

A STUDY OF PEDOGENESIS IN THE ROCKY MOUNTAIN TRENCH REGION

OF SOUTH-EASTERN BRITISH COLUMBIA

by

FRANCIS CLIFT DARCEL

B. Sc. (Hons.), University of Reading, 1948

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE IN AGRICULTURE

in the Department

of

SOIL SCIENCE

We accept this thesis as conforming to the
required standard

THE UNIVERSITY OF BRITISH COLUMBIA

April, 1957

ABSTRACT

A study was undertaken of the pedogenesis of a Brown Wooded, a Grey Wooded and a Podzolized Grey Wooded soil developed over the highly calcareous Wycliffe till in the southern portion of the Rocky Mountain Trench, British Columbia.

The investigation was divided into three phases. These were a study of the till at the three sites, its genetic relationship to the solum and the relative degree of soil formation and weathering in the three profiles.

Analyses included mechanical analyses using the hydrometer and pipette procedures, plasticity measurements and soil reaction. Carbonates were measured by the gravimetric loss of carbon dioxide, exchangeable cations by ammonium acetate extraction and free iron by Mackenzie's dithionite technique.

Samples of the clay fraction were separated by sedimentation, cleaned of sesquioxide coatings by Mackenzie's method, and analyzed for total chemical composition. Piper's sodium carbonate fusion and Corey and Jackson's hydrofluoric acid procedure were used to bring the clay into solution. Ferron and Tiron reagents were used for the spectrophotometric analysis of iron and aluminum and iron and titanium, respectively. Silica was determined gravimetrically by Piper's method. Calcium and magnesium were found by the versenate technique of Cheng and Bray after the removal of interfering heavy metals with sodium diethyl thiocarbamate. Potassium was analyzed with a Perkin-Elmer flame photometer.

Other tests on the clay included determinations of the cation exchange capacity by Mackenzie's micro-Kjeldahl technique, X-ray diffraction patterns and dehydration curves.

A mineralogical study was made of the very fine sand fraction. A method was devised for counting the magnetite grains in samples of from 1,000 to 2,000 heavy minerals using a magnetized needle.

It was found that although there was considerable variation in the till at the three sites, particularly in mechanical composition, there were similarities in the mineralogical composition of the fine sand and clay fractions. Indeed, no satisfactory basis could be found for subdividing the till into two types.

Variations down the profile of the relative abundance and composition of the coarse fraction, the shape of the summation percentage curves and the proportion of magnetite in the heavy minerals of the very fine sand indicated that the Wycliffe profile was composite while the Kinbasket was an A-B-C profile. The possibility was also noted that the Yoho profile could also be composite.

The main soil formation processes were studied, including de-calcification and the movement of iron, organic matter, bases and clay. Results show that most soil development has taken place in Podzolized Grey Wooded profile, with somewhat less in the Grey Wooded soil and least in the Brown Wooded. Mineralogical studies of the very fine sand and clay fractions, however, indicate that there has not been appreciable weathering of the mineral constituents even in the intensely leached A_{2p} horizon of the Podzolized Grey Wooded Soil.

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the Head of my Department or by his representative. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of Soil Science

The University of British Columbia,
Vancouver 8, Canada.

Date April 17, 1957.

ACKNOWLEDGEMENT

This study was made possible by a grant from the Canadian Department of Agriculture during the summer of 1956. Particular acknowledgement is offered to Dr. C. A. Rowles, Professor and Chairman of the Department of Soil Science, The University of British Columbia, for suggesting the nature of the research, for assistance and encouragement during its progress, and for placing the facilities of the Department at the writer's disposal.

The helpful suggestions of Dr. J.C. Clark, Department of Soil Science, and members of the Soil Survey Division, Experimental Farms Service, are also gratefully acknowledged.

Especial thanks are due to members of the Department of Geology and Geography; in particular, Dr. R. M. Thompson for the X-ray analyses, Dr. W. H. Matthews and Dr. R. E. Delavault for assistance with the mineralogical study, and Miss C. A. Cross for the spectroscopic analyses. The writer would also like to express his gratitude to Dr. J. J. R. Campbell of the Department of Dairying for the use of the Beckman DU spectrophotometer.

TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	
<u>SECTION I - LITERATURE REVIEW</u>	1
I - DESCRIPTION OF SOILS	1
(1) CLIMATE AND VEGETATION	1
(2) GEOLOGY	2
(3) SOIL PROFILE DESCRIPTIONS	3
Wycliffe Series	4
Kinbasket Series	5
Yoho Series	6
II - CLASSIFICATION AND CHARACTERISTICS OF PODZOLIZED SOILS	7
(1) CLASSIFICATION	7
(2) BROWN WOODED SOILS	8
(3) GREY WOODED SOILS	10
(4) PODZOLIZED GREY WOODED SOILS	12
(5) INTER - RELATION OF SOILS	12
III - CRITERIA FOR ESTABLISHING THE ORIGIN OF GLACIAL SOILS	15
IV - PROFILE DEVELOPMENT AND DEGREE OF WEATHERING	15
(1) LEACHING OF CALCIUM CARBONATE	15
(2) MIGRATION OF IRON	16
(3) MOVEMENT OF BASES	17
(4) MOVEMENT OF ORGANIC MATTER	18
(5) ELUVIATION OF CLAY	19
(6) DEVELOPMENT OF STRUCTURE	20
(7) DEGREE OF WEATHERING IN SAND FRACTION	21
(8) DEGREE OF WEATHERING OF CLAY MINERALS	21
V - SOIL MINERAL WEATHERING IN NORTH AMERICA	24
<u>SECTION II - A DESCRIPTION AND DISCUSSION OF METHODS</u>	27
I - FINE SOIL	27
(1) MECHANICAL ANALYSES	27
(2) PLASTICITY	28
(3) ORGANIC MATTER	28
(4) OTHER PHYSICAL PROPERTIES	28
(5) SOIL REACTION	28
(6) CARBONATES	29
(7) EXCHANGEABLE BASES	30
(8) FREE IRON OXIDES	32

	<u>Page</u>
II - TOTAL CLAY	32
(1) TOTAL CHEMICAL ANALYSES	32
(2) CATION EXCHANGE CAPACITY	34
(3) X-RAY DIFFRACTION PATTERNS	34
(4) DEHYDRATION CURVES	35
III - MINERALOGICAL EXAMINATION	36
<u>SECTION III - RESULTS AND DISCUSSION</u>	37
I - THE NATURE AND COMPOSITION OF THE UNDERLYING TILL	37
(1) COARSE FRACTION	37
(2) SAND FRACTION	38
(3) CARBONATES	39
(4) CLAY FRACTION	40
(5) PHYSICAL PROPERTIES	41
(6) SURFACE ALTERATION OF THE TILL	41
II - GENETIC RELATIONSHIPS OF THE TILL AND SOLUM	43
III - SOIL MATURITY AND WEATHERING	46
(1) LEACHING OF CALCIUM CARBONATE	46
(2) MOVEMENT OF FREE IRON OXIDES	47
(3) DISTRIBUTION OF ORGANIC MATTER AND EXCHANGEABLE BASES	49
(4) ACCUMULATION OF SILT AND CLAY	50
(5) SOIL STRUCTURE	52
(6) WEATHERING OF SAND FRACTION	53
(7) WEATHERING OF CLAY	54
<u>SECTION IV - CONCLUSIONS</u>	56
APPENDIX I - ANALYSIS OF THE FINE SOIL FRACTION	
I - MECHANICAL COMPOSITION	57
II - SUMMATION PERCENTAGE CURVES	
III - PHYSICAL AND CHEMICAL PROPERTIES	58
APPENDIX II - ANALYSIS OF THE TOTAL CLAY	
I - CHEMICAL ANALYSIS	59
II - DEHYDRATION CURVES	
III - X-RAY DIFFRACTION PATTERNS 60, 61, 62, 63	
APPENDIX III - DISTRIBUTION OF MAGNETITE IN THE HEAVY MINERAL FRACTION	64
LITERATURE CITED	65-74

INTRODUCTION

Recent soil researches in the southern portion of the Rocky Mountain Trench region of British Columbia have shown the presence of soils with related but not completely understood genesis and properties (Lindsay, 1954; Kelley, 1955). Three of these soils, the Wycliffe, Kinbasket and Yoho series (Kelley, 1955, 1956), were selected for special study with a view to determining:

- (1) The similarity, or otherwise, of the till in the three profiles.
- (2) The relationship of the underlying till to the solum.
- (3) The relative stages of soil formation and weathering in the different horizons of the three profiles.

To provide answers to these questions samples were obtained from the three soils and used in a series of physical and chemical laboratory studies. These studies and their interpretation are the basis for this thesis.

LITERATURE REVIEW

I - DESCRIPTION OF SOILS

(1) CLIMATE AND VEGETATION

Meteorological data is available for Cranbrook and Golden and may be taken as indicative of the climatic environment of the Wycliffe and Yoho profiles, respectively. Intermediate values probably apply for the Kinbasket site.

Average annual rainfall figures for Cranbrook and Golden are 14 inches and 18 inches, respectively, and of these totals 4.0 inches and 4.5 inches fall in summer (Brink, 1948). The Precipitation Effectiveness Indices are 41 and 56 for these stations.

Average annual air temperatures are very similar, varying from 41°F. at Cranbrook to 39°F. at Golden with an average yearly maximum of 41° to 52° and minimum of 27° to 28°.

Figures for the number of frost-free days per annum at Cranbrook are variously given as 77 days (Connor, 1949) and 82 days (Brink, 1948) with an average of 148 days above 26°F. Golden has from 90 to 96 frost-free days; frequently, there is frost every month of the year.

There are a relatively large number of freezes and thaws per annum. Unpublished data collected by Dr. W. H. Mathews shows that the air temperature dropped below 28°F. and rose above 33°F.

Obviously, there have been changes in climate since the soils were deposited. Pollen studies in eastern Washington indicate a xerothermic stage about 6,000 years ago (Hansen, 1947, 1955); a less well defined warm-dry period also occurred farther north, even extending into southeast Alaska and the Yukon.

