximum and minimum temperatures for April, October and November were 49° and 24° , 51° and 26° , and 32° and 13° F., respectively. These values indicate the wide daily variation of temperatures around the freezing point during the early spring and mid-autumn seasons. Although no soil temperatures are available for the soils of the area in question, it is expected that wide variations in soil temperature would also occur during the months



mentioned, particularly in the upper horizons. Even though temperature variations would be less pronounced in forested soils than in grassland soils, the conditions of saturation that more frequently exist in the former make the action of frost much more effective in terms of breakdown of rock material and the development of platy structure.

In this study, the Grey Wooded soil has been shown to have distinct properties which serve to separate it from true Podzol soils. The thin L-H and Ah horizons, the thick, light colored, platy Ae and the heavy impervious textural B horizon are its characteristic morphological features. Unlike true Podzols, this soil is highly base-saturated, the exchange complex being dominated by calcium. The translocation of iron within the Grey Wooded soil results mainly from the translocation of iron-rich clay minerals. The marked destruction of secondary minerals in the eluviated horizon, which Rode (124) considers to be the major characterizing process in Podzol soils, is not evident in the Grey Wooded soil. Although chemical weathering of minerals has occurred to some degree within the solum, it has certainly not been pronounced. The marked disintegration of coarse sized minerals in the Ae horizon and the subsequent increase of intermediate sized particles is another characteristic of this soil. The above-mentioned criteria serve to separate the Grey Wooded from the true Podzol soils.

SUMMARY

1. The four soils under study, ranging from chernozemic Black to podzolic Grey Wooded, exhibit marked variations in morphology as observed in the field. The gradation of properties observed in going from the Black to the Grey Wooded soil are:
 - a) a general increase in the thickness of the solum;
 - b) a less pronounced lime accumulation layer;
 - c) a decrease in the thickness of the Ah horizons and in the expression of blocky structure within the Ah horizons;
 - d) an increase in the degree of leaching as exhibited by variations in color and platiness of the Ahe and Ae horizons;
 - e) a change from strong to weaker and more irregular, and finally to the absence of, prismatic structure in the B horizons; and
 - f) an increase in the degree of development of textural B horizons.
2. The fabric of the well-aggregated, porous humic Ah horizon of the Black soil is typical of Chernozemic fabric. Although the fabric of the Ah horizons of the other three soils show some similarity to that of the Black Ah horizon, the inorganic fraction of the soil

is not as intimately associated with the organic fraction, particularly in the Dark Grey Wooded and Orthic Grey Wooded profiles. This results in a decrease in the degree of stabilization of the soil colloids in going from Chernozemic to Podzolic soils. As a consequence, more clay has been moved out of the A horizon of the Grey Wooded soil than of the Black soil.

3. The development of textural B horizons is dependent to a large measure upon the nature of the overlying A horizons, for the reasons explained above. The increased illuviation which occurs in going from the Black to the Grey Wooded soil is indicated by the degree of expression of cutans, channel fabric, and flow structure in the B horizons. Mechanical analysis and bulk density measurements serve to confirm this.
4. All four soils are highly base-saturated, calcium being the dominant cation on the exchange complex. However, the amount of leaching within the profiles is seen to have increased in intensity in going from the Black to the Grey Wooded soil, as evidenced by the decrease in solum pH values.
5. The fine clay fraction ($<0.2 \mu$) of the parent materials is composed almost entirely of montmorillonite and illite which occur in the ratio of approximately 3 to 1. Trace

amounts of kaolinite and chlorite are present. In the coarse clay fraction (2.0-0.2 μ) montmorillonite and illite occur in about equal amounts but account for less than three-quarters of the total weight of the fraction. Kaolinite, chlorite and primary minerals make up the remainder of the fraction.