Douglas fir and lodgepole pine occur in relatively open stands in the three areas although the main species at the Wycliffe site was ponderosa pine. This species was much more abundant in the past throughout the area as shown by the prevalence of its pollen in peat bogs(Hansen, 1955).

(2) GEOLOGY

During the Wisconsin glaciation the main accumulation of ice in the area was in the western section of the Purcell and Selkirk ranges. A break-through of ice down the Spillimacheen Valley into the Trench fed a glacier 5,000 feet thick and 12 miles wide at the 49th parallel. On its retreat, Wycliffe till, sorted by melt-water, was uncovered (Kelley and Sprout, 1955). However, it is probable that some of the till was derived from source rocks farther north.

Schofield (1915) described the Wycliffe till as a greyish-white, strongly calcareous mixture of silt, grit, gravel, stones and boulders in varying amounts but with very little clay. The material was compressed and cemented when dry but soft when wet. The beds varied in thickness up to 50 feet.

If the till was derived from ice formed in the Purcell Range area material from the following geological formations can be expected in the till (Walker, 1926; Rice, 1936, 1937). The Purcell Series of Pre-Cambrian age consist chiefly of slates, shales, argillites, quartzite and a large proportion of variously coloured magnesium limestone. The Windermere series overlying the Purcell comprise quartzite and limestone shale conglomerate, multi-coloured shale and blue-grey crystalline or semi-crystalline grey magnesium limestone, together with successions of calcareous shales and argillaceous limestone, and

grade upwards into blue-grey limestone.

These rocks under-lie black shale and interbedded mud rock and bluish limestone and argillaceous sandstone of the Glenogle shale and the crystalline magnesium limestone of the Beaverfoot-Brisco formation.

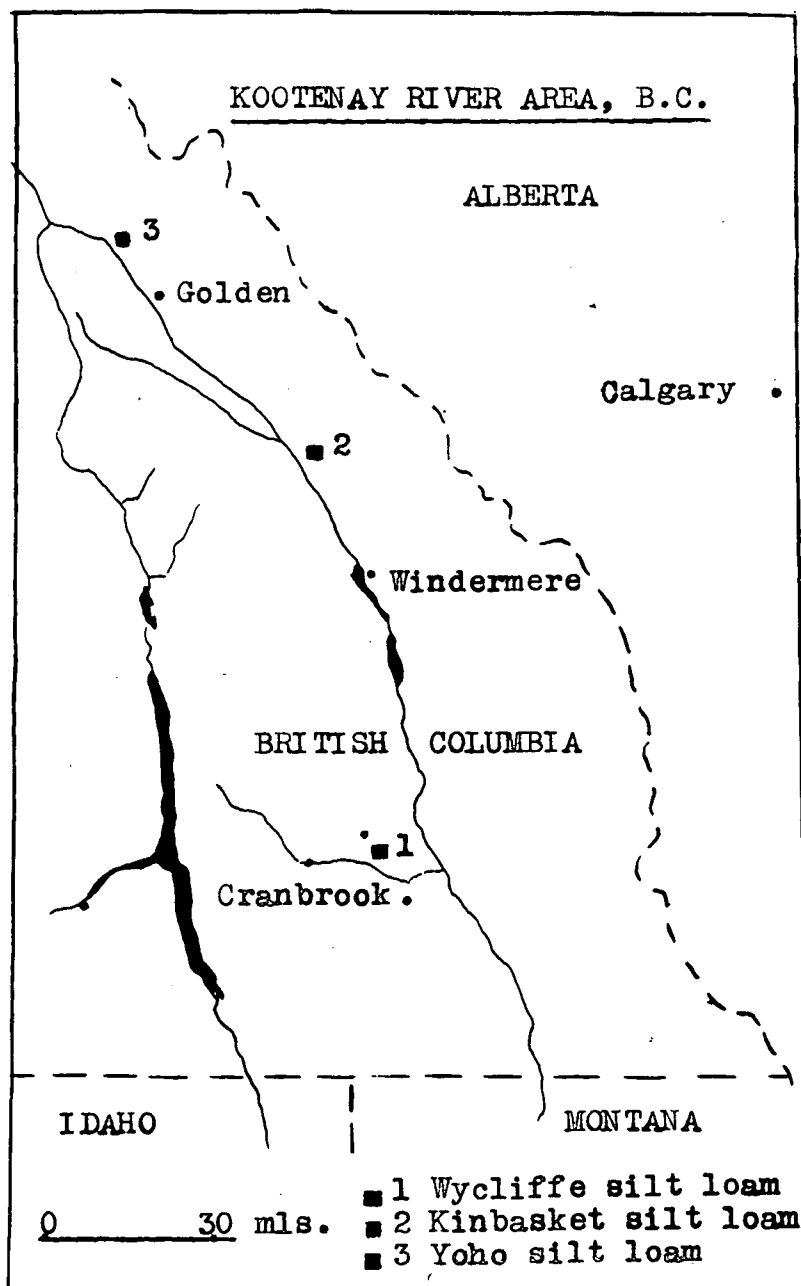
Also of interest are the Mesozoic granite stocks of Horsethief Creek in the Purcells. Intrusions caused contact metamorphism with the formation of quartz mica schists and chlorite.

Rocks of these types were subjected to varying degrees of mechanical degradation during transportation.

The Wycliffe and Kinbasket series are believed to have developed over the Wycliffe till (Kelley, 1955). The Yoho series (then called the Flatbow) was also thought to have developed on the same parent material although recently (Kelley, 1956) the series was related to Cedrus till, derived largely from the Ordovician McKay formation, a relatively thick series of fossiliferous limestone and shale strata. Kelley described this material as soft, whitish calcareous silt to silty clay shale.

(3) SOIL PROFILE DESCRIPTIONS

The Wycliffe, Kinbasket and Yoho series were selected as representatives of the Brown Wooded, Grey Wooded and Podzolized Grey Wooded soil groups developed over similar material. The location of the three sites is shown on the following map.



Wycliffe Silt Loam

The Wycliffe series occurs chiefly along the west side of the Rocky Mountain Trench between Canal Flats and Forster Creek (Kelley, 1956); to the north, the series grades into the Kinbasket series.

The soil profile under study was sited about one mile south-east of Kimberly airport, near Cranbrook. The main features of the field description (McKeague, 1955) are given below.

Horizon	Depth (ins.)	Description
A ₀ ★	$\frac{1}{2}$ - 0	Organic horizon - mull.
A ₂ ★	$\frac{1}{2}$ - 3	Light yellow brown silt loam. No stones.
B ₂	3 - $6\frac{1}{2}$	Light yellow brown silt loam. No stones.
B ₃	$6\frac{1}{2}$ - 10	Pale brown silt loam; soft; granular.
B ₄	10 - 14	Light grey silt loam; hard, light grey nodules; some stones. Weakly blocky.
D ₁	14 - 19	White loam; stony till. Dead root mat.
D	19 +	White, weakly cemented, stony till.

★ These horizons are better designated as the A₁₁ and A₁₂ horizons.

NOTE: The designations A₁₁ and A₁₂ are more satisfactory because soil forming processes are at a minimum in this profile.

Kinbasket Silt Loam

The profile under study was sited two miles north of North Vermilion Creek, about one mile off the highway between Edgewater and Brisco, on a gently sloping "bench". The soil horizons were as follows:

Horizon	Depth (ins.)	Description
A ₀	1 - 0	Partly decomposed needles, twigs, etc. (mor).
A ₂₁	0 - 3½	Pinkish - grey (dry), light yellowish brown (moist), soft silt loam. Strongly platy.
A ₂₂	3½ - 7½	Similar; friable crumb structure
B ₂₁	7½ - 9½	Pale brown (dry), brown (wet) clay loam. Fairly hard, moderately blocky.
B ₂₂	9½ - 11½	Light yellowish brown (dry), brown (wet) clay loam. Hard; angular blocky.
C ₁	18 - 27	Light grey (dry), pale olive (wet) silt loam. Compact; hard. Dead root mat.
C ₂	27 +	White (dry), pale olive (wet) silt loam. Weakly cemented; very hard.

Yoho Silt Loam

The Yoho series occurs only in the northern reaches of the Rocky Mountain Trench on undulating to steeply rolling morainal topography. The profile was located about 15 miles north of Golden, sampled and described by T. G. Arscott (1956).

Horizon	Depth (ins.)	Description
A ₀	4 - 0	Partly decomposed organic layer (mor).
A _{2p}	0 - 2 $\frac{1}{2}$	White to light (dry) grey sandy loam. Single grain.
B _{21p}	2 $\frac{1}{2}$ - 7 $\frac{1}{2}$	Strong brown (dry) loam. Weak crumb structure.
B _{22p}	7 $\frac{1}{2}$ - 11 $\frac{1}{2}$	Yellowish red to reddish yellow silty clay loam.
A _{2gw}	11 $\frac{1}{2}$ - 15	Light yellowish brown (dry) silt loam to silty clay loam. Medium sub-angular blocky.
B _{2gw}	15 - 20	Light olive brown (dry) clay. Medium to large sub-angular blocky.
C _{gw}	20 +	Light olive brown (dry) clay loam till.
C		Stony till.

II CLASSIFICATION AND CHARACTERISTICS OF PODZOLIZED SOILS

(1) CLASSIFICATION

Originally, the criterium for podzolization in soils was the presence of an ash-coloured layer in the profile (Aarnio, 1915). Later, the term was broadened to include profiles with a lighter coloured A_2 horizon underlain by a B horizon of darker and/or stronger colour. (Hallsworth, Costin and Gibbons, 1953).

Joffe (1949) stated that the B horizon is characterized by a relatively low silica content, high sesquioxides, and an increase in base content relative to the A_2 horizon; i.e. the eluviation of bases and iron and aluminum compounds. The clay and organic matter contents of the B are also high relative to the A horizon and there is usually more structure development.

The National Soil Survey Committee of Canada (1955) classified soils showing varying degrees of podzolization as follows:

CATEGORY V - Class 3 (Podzolic soils).

1. Grey-brown Podzolic
2. Grey-wooded.
3. Humus podzols.
4. Podzols (orstein).
5. Podzols (orterde).

CATEGORY IV - These major divisions were subdivided again in Category III into the modal soil and various intergrades.

The separation of the "podzolic" soils into Grey-brown Podzolic and Grey-wooded soils depends mainly on the nature of the surface horizon (A_1 - mull or A_0 - mor). They are alike in that clay accumulation is the dominant process in the B.

The Forested Brown soils (Class 4) are also of interest in this study. They are characterized by an A_1 or A_0 and a colour and/or structure B horizon but lack a distinct eluvial A_2 horizon. The major soil-forming processes are variable; the upper horizons are weathered but there is no translocation of sesquioxides, organic matter or clay. Indeed, decalcification is the dominant process.

The class is sub-divided as shown below:

Calcareous parent material

1. Brown Forest - mull A_1
2. Brown-wooded - A_0 ; A_1 very thin or absent.

Non-calcareous parent material

3. Brown Podzolic
4. Shotty Brown

(2) BROWN WOODED SOILS

Krusekopf (1925) regarded the "brown" soils of the North Central States as a regional soil belt between the grey forest and podzol soils to the north and the yellow and grey soils to the south. Tyulin (1930) described them as "concealed podzols" with very little movement of sesquioxides and no translocation of clay.

Ramann (1928) discussed the distribution of "brown earths" in relation to climate. He stressed the influence of the parent rock on the soil properties and stated that the lack of readily dispersed humus bodies was due to the alkaline reaction of the soil. The ascent of ground waters during dry periods was also shown to be a possible factor in the genesis of the brown earths.

Tamm (1930) associated the brown earths of Sweden with beech forest and attributed them to the relatively high calcium oxide content of the ash of this tree (2.46%) compared with the much lower content for pine (.59%). Tamm differentiated the climatic type developed on soils poor in lime and the acclimatic type on parent rock high in calcium. This latter type corresponds with the Brown Forest Brown-wooded soil groups. There was no general tendency to podzolization; rather the reverse (Tamm, 1932).

Lundblad (1934) compared the changes in reaction, loss on ignition, and acid-oxalate extracted silica, iron and manganese down the profile of the Brown Earths and the podzol. In later work (1936), he studied the distribution of sesquioxides, base exchange values, iso-electric point, ultimate pH, exchange acidity and dye adsorption.

Profile characteristics believed to characterize the Brown-wooded soil group are the leaching of free lime to 6 inches and Tyulin's original criteria of no eluviation of clay or sesquioxide.

Other profile features are a thick granular A₁, little or no A₂ and a strong structural B.

Leahey (1953) described a Brown-wooded soil in the Hay district of Alberta at latitude 60° N. developed on silty clay alluvium. Free lime was leached to 9 inches and there was some loss of organic matter. In the profile examined by Lindsay (1954) over silty clay loam, carbonate had leached to 6 inches and there was slight B development (colour and consistence). There was also some translocation of organic matter with 2.88 per cent in the A and 1.76 per cent in the B horizon. Some movement of clay was also indicated as there was a 7 per cent increase between the A₂ and the B but this was somewhat offset by the fact that the A₂ was only 1 inch thick.

The main area of occurrence of Brown-wooded soils in British Columbia is in the northern part of the Rocky Mountain Trench with some in the southern portion of the Kootenay River Valley. In all, there are about 5,170,000 acres in British Columbia (Rowles, Farstad and Laird, 1956). The soils occur under considerable variations of climate and under a vegetation of white and black spruce, lodgepole pine, aspen, willow and birch.

Rowles, Farstad and Laird (1956) in British Columbia described the B₂ as a yellow-brown to brown mineral horizon, slightly acid to strongly alkaline (pH 5.5 - 8.0), rarely over 14 inches thick. The group is considered immature in British Columbia because it always occurs on calcareous parent material.

(3) GREY WOODED SOILS

Wyatt and Newton's paper (1928) is one of the earliest on what are now known as Grey-wooded soils. Soils of this type were described by them as "podzol-like". Joffe (1937) described this group as it occurred in New Jersey. Thorp and Smith (1949) defined the characteristics of the group. They were shown to be well developed, well drained soils with moderately thin A₀ horizons over bleached A₂ and brown, more clayey, blocky or nuciform B horizons, grading into lighter coloured more friable B₃ and C horizons.

The A₂ is 4 inches to 16 inches thick in some parts of Alberta and Montana (Williams and Bowser, 1952); indeed, it seems to be twice as thick as the A₂ of the podzol. The structure of the A₂ is usually platy (Williams and Bowser, 1952).

These workers also pointed out that the B₂ horizon has more clay than either the A or C horizons and has moderately to strongly developed

blocky structure. They also noted the frequent occurrence of a lime horizon in the C horizon with neutral to slightly acid soil above.

The group has been correlated with Stebutt's grey forest soils of Russia and they seem to be very similar to the "podzols" of Glinka and de Sigmond.

Stobbe and Leahey (1947) pointed out the widespread distribution of the Grey-wooded soils across the prairies, Central British Columbia and the clay belt of Northern Ontario.

Ellis (1938) described the group in Northwest Manitoba; Leahey (1946) in the North West Territories; Odynsky and Newton (1950) in Alberta and Kelley and Farstad (1946); Grey-wooded soils in British Columbia.

Recent studies include the work of Holt and McMillar (1956) in Minnesota; Wilde, Voight and Pierce (1954) in the Algoma District of Alberta, and Moss and St. Arnauld (1955) on similar soils in Saskatchewan.

Podzolization is believed to be the dominant process in spite of the development of Grey-wooded soils on highly calcareous parent material (Moss, 1930; Farstad and Leahey, 1949). There is free carbonate in the solum, basic reaction and a slight unsaturation of the base exchange (Moss, 1938). Wilde, Voight and Pierce (1954) attributed podzolization to fungal activity rather than the leachate from the near-neutral leaf litter. Evidence of clay eluviation was noted by Leahey. Lindsay (1954) found a relatively high clay content in the B₂₂ of the Kinbasket series. However, it seems that the leaching of iron and aluminum is considerably more extensive than the eluviation of clay in spite of the upper horizon frequently being alkaline (Nygard,

McMillar and Holt, 1952; Gallagher and Walsh, 1942). Silica also seems to be leached.

Other features noted by Moss and St. Arnauld were the accumulation of silt in the A horizon and nitrogen in the B.

The strong structural development in the B has been noted. One theory of its formation is that penetrating roots cause the loss of calcium carbonate; the subsequent reduction in volume contributes to the development of nutty structure (Wilde et al., 1954).

(4) PODZOLIZED GREY - WOODED SOILS

Nygard et al. (1952) described Podzolized Grey-wooded soils in North Minnesota, Odynsky and Newton (1950) in Alberta, and Farstad and Laird (1954) in British Columbia.

In British Columbia Podzolized Grey-wooded soils occur chiefly along the Hart Highway from Parsnip River to Prince George, along some river valleys in the Peace River area and in the Rocky Mountain Trench as far south as Golden (Rowles, Farstad and Laird, 1956).

In the typical profile there is a thick A_0 of undecomposed organic matter and a highly leached, light grey, strongly acid A_2 above a thick strong brown B_2 with an accumulation of iron and organic matter. This horizon grades below through a greyish, slightly acid horizon into a brown secondary B of clay and sesquioxide accumulation above highly calcareous parent material. The soil is usually associated with sandy and gravelly deposits.

(5) INTER - RELATION OF SOILS

Cline (1949) showed evidence of a continuous geographic sequence of

Brown Wooded, Grey Wooded, Grey Wooded Brown Podzolic intergrade, Podzolized Grey Wooded and Podzol on calcareous parent material.

Williams and Bowser (1952) stated that the Grey Wooded soils of Montana and parts of Alberta graded into Degraded Chernozem on one side and Brown Podzolic on the other. Holt and McMillar (1956) identified a series of Podzol, Brown Podzolic, Grey Brown Podzolic and Grey Wooded soils on glacial drift. Moss and St. Arnauld (1955) stated that of the soil groups, the Grey Brown Podzolic was most similar to the Grey Wooded.

Kelley (1956), following up the work of Lindsay (1954), suggested the following sequence for soils developed over calcareous parent material in the Rocky Mountain Trench: Dark Brown soils under stunted grass in the most arid areas; Brown Wooded soils under Ponderosa pine and grass with slightly more rainfall; Grey Wooded soils and then Podzols under increasingly heavier rainfall. Indeed, he regarded the Brown Wooded soil as a weakly developed Grey Wooded profile.

In the Brown Wooded and Grey Wooded soils examined by Leahey in Alberta, free lime was leached to 9 inches in the Brown Wooded compared with 14 inches in the Grey Wooded. The B_{Ca} horizon lies at usually 24 inches to 40 inches in the Rocky Mountain Trench (Farstad and Leahey, 1949).

Per cent base saturation is highest in the Brown Wooded and lowest in Podzolized Grey Wooded (Lindsay, 1954).

There is least movement of silica in the Brown Wooded (Lindsay, 1954). The widest spread in silica content is between the A_2 and B_2 of the Podzolized Grey Wooded and it is in this soil group that there is the maximum movement of clay.

III - CRITERIA FOR ESTABLISHING THE ORIGIN OF GLACIAL SOILS

Boulders and stones can be moved great distances by glacial action; during transport they are subjected to varying degrees of abrasion, often with the formation of relatively flat surfaces and sharp angles (Flint, 1947). Softer rocks such as shale, limestone and dolomite, are broken down by abrasion more rapidly than chert, which is a relatively hard rock. A study of the coarse fraction, therefore, may indicate the source of the material and the method of transport.