6. The clay fractions have undergone small but significant changes as a result of pedogenic processes. Fixation of potassium by expanding-type clay minerals has resulted in the increase in illite content within the solum of all four profiles. Illitization is most pronounced in the Ah horizon of the Black soil.
7. There has been a decrease in the chlorite content of clays within the solum of all profiles, the greatest decrease occurring in the Ae of the Grey Wooded soil. This indicates more intensive weathering in the Podzolic than in the Chernozemic profile.
8. There is some indication that clay may have formed in situ within the Black soil and to a lesser degree within the Grey Wooded soil, but additional work is required to substantiate this.
9. The translocation of iron within all four profiles appears to be closely associated with clay movement.

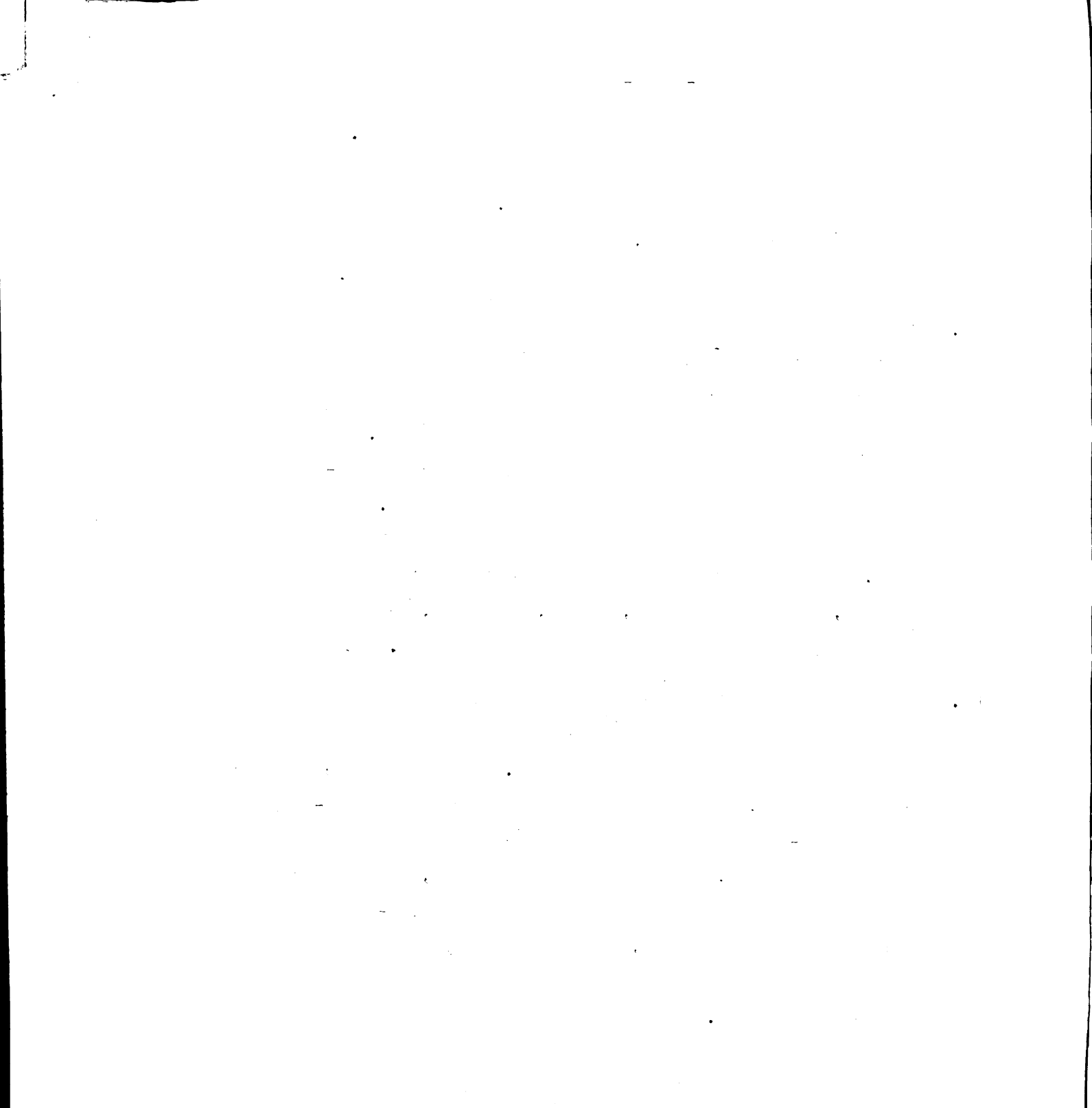
A higher correlation between total iron and clay content than between free iron and clay content indicates that the horizon of maximum accumulation of free iron may not always coincide with the horizon of maximum accumulation of total iron and clay. The uniform iron content (12.0-13.0% Fe_2O_3) of the fine clay fraction of all four profiles indicates that the iron may occur as an integral part of the clay mineral structures. In addition, it indicates that the clays have undergone little alteration as a result of weathering. The movement of iron-rich clays accounts for most of the iron moved within the soils studied. There is no evidence to indicate that organic compounds have been responsible for the translocation of any iron within the profiles.