The comparative study of the mineral composition of the fine or very fine sand appears to be the most satisfactory method for establishing the source of different parent materials (Smithson, 1953; Smithson, 1956). The usual procedure is to separate out the heavy minerals with bromoform or tetrabromethane (Twenhofel and Tyler, 1941; Jeffries and Jackson, 1949) and determine the proportion of accessory minerals relatively resistant to weathering such as zircon, garnet, tourmaline and rutile (Jeffries and Jackson, 1947). Magnetite is also relatively resistant. It is a common accessory mineral in igneous rocks and metamorphic limestones and has the advantage that it can be separated magnetically (Duchaufour, 1955). Again, its formation as an oxidation product in the zone of weathering is known to be rare (Palache, Berman and Frondel, 1944).

Another line of approach, particularly with parent materials low in heavy minerals, is a study of the silica particles (Smithson, 1956).

The examination of the clay fraction can also help to establish the origin of glacial material in Canada since it has been shown that the clay minerals have remained almost unaltered since deposition (Ehrlich and Rice, 1955). As an example, the predominance of illitic type clay minerals could indicate that the clay fraction was formed by the mechanical

abrasion of limestone and shale; these rocks are relatively easily broken down and usually have a high illite content (Robbins and Keller, 1952; Grim, 1953; Keller, 1956; Nelson, 1956).

Similar methods can be used to determine the relationship of the solum to the underlying material. Marked dissimilarity in the relative abundance of stones and differences in summation percentage curves and heavy mineral content have been suggested as useful criteria for depositional differences. Marshall (1940) suggested, as tests for the absence of depositional variation, that the relative proportion of highly resistant minerals should be the same throughout the profile and, similarly, that there should be no changes with depth in the particle size distribution of a given resistant mineral. The weathering out of the less resistant minerals, however, influences the distribution of heavy minerals down the profile (Jeffries and Jackson, 1949).

Heavy mineral studies were used by Carroll (1944) for recognizing the parentage of some Australian soils.

IV - PROFILE DEVELOPMENT AND DEGREE OF WEATHERING

(1) LEACHING OF CALCIUM CARBONATE

The leaching of calcium carbonate is one of the first pedogenic processes (Jackson, Hseung et al., 1952). Dolomite, if present, is also leached although at a somewhat slower rate because of its lower solubility in water, especially in soil water with dissolved carbon dioxide (Chillingar, 1956). The solution/^{rate}of carbonates is also a function of particle size; hence, it can be expected that particles in the clay fraction will be leached first while carbonates in the coarse skeleton will survive until a later stage of weathering.

The carbonates taken into solution are often deposited lower in the

profile in a B_{Ca} horizon. This is particularly evident in Grey-wooded soils and to a less marked extent in Brown-wooded (Lindsay, 1954).

The depth of leaching of carbonates is of interest but, because of its wide variability from one site to the next, it is probably of little significance.

It has already been mentioned that decalcification is believed to be the dominant process in the Brown-wooded soils. In the Grey-wooded soils, however, the solum has been leached free of carbonates except for the B_{Ca} accumulation zone.

(2) MIGRATION OF IRON

The migration of iron has been the subject of considerable research, particularly the mechanisms responsible for its movement. A series of papers have been published recently by Bloomfield on the part played by water extracts of fallen leaves on the reduction and solution of iron (Bloomfield, 1953, 1954, 1955, 1956) and similar studies have been conducted by McGill workers (Lutwick, Coldwell and DeLong, 1952; DeLong and Schnitzer, 1955; Schnitzer and DeLong, 1955).

The sesquioxide content has been used to indicate the degree of leaching; Joffe (1949) suggested the use of the silica-sesquioxide ratio of the A_2 horizon as an index of weathering. Sesquioxides tend to accumulate in the B horizon during soil formation, especially iron compounds and sometimes aluminum. However, alumina is known to occur only in minor amounts in the soils under study and so will not be considered further.

Although the movement of iron is generally down the profile it may also segregate out in the form of concretions and nodules in both the A and B horizons, often in association with varying amounts of organic matter and manganese (Winters, 1938; Joffe, 1949). In podzol profiles such concretionary forms usually occur in the bottom of the A_2 horizon

and the top of the B.

The content of free iron oxides down the profile is of more significance than the total iron content. It has been shown in studies with podzol soils that the free iron is often over 50 per cent of the total iron content and that the ratio of free to total iron decreases with depth (Coppenet and Helias, 1956). Possibly of significance were the observations of Swenson and Riecken (1955) that free iron tended to accumulate in the $<20 \mu$ fraction in the A and upper B horizons and that movement of iron into the clay lattice was most pronounced in the B horizon, particularly in the very fine clay fraction ($<0.2 \mu$).

Also of interest is the free iron oxide in close association with the clay particles. Jackson, Tyler et al., (1948) suggested that hematite monolayers form as a result of weathering but it is also possible that the iron coatings may be formed by the migration of iron towards the clay fraction. Another possibility is that iron oxides may form part of the clay fraction themselves (Martin, Torrence and Bushnell, 1952).

Research has also been directed towards improved techniques for extracting the free iron with the minimum attack of soil minerals. Methods which have proved most successful make use of sodium thiosulphite as a reducing agent for the iron (Aguilera and Jackson, 1953; MacKenzie, 1954; Stace 1956).

(3) MOVEMENT OF BASES

The leaching of bases from the solum and their replacement by hydrogen ion is a normal process in soil development. In the presence of calcium carbonate and dolomite leaching will be almost completely restricted to calcium and magnesium ions and the soil colloids will remain 100 per cent base saturated. This state is indicated by a neutral or

slightly alkaline soil reaction (Yaalon, 1955).

Hydrogen ions, therefore, will only enter the exchange complex when most of the carbonates have been leached. Calcium, magnesium and potassium from the clay minerals then enter exchange reactions and are continuously replaced by hydrogen with the resultant degradation of the clay minerals (Jackson, Hseung et al., 1952). At the same time, soil minerals in the silt and sand fractions are also broken down, once the protecting effect of calcium carbonate is removed (Yaalon, 1955), with the release of bases into the soil solution.

Some indication of the release of bases can be obtained from an interpretation of the exchangeable cations although these figures are almost meaningless in the presence of free calcium carbonate. Acid reaction values indicate the replacement of bases by hydrogen ions.

(4) MOVEMENT OF ORGANIC MATTER

The movement of organic matter down the profile has been shown by numerous workers to be a normal pedogenic process (Joffe, 1949).

The literature on soil organic matter is expanding rapidly and the reader is referred to the review by Bremner (1956). Recent research of possible significance in relation to its movement during podzolization is that of Ambrozha (1955) who found that the fulvic acid fraction of humus predominated over the humic acid fraction in podzol soils and that there was more "mobile" than "bound" humus. This might be related to Kononova's finding (Kononova, 1956) that humic acids were only slightly condensed in podzol soils compared with a high degree of condensation in chernozem soils.

The properties of the surface organic matter, either mull or mor, might well be examined in relation to profile development. Indeed, the

presence of mull or mor is the main distinguishing criterion of the Brown Forest and Brown-wooded soils (National Soil Survey Committee, 1955). However, it appears from the recent work of Handley (1954), that the conditions under which mull or mor form are not clearly defined. Both forms can occur over calcareous rocks and both types can be present under the same climatic conditions; again, there seems to be a ready interchangeability with change of vegetation. Handley suggested that the main differences between the formation of the two types were that in mor tannin-like substances protected the more resistant mesophyl whereas mull consisted of relatively stabilized protein.

(5) ELUVIATION OF CLAY

Clay may accumulate in the B horizon as a result of its eluviation from the A horizon or from its formation in situ by weathering, or by a combination of both processes (Joffe, 1949). Studies of mineral weathering (Ehrlich and Rice, 1955) minimize the second possibly, at least in some Canadian soils.

Adams and Matelski (1955) noted evidence of eluviation of clay. Its migration has been demonstrated by its optical orientation after deposition (Brewer, 1956). Strong orientation was noted in soils with few but relatively large channels, possibly under somewhat similar conditions to the Grey-wooded B horizon.

Tamm (1950) has shown that the deposition of colloids first takes place deep in the profile and that the B horizon builds upwards. Continued deposition was attributed partly to reduction of permeability.

(6) DEVELOPMENT OF STRUCTURE

No clearly defined relationship can be seen between the degree of structure development of the various horizons in a soil profile and the maturity of the soil. This is possibly because several factors contribute to the genesis of soil structure including biotic factors, organic matter, clay, free iron oxides and the content of bases. The literature in this field is extensive (Frei, 1950).

It is felt, however, that if the factors responsible for the development of soil structure are similar in two related soils then differences in degree of development should reflect a difference in maturity. This might account for the relatively weakly developed structure in Brown-wooded soils compared with strong structural development in Grey-wooded soils (Lindsay, 1954).

(7) DEGREE OF WEATHERING IN SAND FRACTION

The degree of weathering has been related to the relative proportion of resistant heavy minerals (Marshall, 1940; Jeffries and Jackson, 1949). Smithson's stability series (Smithson, 1950) is of interest in this respect. Graham (1953) related the degree of weathering in some Australian soils to the presence or absence of gibbsite, and amount of ferromagnesiums and ferrocalciums and the percentage of feldspar. Hornblende, augite, epidote and chlorite and other relatively easily weathered minerals were shown to be present under conditions of moderate to low weathering.

Adams and Matelski (1955) studied the distribution of heavy minerals in the sand and silt fractions in the Scott silt loam in Nebraska. Of particular interest was the finding that there was a considerable difference in the proportions of various minerals, such as hornblende and zircon, in the very fine sand and silt fractions. Indeed, there were from two to three times more amphiboles in the very fine sand than in the silt. The distribution of zircon was different with the largest percentage in the coarse silt. This work emphasizes the necessity of using the same size grade and, if possible, studying several size fractions.

(8) DEGREE OF WEATHERING OF CLAY MINERALS

Clay mineral studies can also be used to help elucidate the degree of soil weathering. Total chemical analyses are of some value, particularly in relation to chemical alteration within the clay fraction. However, the use of such analysis is limited owing to the wide variation in chemical composition of the clay minerals and also because the clay fraction contains more than one mineral species in variable amounts.

Indeed, clay size particles of other minerals such as quartz, sesquioxides and calcite, can occur in appreciable proportions (Martin, Torrence and Bushnell, 1952).

The presence of minerals other than true clay minerals in the clay fraction is worthy of further mention. Quartz seems to be of almost general occurrence in the clay fraction although usually in minor amounts. Martin, Torrence and Bushnell (1952) found less than 10 per cent of quartz in the coarse clay fraction ($2\mu - 1\mu$) of some Southern New York soils although it did not occur in the fine clay; similarly, the quartz content of the fine clay was low in soils examined by Coleman and Jackson (1946) and Coleman, Jackson and Mehlich (1950). These findings are in accord with the suggestion of Jackson, Hseung et al. (1952) that quartz weathers more rapidly than the clay minerals and that its rate of solution is a function of particle size; hence it is more likely to occur in the coarse clay and silt fractions. This point is considered later in relation to the weathering of illite.

Calcite will also occur in the clay fraction of calcareous soils and in the B_{Ca} horizons of solums otherwise leached free of carbonates. Normally, it is removed by acid treatment prior to mineralogical examination of the clay fraction.

Hematite was described as abundant in the clay fraction of soils in the Western United States (Coleman, Jackson and Mehlich, 1950). This mineral was particularly concentrated in the fine clay with less in the coarse fraction. A similar distribution was noted for gibbsite. Martin, Torrence and Bushnell (1952) made similar observations, providing further evidence for Jackson and Hseung's hypothesis that hematite and gibbsite are very resistant to weathering.

Since an illitic type clay mineral was found to predominate in the

clay fraction of the soils under study it is thought relative to discuss findings on the structure and weathering of the illite clays in some detail.

The structure of illite clay minerals was recently investigated by Bell (1952). It was suggested that the mica-like minerals were formed by the incomplete extraction of alkalis from the micas leaving the original structure unchanged. The illites in general have less potassium and more water than mica and there is only half as much substitution of aluminium for silicon by isomorphous replacement. Magnesium and iron can substitute for aluminum in octahedral co-ordination. The charge deficiency is balanced by potassium ions fitting in holes in adjacent hexagonal siloxane layers (Grim, 1953).

Chemical analyses of illite minerals have been published by Grim, Lamarand, Bradley (1937), Grim and Rowland (1941), MacKenzie et al. (1947).

Jackson, Hseung and collaborators (1952) investigated the chemical weathering of the mica-like clay minerals. The main findings were a decrease in intensity and a broadened angle of basal reflection, the appearance of basal spacings intermediate between 10 \AA° and 18 \AA° , an increase in internal surface, less potassium but more water and/or hydroxyl than theoretical and lower cation exchange values.

The first finding was explained by a decreased number of OOL diffracting planes of 10 \AA° spacing. The intermediate spacings have been interpreted as "mixed" lattices (Pauling, 1930), partial expansion of the lattice (Jackson and Hellman, 1942) and interstratification (Nagelschmidt, 1944). Alternating illite and montmorillonite spacings may also be responsible (Jackson and Hellman, 1942).

The theory was advanced that the micas weather along preferential weathering planes and that alternate interplanes weather more easily than the remaining interplanes, possibly as a result of the pairing of

dioctahedral layers.

Potassium is released from the preferential weathering planes, the driving force being the entrance of water and cations such as the hydrogen ion and, according to Barshad (1948), the hydrated calcium and magnesium ions. Loss of potash may also be favoured by the oxidation of ferrous to ferric with the consequent reduction in the negative charge.

Other weathering reactions are believed to be hydroxylation with the replacement of the potassium by hydrogen, de-alumination and de-silication (Jackson, Hseung *et al.*, 1952).

However, illite and muscovite are thought to be relatively stable although not as stable as kaolinite and montmorillonite. They occur in Stage 7 of Jackson's weathering sequence (Jackson, Tyler *et al.*, 1948); i.e., they are more stable than the feldspars and even quartz. As evidence that illite follows quartz it was stated that mica persists in increasing ratio to quartz as the particle size decreases. This stability was attributed to the layer of aluminum ions beneath the silicon ions in the silica sheet. Lattice factors were said to be more important than specific surface in relation to stability after Stage 7 in the weathering sequence.

V - SOIL MINERAL WEATHERING IN NORTH AMERICA

Research in the United States has provided considerable evidence for weathering in the soil profile. Nikiforoff and Drosdoff (1943) found strong decomposition of minerals such as biotite, orthoclase, albite and the amphiboles in the silt of both the B and the A₂ horizons of the Dayton silt loam of California. Similarly, in the Scott silt loam of Nebraska, Adams and Matelski (1955) found indications of weathering to the B₃ at 76 inches with the most intense weathering in the lower A₂ and the upper B₂ (15 to 34 inches depth). The heavy mineral distribution showed

that the coarse silt fraction was more weathered than the very fine sand.

Both investigations also showed that there was appreciable alteration in the clay fraction. Nikiforoff and Drosdoff propounded that much of the clay was broken down in the A₂ and that there was an accumulation of secondary clay in the B horizon, largely through the decomposition of silt in situ. Adams and Matelski also suggested that clay was formed in the B although there was also considerable evidence of eluviation.

An indication of intense weathering in the podzol A₂ was Tedrow's finding that the clay content of this horizon was higher in quartz than the B and C horizons (Tedrow, 1954).

Some recent findings on the weathering of clay derived from Late Wisconsin till are of interest. Murray and Leininger (1956) in Indiana found that montmorillonite type minerals were dominant in the weathered soil although the relatively unweathered till contained largely illite and chlorite. Important factors were believed to be the oxidation of iron in the lattice and the leaching of magnesium and potassium. Similarly, Whittig and Jackson (1956), working with a Brown Podzolic and a Brown Forest soil in Wisconsin, found that illite and chlorite had weathered to vermiculite and montmorillonite near the surface. Indeed, in the Brown Forest profile, the montmorillonite content in the fine clay increased from 5 per cent in the C to 44 per cent in the A₁ with a corresponding decrease in chlorite from 11 per cent to almost nil. Similarly, Tamura (1956) found a statistical correlation between the change in apparent diffraction spacings as a result of weathering and sample depth for randomly interstratified vermiculite and illite in Connecticut.

However, there appears to have been very little weathering of soils in Canada. Ehrlich and Rice (1955) and Ehrlich, Rice and Ellis (1957) noted the relative uniform distribution of montmorillonite and illite down

the profiles of podzolized soils in Manitoba and concluded that these clay minerals were virtually unchanged since the time of deposition during glaciation. Even in the A₂ of a podzol, weathering was negligible in both the sand and clay fractions (Ehrlich, Chapman and Rice, 1957).

The low degree of mineral weathering in Canadian soils can be attributed to several factors. Some of these factors were pointed out by Ehrlich and Rice (1955). Perhaps the most important is the time factor; soil weathering processes have only been in effect since the time of glaciation some 11,000 years ago (Antevs, 1945; Flint, 1947). Again, a relatively cool dry climate and prolonged periods of freezing tend to inhibit soil weathering agencies. The climate might have been even drier, although perhaps warmer, during the xerothermic period following glaciation, as suggested by Hansen (1955). Another important factor is the presence of calcium carbonate, since Yaalon (1955) has shown that there can be practically no weathering of clay minerals until all the carbonates have been leached.

SECTION II

A DESCRIPTION AND DISCUSSION OF METHODS

The location of the sampling sites and the more important field characteristics of the three profiles have already been described.

For the laboratory study of these soils, samples were collected from each horizon. Each sample was thoroughly mixed by shaking in a large cylindrical container prior to sieving through 5 mm and 2 mm sieves. The coarse fraction held on the 2 mm sieve and the fine soil passing through this sieve were examined separately. The very fine sand (250 - 300 mesh) and total clay fractions (2 mm) were separated from the fine soil fraction for further study.

The study of the coarse fraction was restricted to its determination by weight as a percentage of the total soil and the identification of the rocks by visual inspection and the use of hydrochloric acid for distinguishing limestone and dolomite. A number of tests were conducted on the fine soil and total clay as well as a mineralogical study of the very fine sand. These tests are described below with some discussion as to their significance where necessary.

I - FINE SOIL

(1) MECHANICAL ANALYSIS

Well mixed samples of 2 mm sieved material were used for mechanical analysis using a hydrometer calibrated by Day's method (Day, 1950) for the Wycliffe and Kinbasket profiles and the pipette method of Kilmer and Alexander (1949) for the Yoho soil since much less material was available. Preliminary treatment with 6 per cent hydrogen peroxide and 2 N hydrochloric acid was used to remove organic matter, carbonates and at least some of the sesquioxides. The clay fraction was retained

for further study.

The sand fraction was collected on a 300 mesh sieve and subsequently separated into size grades using a nest of sieves with openings of 0.5 mm, 80 mesh, 150 mesh and 250 mesh. These fractions were weighed and the results used with the data obtained from the hydrometer and pipette analyses for the construction of summation percentage (accumulation) curves.

The sand separates were examined with a microscope and the very fine sand fraction (250 mesh) set aside for mineralogical study.

(2) PLASTICITY

Plasticity measurements of the upper and lower plastic limits were made by the standard A.S.T.M. procedure (A.S.T.M., 1950). Values for the upper liquid limit and the plasticity index were plotted in relation to Casagrande's "line A" (Casagrande, 1947; Burmister, 1950; U. S. Army, 1953) for the interpretation of the plastic properties.

(3) ORGANIC MATTER

Organic matter was determined by the modification of Walkley's rapid method (1947) as described in the Salinity Handbook.

(4) OTHER PHYSICAL PROPERTIES

Physical properties such as apparent and real specific gravities and tension table, porous plate and wilting point measurements were investigated by McKeague (1955) and Arscott (1956) and were not repeated.