10. Particle size distribution of quartz and of the acid-insoluble soil fractions larger than 0.2 microns indicate that a redistribution of sizes has occurred within the solum of all four soils relative to the parent material. A decrease of coarse fractions in the solum is accompanied by an increase in the silt and very fine sand fractions relative to the C. Such a redistribution is attributed to a process of physical breakdown of the larger rock fragments and minerals.

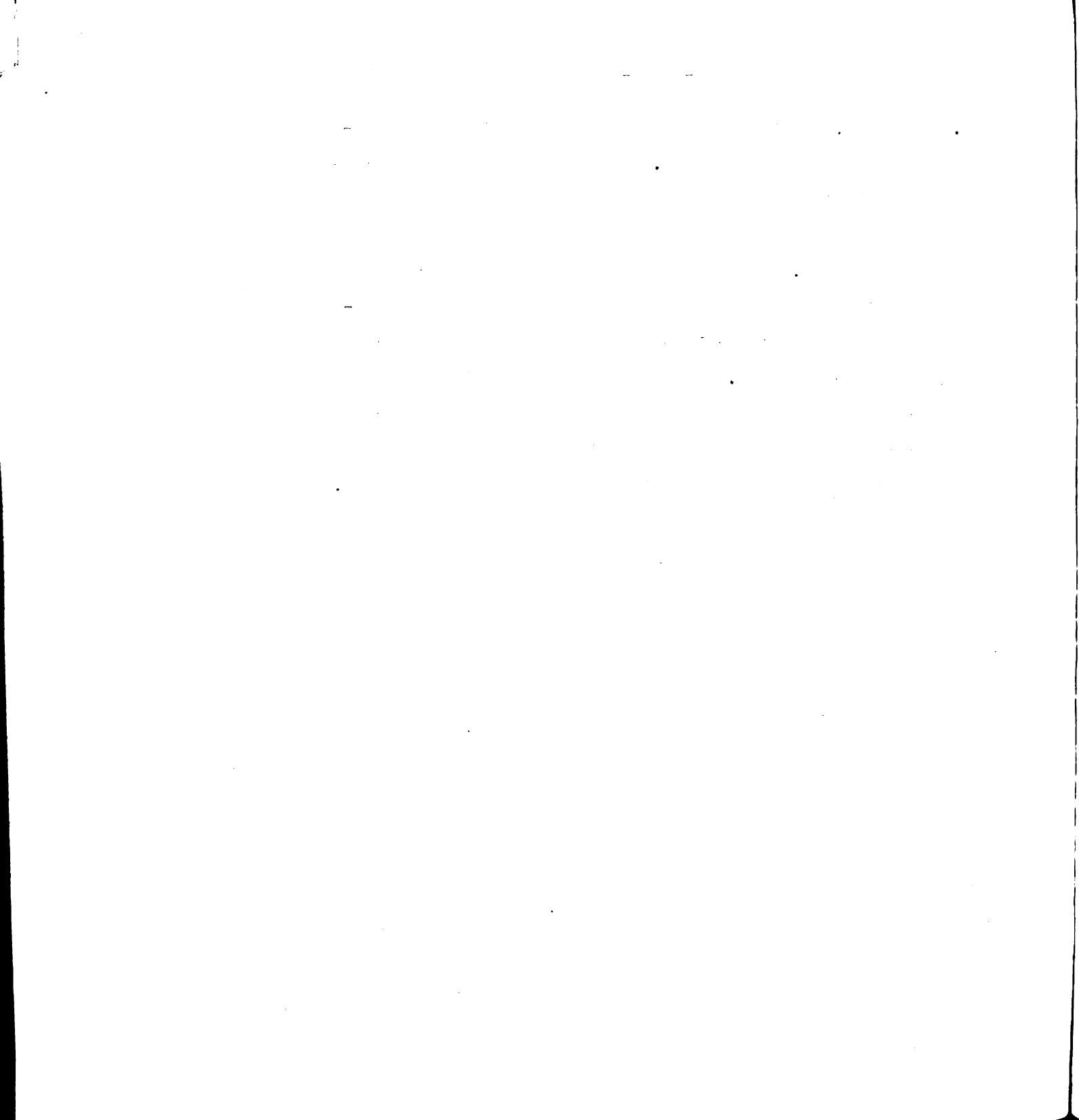
11. Subjection of coarse (> 0.5 mm.) rock and mineral fragments to repeated freezing and thawing under saturated conditions showed a small but significant breakdown of such fractions to sizes smaller than 0.5 mm. This is taken as evidence to indicate that frost action in soils could cause similar breakdown under natural conditions.
12. Although physical breakdown appears to decrease linearly with depth, the extent to which disintegration occurs is apparently affected by the prevalent soil moisture conditions, the insulation afforded by L-H layers, and the presence of impervious subsurface horizons. Physical breakdown appears to be most pronounced in surface horizons underlain by fine, textural B horizons. The periodic conditions of saturation which occur in the upper horizons due to restricted drainage of the subsoil are thought to favor disintegration of minerals by frost action. The greatest amount of breakdown occurred in the Ae of the Grey Wooded profile which possesses the most impervious B horizon of all four soils.
13. The development of platy structure appears to be associated with the degree of drainage within the profile. Conditions which would favor the process of physical breakdown of mineral fractions would also favor the