(5) SOIL REACTION

Soil reaction of non-calcareous samples was measured on 1: 2.5 soil - water mixtures which had been stirred several times during a

period of two hours; a Beckman pH meter was used with its calomel electrode in the relatively clear supernatant solution and the glass electrode in the soil suspension below. The calcareous samples were treated differently as Turner and Clark (1956) have shown that the pH of soil systems containing free calcium carbonate depend largely on the partial pressure of carbon dioxide; these workers found that equilibrium was reached by aerating the soil - water mixture with clean air for 48 hours. In the present study 1: 5 soil - water mixtures were used, aerated for two days and the pH measured immediately, followed by the versenate titration of soluble calcium in a filtered or centrifuged aliquot.

Even these pH values are not as accurate as perhaps desirable (pH being a logarithmic measurement) owing to insensitivity and tendency to drift in the pH meter. Measurements with a meter accurate to .01 of a pH unit would have been more satisfactory.

(6) CARBONATES

The gravimetric loss of carbon dioxide was measured from 1 or 2 gram samples treated with 3 N HCl in lightly stoppered 50 ml. Erlenmeyer flasks (U.S.D.A. Salinity Handbook, 1954). This method was used because the high content of calcium carbonate in most samples caused appreciable change in weight; the simplicity of apparatus compared with that for a manometric method, such as that of Martin and Reeve (1955), was also in its favour. The data for carbon dioxide loss was converted into calcium carbonate equivalent by multiplying by a factor of 2.274.

Some estimate of the relative amount of dolomite was obtained by combining the data for the gravimetric loss of carbon dioxide with figures obtained for calcium and magnesium after treating the soil

with aqua regia. It was considered that this treatment released all the magnesium from the dolomite and from 0 to 100 per cent of the combined magnesium in the clay. No allowance was made for the magnesium originating from the solution of ferromagnesium minerals. It was then assumed that all the calcium was in the form of calcium carbonate and that the rest of the carbonate, measured by the loss of CO_2 , was combined with magnesium carbonate in the form of dolomite. The percentage of calcium carbonate equivalent to the magnesium carbonate was then subtracted from the figure for total calcium carbonate. Any magnesium in excess of that required to form dolomite was calculated in terms of magnesium hydroxide as this compound is believed to be the most stable form likely to be present in soils. However, these values are only very rough estimates as they include all the errors and the values are probably high owing to the magnesium dissolved from the ferromagnesiums.

(7) EXCHANGEABLE BASES

Exchangeable calcium, magnesium and potassium were determined in a neutral N ammonium acetate extract from 5 grams of soil obtained by Bower, Reitemeier and Fireman's method (1952). Organic matter and ammonium acetate were removed by evaporation with aqua regia. Aliquots of a .2 N nitric acid solution were titrated for calcium and magnesium with versenate (Cheng and Bray, 1951). The versenate method was used because of its rapidity. Some trouble was experienced in the calcium titration with murexide indicator because of the slow change in colour at the end point. There was little trouble from interfering ions and these could be avoided by taking a smaller aliquot if necessary.

Another aliquot was analyzed for potassium with a Perkin - Elmer flame photometer using 25 p.p.m. lithium as internal standard after

centrifuging out calcium as the oxalate. This was necessary since it has been found that large amounts of calcium depress the luminosity of potassium (Toth and Prince, 1949; Pienaar, Lotz and Pigget, 1955).

The accurate measurement of the exchangeable bases is particularly difficult, however, in the presence of calcium carbonate. Ammonium acetate was used as in the standard procedure although it was realized that this extractant dissolves appreciable quantities of calcium carbonate and causes serious errors in the measurement of exchangeable calcium. Other factors which will also affect the other exchangeable cations, are the masking effect of calcium carbonate on the exchange positions (Thompson, 1953) and the finding of Chapman and Kelley (1930) that as long as calcium ions are in solution quantitative replacement by monovalent ammonium ions is not possible.

A more satisfactory method is the preliminary leaching with .5 N or 1 N acetic acid followed by ammonium acetate extraction (Thompson, 1953). Mehlich (1948, 1953) used barium chloride buffered to pH 8.1 with triethanolamine as the extractant as this has little solvent action on calcium carbonate. Soils high in carbonate were first boiled with 2 N ammonium chloride (Mehlich, 1948).

Tucker (1954) leached calcareous soil with N ammonium chloride in 60 per cent ethyl alcohol adjusted to pH 8.1 and found that the results agreed well with those obtained by Hissink's method. In a recent method (Tobia and Milad, 1956) the extractant is .2 N potassium chloride brought to equilibrium with solid calcium carbonate. Metson (1956) varied the procedure according to the percentage of calcium carbonate.

Since research is still needed in this field and the exchangeable cation content is of little significance in the pedogenesis of these

soils this aspect of the study was not investigated further.

(8) FREE IRON OXIDES

The distribution of free iron oxides down the three profiles was also determined. The iron was extracted by several alternate washings with very fresh sodium thiosulphite (dithionite) solution and .05 N hydrochloric acid followed by two final washings with N sodium chloride (MacKenzie, 1954). The iron taken into solution was analyzed by the Ferron method (Davenport, 1949). How effective this method of extraction is in the presence of large quantities of calcium carbonate is worthy of further study.

Another factor which should be taken into account is that some horizons contained nodules which were probably relatively high in iron oxide. It is quite possible that the standardized procedure for extracting the free iron only partially extracted the iron in the nodules (Robichet, 1955). Again, some nodules were larger than 2 mm and were taken out with the gravel.

II - TOTAL CLAY

(1) TOTAL CHEMICAL ANALYSIS

Carefully weighed samples of oven-dried extracted clay (material $\leq .002$ mm) were analyzed for total chemical composition using both sodium carbonate fusion and hydrofluoric acid digestion. Piper's macro-method using 1 gram of material (Piper, 1950) was used for the sodium carbonate fusion of most samples and a simplification (Miller, 1956) of Corey and Jackson's micro-method (1953) for the hydrofluoric acid digestion of .1 gram. In this modification the material is treated with 1 ml. 1:1 nitric acid, .5 ml. 60 per cent perchloric acid and 5 ml. 48 per cent hydrofluoric acid and heated on a sand bath

at 120°C. When solution is complete the digest is evaporated to dryness and taken up in .2 N nitric acid. Iron, aluminum, titanium, calcium and magnesium were analyzed in the sodium carbonate solution and potassium in the hydrofluoric. The two digests were necessary partly because potassium cannot be determined by the flame method in the presence of large amounts of sodium and also too because of the danger of volatilization at the temperature of fusion. The sodium content could not be analyzed owing to contamination with sodium during pretreatment, but this was not important as the sodium content of these soils is known to be low (Kelley, 1955).

Iron and aluminum were analyzed in the same aliquot using the Ferron spectrophotometric method of Davenport (1949) using wave lengths of 600 mμ and 370 mμ, respectively. Similarly, iron and titanium were complexed with Tiron (Yoe and Armstrong, 1947). In this method the intensity of the colour of the iron complex is measured at 565 mμ, the colour destroyed with dithionite and the colour intensity of the titanium complex read at 400 mμ. The method was adapted for use with the Beckman DU spectrophotometer. Iron determined by Ferron and Tiron checked satisfactorily.

Cheng and Bray's method (1951) was used in the analysis of calcium and magnesium after complexing interfering metals (especially iron) with sodium diethyl thiocarbonate and extracting the complex with iso-amyl alcohol (Cheng, Melsted and Bray, 1953).

Potassium was determined in a 0.2 N nitric acid solution of the residue from the hydrofluoric acid treatment using a Perkins and Elmer Model 146 flame photometer and 25 p.p.m. lithium as internal standard. The interference effect of calcium was disregarded as this element was less than 100 p.p.m. in the final solution.

Silica was found gravimetrically in the sodium carbonate solution using Piper's method. Total sesquioxides were also measured gravimetrically for a number of samples as a check on the colorimetric analyses.

Air-dry moisture was measured on the samples taken for analysis by weighing before and after oven drying at 105°C.

(2) CATION EXCHANGE CAPACITY

Cation exchange capacity of the total clay samples were obtained by Mackenzie's micro-Kjeldahl method (Mackenzie, 1951). This method involved six extractions with neutral normal ammonium acetate using a wrist action shaker, several washings with 95 per cent ethyl alcohol and the steam distillation of adsorbed ammonia after its release with 50 per cent sodium hydroxide. The ammonia was collected in 4 per cent boric acid and titrated with .007 N sulphuric acid using a mixed indicator.

(3) X-RAY DIFFRACTION PATTERNS

X-ray diffraction patterns were obtained using powdered hydrogen clay samples in a Picker X-ray Corporation apparatus with iron radiation and an MnO filter. Unfortunately, it was difficult to distinguish between illite and muscovite, which have very similar diffraction patterns, and to estimate the amount of quartz in the clay fraction, since even 2 per cent to 5 per cent of quartz can give strong diffraction lines. This can be seen from the diffraction pattern of the standard sample of Fithian illite which contains a low percentage of quartz.

However, more complete information could have been obtained using recently developed techniques and equipment some of which are described below.

Indeed, the most fruitful line of clay analysis seems to be in the field of X-ray diffraction studies, particularly as a means of identifying the particular minerals involved (Milne and Warshaw, 1956). Considerable research has been directed towards sample preparation in order to obtain the maximum information from the diffraction data. Useful advances in this field were made by Jackson and Hellman (1942), MacEwan (1949), Brown (1953), Greene-Kelly (1953) and Milne and Warshaw (1956). Most of this work was directed towards positively distinguishing the illitic and montmorillonoid minerals; kaolinite being relatively easily identified. Probably of interest in future work is the finding of Milne and Warshaw that relative humidity has a marked influence on the spacing and intensity of the basal diffraction peaks. Wet air was found even more satisfactory than glycerol or ethyl glycol in the interpretation of patterns from montmorillonite-illite mixtures and dry air could be used as a substitute for heat treatment.

(4) DEHYDRATION CURVES

Dehydration curves were obtained on two samples (Kinbasket B₂₂ and C horizons) to check the X-ray findings. Material was heated in platinum crucibles and the loss of weight measured after intervals of 48 hours at 100°C. increments up to 800°C., following the work of Grim, Bray and Bradley (1937) and the findings of Roy (1949) in relation to the gradual loss of moisture from muscovite over a prolonged period of heating. Unfortunately, changes in weight may also result from other reactions, such as the oxidation of iron compounds and the volatilization of potassium. A marked loss of weight between 400°C. and 600°C. is nevertheless a good indication of the presence of illitic type clay minerals.

III - MINERALOGICAL ANALYSES

The mineralogical examination of the very fine sand fraction was undertaken in an attempt to correlate soil horizons and to estimate the degree of weathering. The heavy fraction was separated out from 0.5 to 1.0 grams of very fine sand with s-tetrabromethane (Twenhofel and Tyler, 1941), the specific gravity of which was found to be 2.94 using a pycnometer bottle.

A representative portion of the heavy minerals was mounted in Canada balsam and examined with a petrological microscope. An attempt was made to count hornblende crystals but this was found to be impracticable. Another portion was placed on 1 mm squared graph paper under a low powered binocular microscope and the particles of magnetite picked off and counted using magnetized needle. The other heavy minerals, usually between 1,000 and 2,000, were also counted and the percentage of magnetite obtained on the basis of the total number of heavy minerals.

A spectrographic analysis was also made of fine sand and very fine fractions using a Hilger spectrograph as an additional aid to the study.

SECTION III

RESULTS AND DISCUSSION

The detailed results of this study are given in the Appendices. These results are discussed below under three main headings:

The Nature and Composition of the Underlying Till

Genetic Relationships of the Till and Solum

Soil Maturity and Weathering

I - THE NATURE AND COMPOSITION OF THE UNDERLYING TILL

(1) COARSE FRACTION

The relative abundance of gravel and stones in the till underlying the three profiles was measured as a percentage by weight of the total soil. These values are shown in Table I of Appendix I. The coarse skeleton material was most abundant in the till below the Wycliffe profile (38.8 per cent) and least prevalent in the Kinbasket C horizon (7.2 per cent); the Yoho C was intermediate with 16.2 per cent although this value may not be significant because of much smaller quantity of material sampled.

The coarse skeleton of the till underlying the Wycliffe profile consisted predominantly of black chert and variably coloured fine grained quartzite (white, green, red and black). There were also some smaller stones of shale, a coarse grained quartzite, some highly calcareous rock and medium grey dolomitic material. Of interest was the observation that many of the fragments had rounded edges suggesting the possibility of movement by water although the presence of flattened surfaces indicated glacial transport.

On the other hand, the coarse skeleton of the till in the Kinbasket profile was more homogeneous, uniform and angular. At once obvious was the thick platy form of some of the dark grey fragments, a feature either of original bedding or glacial action. Most of these fragments effervesced and disintegrated with either dilute or concentrated hydrochloric acid, indicating variably dolomitized limestone.

Also present were smaller fragments of white and pale brown fine grained quartzite, a coarse grained quartzite and minor amounts of shale.

Only a small amount of coarse skeleton was available for inspection from the Yoho site. One of the larger stones, 1 inch to 2 inches across, with flattened surfaces, was of interest as it was identified as dolomite with fine criss-crossing carbonate veinlets, very similar to materials occurring in the Windermere series. Some fairly large fragments of pure white calcite were also present.

(2) SAND FRACTION

The total carbonate-free sand content was highest in the Kinbasket till (47 per cent), somewhat lower in the Yoho (34.6 per cent) and lowest in the Wycliffe (27 per cent). The percentage of very fine sand and silt was about the same in the Wycliffe and Yoho materials (39 to 42 per cent) although the clay content was materially higher in the former (34 percent compared with 24 per cent); the Kinbasket C was low in both silt and clay. The accumulation curves show approximately the same pattern, however, indicating a similar mode of deposition (See Appendix I).

In appearance, the carbonate-free sand fraction of the till at the three sites was very similar. The larger angular fragments consisted mainly of chert and quartzite; the Yoho material seemed to have the largest proportion of larger fragments followed by the Wycliffe.

The finer fraction (<150 mesh) was well speckled with black particles, particularly in the Wycliffe. Indeed, a large proportion of the heavy minerals in the 80 - 150 mesh fraction were magnetic as well as many of the larger grains. Similarly, magnetite was more prevalent in the heavy mineral fraction of the very fine sand of the Wycliffe material. The lowest proportion of magnetic particles was found in the Yoho soil (Appendix III).

Micaceous minerals were also in evidence, especially in the fine sand at the Yoho site, less so in the Kinbasket and least in the Wycliffe. Relatively unweathered ferro-magnesium minerals were noted in the very fine sand fraction.

(3) CARBONATES

Perhaps the most interesting feature of the till was the high content of carbonates in amorphous or finely crystalline form, ranging from 20.6 per cent as calcium carbonate in the Kinbasket till to 36.2 per cent in the Wycliffe (See Table I in Appendix I). However, a fairly high proportion of dolomite was also indicated, particularly in the Kinbasket C horizon (i.e., 12 per cent calcite; 8 per cent dolomite). The ratio between calcite and dolomite was wider in the Yoho material (27 per cent and 5 per cent, respectively).

Although these figures for the proportions of calcite and dolomite are only approximate it is evident that dolomitized limestone must be present; partly because magnesium limestone forms one of the source rocks and also because dolomite was identified in the gravel.

(4) CLAY FRACTION

Analysis of the clay fraction showed it to be relatively high in silica (40 per cent to 43 per cent) for illitic type clay when compared with published analyses such as those given by Grim (1951). The alumina content ranged from 22 per cent to 26 per cent and ferric oxide from 5 per cent to 8 per cent (See Appendix II). The magnesia content was relatively constant at the three sites (4.3 to 4.9 per cent) with more variation in the content of calcium oxide (0.8 per cent to 5.5 per cent); the low value for the Kinbasket may be correlated with the lesser amount of calcium carbonate at this site.

X-ray diffraction and dehydration studies showed that the clay fraction is composed of illite, quartz and possibly some muscovite. This finding was supported by the relatively low values for loss of moisture at 100°C. (1 per cent to 2 per cent) and exchange capacities of 17 to 22 milli-equivalents per 100 grams. Indeed, these values, and the sharp diffraction lines indicated a high degree of crystallinity with a correspondingly low surface area and possibly a moderate amount of muscovite. Dehydration studies of the clay fraction of the Kinbasket C horizon, however, showed a fairly well marked loss of weight between 400°C. and 600°C. which indicated illite rather than the gradual loss of moisture expected from muscovite (Grim, Bray and Bradley, 1937).

The chemical composition of the clay is very similar at the three sites; indeed, it is very probable that the clay is virtually the same as that present in situ in the shales and other sedimentary rocks from which the till was derived. Illite is, in fact, the major clay constituent of shales and limestones (Grim, 1953).

It is suggested that this clay was released by mechanical degradation during glacial transport, particularly from the relatively soft shales. It is perhaps significant in this respect that very little shale was found in the coarse fraction of the till. Possibly, there was some comminution of the clay particles themselves since a high proportion of the clay is in the form of fine clay.

(5) PHYSICAL PROPERTIES

Soil physical properties studied by McKeague and Arscott show relatively low values for total porosity and percentage of macro-pores (responsible for drainage and high apparent specific gravity figures) indicating a dense, compact structure. This was borne out by permeability measurements; indeed, the till under the Kinbasket was almost impermeable and nearly so at the other sites. This dense structure and low permeability can be partly attributed to the close packing effect of the finer particles filling in the interstices between the larger ones (Burmister, 1954; Lambe, 1954).

(6) SURFACE ALTERATION OF THE TILL

The surface of the till (the D_1 , C_1 and C_{gw} horizons, respectively) has been weathered to a variable depth of up to 9 inches. The most obvious effect of soil formation is an improvement of soil structure as indicated by increased macro-pore space, decreased apparent specific gravity, a rise in both the plastic limits and an increase in the organic matter content (Appendix I). The small changes in the size distribution of the mineral fraction, the carbonate content and the chemical composition of the clay fraction are not considered significant except, possibly, the slight increase in silica. Values for exchange capacity of the clay are very similar to those obtained with the unweathered

material below indicating no change in surface area as a result of mechanical degradation.

The "B_{Ca}" horizon of the Kinbasket series was identified in the field by its light yellow colour and well developed structure. In the profile examined there was a material reduction in total sand content and an increase in clay, possibly due to a sorting effect during deposition. However, the characteristics of the clay fraction, such as chemical composition and cation exchange capacity, are more similar to those of the C horizon than they are to the rest of the B horizon.

It is concluded that the major difference between the till at the three sites is the relative abundance of gravel and stones. At the Wycliffe site there is evidence of abrasion by running water while the high angularity of the fragments at the Kinbasket and Yoho sites indicate glacial movement only.

Chert, dolomitized limestone and quartzites were the principal rock types. Chert and quartzite seemed to be most abundant in the Wycliffe profile with limestone and dolomitized limestone predominating in the underlying till of the other two sites. These observations may be related to the distance of the till from the source rocks. Since the Wycliffe material is probably furthest from the source of the till its coarse fraction was subjected to relatively more abrasion during glacial transport, resulting in the survival of quartzite while softer rocks, such as the limestones, were broken down to finer particles.

Other features of interest were the presence of magnetite and muscovite in the sand fraction. Magnetite was most abundant in the very fine sand fraction of the Wycliffe; in comparison, mica seemed to be relatively more prevalent in the Yoho. There did not appear to be

any real difference in the heavy mineral suites, however, and the clay minerals were very similar as shown by X-ray and chemical analysis.

In view of the heterogeneous nature of till, material from other sites should be examined before any bases can be established for differentiating Cedrus and Wycliffe tills.

II - GENETIC RELATIONSHIPS OF THE TILL AND SOLUM

An attempt was made to relate the underlying till to the solum largely by means of heavy mineral analysis.

Magnetite was used as the indicator mineral as it was relatively abundant, has a high resistance to weathering and is not normally formed by pedogenic processes. It could also be readily identified with the help of a magnetized needle. Tourmaline, zircon or rutile might perhaps have been more satisfactory but were not used because of the infrequency of their occurrence and the difficulty of identification in the very fine sand fraction. The source of the magnetite is probably as an accessory mineral in the igneous rocks of the area, such as the granite of the Purcells; it may also originate in metamorphic limestone.