development of platy structure within surface horizons. The effect of ice lenses within a saturated soil could lead to the formation of platy structure. As was the case for physical breakdown, the highest degree of platiness occurred in the Ae of the Grey Wooded profile.

14. Mineralogical studies of both the light and heavy minerals within the fine sand fractions of all four soils showed inconsistencies in distribution which could not be accounted for by chemical weathering processes alone. Redistribution of minerals resulting from physical breakdown could account for the inconsistencies observed. The mineral suites of all horizons were qualitatively alike. Quartz and feldspars were the dominant light minerals, whereas hornblende, garnet, magnetite, tremolite and opaques made up the bulk of the heavy minerals.
15. Humification and maintenance of a high base status appear to have been the two dominant processes affecting the formation of the chernozemic Black soil. In the podzolic Grey Wooded soil, the dominant processes are: the development of an L-H layer and the related lack of humification of the mineral soil, the translocation of clays, the development of a more acid solum despite the persistence of a high base status, and the accumulation of silt in the Ae resulting from the physical breakdown of coarser fractions.



16. Chemical, physical and mineralogical studies are important in pedogenic studies. The study of the soil micromorphological features has also proven particularly valuable in establishing the pedogenesis of the soils investigated. The greater use of micropedological techniques and of more intensive studies of both macro- and micromorphological properties of soils are advocated for future studies. Such studies undoubtedly will assist greatly in the recognition and evaluation of genetic processes and should be useful in a more accurate separation and classification of the soils investigated.



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APPENDIX

TABLE 16. QUARTZ DISTRIBUTION WITHIN THE SOIL SEPARATES OF THE MAJOR HORIZONS OF THE FOUR PROFILES.
(Expressed as percentage of total quartz in each horizon.)

Fraction	Horizon	Orthic Black	Orthic Dark Grey	Dark Grey Wooded	Orthic Grey Wooded
Coarse Clay	Ah	2.1	3.1	-	-
	Ahe, Ae	-	4.0	2.7	2.9
	Bmt, Bt	2.7	4.3	6.1	3.1
	C ₁₋₁	1.4	1.4	1.3	1.8
Fine Silt	Ah	3.5	4.3	-	-
	Ahe, Ae	-	4.3	4.3	6.1
	Bmt, Bt	3.5	3.1	3.6	4.3
	C ₁₋₁	2.6	3.5	4.4	4.2
Medium Silt	Ah	10.9	18.0	-	-
	Ahe, Ae	-	17.5	17.4	22.6
	Bmt, Bt	12.7	13.1	12.4	13.8
	C ₁₋₁	11.6	10.4	12.9	14.4
Coarse Silt	Ah	14.2	19.8	-	-
	Ahe, Ae	-	19.6	15.0	18.0
	Bmt, Bt	14.8	12.4	12.2	11.7
	C ₁₋₁	14.1	15.7	11.8	12.1
Very Fine Sand	Ah	23.0	17.7	-	-
	Ahe, Ae	-	20.3	22.9	21.1
	Bmt, Bt	18.7	25.3	19.3	22.5
	C ₁₋₁	18.6	16.7	20.3	22.0
Fine Sand	Ah	23.3	16.8	-	-
	Ahe, Ae	-	16.8	17.6	11.7
	Bmt, Bt	25.3	19.8	19.9	20.4
	C ₁₋₁	24.9	24.3	22.2	20.4
Coarse & Medium Sand	Ah	23.0	20.5	-	-
	Ahe, Ae	-	17.5	20.1	17.6
	Bmt, Bt	22.3	22.0	26.5	24.2
	C ₁₋₁	26.8	28.1	27.3	25.1

TABLE 17. PARTICLE SIZE DISTRIBUTION WITHIN THE MAJOR HORIZONS OF THE FOUR PROFILES. (Expressed as per cent. of fine clay-free, organic matter free, acid insoluble, oven-dry soil.)

Fraction	Horizon	Orthic Black	Orthic Dark Grey	Dark Grey Wooded	Orthic Grey Wooded
Coarse Clay	Ah	9.4	9.8	-	-
	Ahe, Ae	-	12.2	6.8	6.2
	Bmt, Bt	11.3	10.0	19.6	11.1
	C1-1	10.2	12.5	9.7	12.9
Fine Silt	Ah	5.1	6.9	-	-
	Ahe, Ae	-	6.5	6.1	7.6
	Bmt, Bt	4.7	5.2	4.8	6.2
	C1-1	4.3	5.5	6.7	6.3
Medium Silt	Ah	12.8	21.8	-	-
	Ahe, Ae	-	20.6	18.7	24.9
	Bmt, Bt	13.4	14.4	12.7	16.1
	C1-1	13.2	13.3	14.6	16.0
Coarse Silt	Ah	12.8	19.2	-	-
	Ahe, Ae	-	17.1	14.7	17.2
	Bmt, Bt	13.0	13.0	10.7	11.4
	C1-1	13.5	14.0	11.3	11.4
Very Fine Sand	Ah	20.6	15.1	-	-
	Ahe, Ae	-	17.7	21.2	19.1
	Bmt, Bt	16.4	22.9	16.2	17.6
	C1-1	16.1	14.4	18.6	17.6
Fine Sand	Ah	18.6	11.9	-	-
	Ahe, Ae	-	12.4	14.6	10.5
	Bmt, Bt	19.6	15.9	14.3	16.4
	C1-1	19.9	17.9	17.1	15.4
Coarse & Medium Sand	Ah	20.7	15.3	-	-
	Ahe, Ae	-	13.5	17.9	14.7
	Bmt, Bt	21.7	18.6	21.7	19.7
	C1-1	22.7	22.4	22.0	20.5

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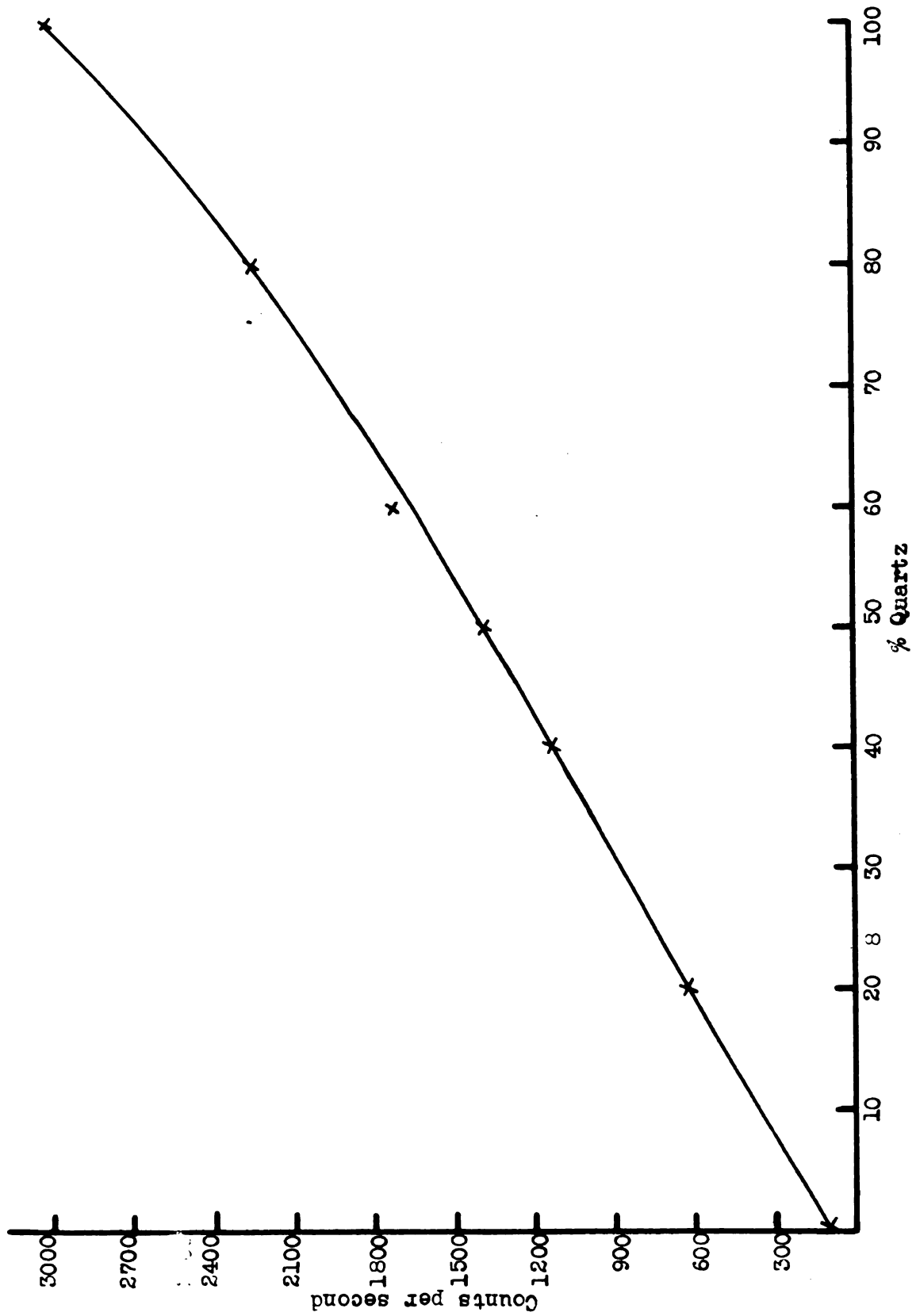


Figure 18. Relation of percent. quartz in standard mixtures to X-ray intensity of the 3.35 Å peak.

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