A count was made of magnetite grains in the heavy mineral fraction of the very fine sand in several horizons of each profile. Between 1,000 and 2,000 heavy mineral particles were counted in each separate. Wide differences in the proportion of magnetite to total heavy minerals were found in the solum of the Wycliffe and the podzolized horizons of the Yoho compared with the underlying material (Appendix III); these differences suggested variations in deposition. On the other hand, the proportion was fairly uniform down the profile of the Kinbasket silt loam indicating an A-B-C profile.

Indeed, McKeague regarded the underlying till of the Wycliffe as the D rather than the C horizon. An obvious feature is the marked change from the gravelly till to the almost stone-free silt. There is also a marked difference in the shape of the accumulation curves of the A and B horizons and the till; the texture of the solum lies largely in the silt range compared with the more uniform size distribution of the till. The quartz grains of the very fine sand fraction also appeared to be more rounded in the B horizon than in the D; possibly indicating that the material forming the solum had been transported by wind. Spectrographic analyses were made of the fine sand from the B and D horizons. Unfortunately, no significant differences in trace metals could be detected.

There is also the possibility of depositional differences between the A and B horizons. The magnetite count of the A₁₂ horizon was 4.61 per cent compared with 1.32 per cent in the B₄ and 5.54 per cent in the D horizon (Appendix III). Additional evidence is the presence of a higher proportion of silica in the total clay of the A horizon compared with the B (Appendix II). These differences are more than can be expected from the weathering of a relatively immature soil and also point to depositional variations.

The magnetite content was five times as high in the very fine sand of the podzolized A and B horizons of the Yoho profile compared with the grey-wooded lower section of the profile. It has already been suggested that this is possibly due to selective weathering of less resistant heavy minerals. There was a fairly large amount of

hornblende in the A_{2p} horizon, however, which appeared to be little weathered as indicated by the clean crystal surfaces. Unfortunately, this may not be a fair criterion, as hornblende is known to weather internally followed by the complete collapse and disappearance of the crystal. Indeed, a rough count of the hornblende crystals indicated a lower content of hornblende in the A_{2p} horizon compared with the C horizon but many more would have to be counted before a statistical relationship could be obtained. Even then, such evidence could not be taken as conclusive proof because of the possibility of differences in initial content of hornblende.

The problem was also investigated by spectrographic analysis. Iron, titanium, manganese and potassium were higher in the total very fine sand fraction of the Yoho A_{2p} compared with the C horizon. The iron can be attributed to the magnetite as well as hematite and possibly limonite; the titanium to minerals such as ilmenite, rutile and sphene; the manganese to its association with magnetite and other forms; potassium to its presence in micas and feldspars. Magnesium was relatively high in both samples and can be attributed largely to the relative abundance of ferromagnesiums. Zirconium lines were not seen in the spectrum.

These differences are of interest but still do not prove whether the podzolized solum of the Yoho soil is derived from the soil below or is a depositional feature. There is also the possibility that it could be a combination of both factors; viz: deposition at an early stage in soil formation followed by intensive leaching.

III - SOIL MATURITY AND WEATHERING

(1) LEACHING OF CALCIUM CARBONATE

There has been some movement of carbonates in the Wycliffe profile (Appendix I). Free carbonates were found close to the soil surface but the percentages were much lower in the A than in the B horizon. The zone of maximum accumulation of carbonates was in the B₄ and possibly the D₁ horizons.

In the Kinbasket profile the solum was leached of lime to the bottom of the B₂₂ horizon at 11½ inches except for a slight trace in the A₂₁. There was a sharp change below to the B_{Ca} horizon with nearly 20 per cent of calcium carbonate. Analyses indicated that there was no dolomite in this horizon although possibly from 2 to 3 per cent of magnesium hydroxide.

The Yoho profile was leached to the bottom of the A_{2gw} horizon; only 1 per cent of calcite was found in the B_{gw} although possibly there was from 2 to 3 per cent of magnesium hydroxide. Calcite was most abundant in the C_{gw} horizon (37 per cent); probably this is the main horizon of accumulation although some of the calcite may be residual as there was also a significant amount of dolomite present.

(2) MOVEMENT OF FREE IRON OXIDES

The distribution of free iron down the three profiles is of interest in relation to soil formation.

The percentage of free iron in the Wycliffe profile, calculated as ferric oxide (Fe_2O_3) ranged from 0.9 per cent in the B_3 to 1.8 per cent in the A_{12} compared with the 0.6 per cent in the till below (Appendix I). Segregation of iron into fairly soft nodules was noted in the coarse sand size fraction in the A_{12} ; some of these may not have been dissolved by the thiosulphite treatment; hence the free iron content may be somewhat higher than that reported with a maximum of just over 2 per cent in the B compared with 0.8 per cent in the A_{21} , 1 per cent in the A_{22} and 0.7 per cent in the till. Again, there seemed to be segregation in the A horizon. A few dark red-brown nodules were noted in the coarse sand fraction of the A_{21} and some larger brownish-yellow nodules amongst the fine gravel of the A_{22} . These larger nodules were stained dark brown inside; they were non-magnetic, non-calcareous, and could be broken down into very fine grained material. Very probably the free iron content of the A horizon is higher than the values found by analysis. Some of the smaller nodules may not have been completely dissolved by the thiosulphite - hydrochloric acid treatment and those larger than 2 mm had been separated out prior to treatment.

The values obtained for free iron down the Yoho profile by the standard procedure are of interest. The biggest variation occurred between the A_{2p} and the B_p (0.3 per cent and 1.2 per cent, respectively). Indeed, the A_{2p} was the typical "ash" colour of the true podzol. Very similar values of just over 1 per cent were obtained for the A_{2gw} and the B_{gw} , almost twice the content of the C_{gw} and the C horizons. Again, nodules were prevalent. Bright red medium to small nodules occurred in the sand fraction of the A_{2p} ; similarly, the B_p sand was

full of reddish-brown nodules. X-ray analysis indicated the presence of limonite associated with quartz and perhaps mica; some of the particles were magnetic.

Some of the free iron is closely associated with the clay particles. It was not removed by preliminary treatment with 2 N hydrochloric acid for the removal of carbonates although it was brought into solution with sodium dithionite. The percentages of free iron oxide obtained in this manner may have some significance both in the movement of iron down the profile and the weathering of clay minerals.

The relatively uniform values of between 2.40 per cent and 3.10 per cent free Fe_2O_3 for the Wycliffe solum (Appendix II), except for the low value obtained for the A_{11} clay, may indicate both little iron movement and a similar degree of weathering down the profile. These figures were even more constant than those for total free iron. The highest percentage was obtained in the D horizon although the total free iron was low.

The wider range in percentages of free iron in the Kinbasket follows the same trend as values for total free iron with maximum amounts in the B horizon. This distribution might be the result of more intense weathering in the B, (discussed below), the illuviation of iron, a larger surface area of particles or iron oxide occurring in clay size particles.

The lowest values for percentage of iron were found in the A_{2p} and the A_{2gw} of the Yoho profile with much larger amounts in the two B horizons, particularly the B_{gw} . This iron distribution suggests leaching and deposition, especially in the A_{2p} , in which the total free iron was also very low.

Possibly of significance is the similarity of free iron content attached to the clay particles in the underlying till at the three sites.

It can perhaps be assumed that this is the product of weathering since the movement of iron in the till is probably negligible. This is supported by the observation that the total free iron content of the till is relatively low; hence much of the iron is tightly associated with the clay fraction.

It is evident that there has been a maximum amount of movement of iron in the podzolized horizons of the Yoho soil since particularly low values were obtained for total free iron and "tightly-bound" free iron oxide in the A_{2p} horizon compared with the B_p horizon. The ratio between the total free iron of the A_{2p} and B_p horizon was 1: 4.5. This suggests that the process of podzolization is well developed in this profile. In the Kinbasket profile, however, the ratio for total free iron between the A_{22} and B_{22} horizons was narrower (about 1: 2) although the percentage of free iron was twice as high as in the Yoho B_p . In the Wycliffe there was no appreciable difference in content between the A_{12} and the B_4 , indicating practically no movement of iron.

(3) DISTRIBUTION OF ORGANIC MATTER AND EXCHANGEABLE BASES

The distribution of organic matter in the three profiles is of interest in relation to soil formation. Values for percentages of organic matter (Appendix I) indicate that there has been little movement down the Kinbasket profile and even less in the Wycliffe. Considerably more movement has taken place in the Yoho soil, particularly from the A_{2p} horizon. This was shown by the grey colour of this horizon and its low content of organic matter (0.8 per cent) compared with that of the B_p horizon (2.0 per cent).

It is apparent from an inspection of the pH changes down the

profiles of the Brown Wooded(Wycliffe) and Grey Wooded (Kinbasket) soils that the exchange complex is 100 per cent base saturated in the solum of the Brown Wooded soil although somewhat less so in the A and B horizons of the Grey Wooded (Appendix I, page 58).

Relatively low pH values, ranging from 5.1 in the A_{2p} to 5.9 in the A_{2gw} (the C_p horizon), and low values for exchangeable calcium were obtained in the podzolized upper horizons of the Podzolized Grey Wooded profile. Of interest is the rapid rise of pH from 5.9 in the A_{2gw} to 8.1 in the B_{gw} horizon immediately below, indicating a carbonate accumulation zone.

Maximum movement of organic matter and bases has occurred in the Podzolized Grey Wooded soil and the least in the Brown Wooded profile. In the Grey Wooded soil there has been appreciable leaching of bases but little migration of organic matter.

(4) ACCUMULATION OF SILT AND CLAY

It is apparent from the mechanical analysis of the Brown Wooded soil under study that there has been no significant movement of clay through the solum. In the Grey Wooded soil (Kinbasket silt loam), however, it is evident that both the silt and clay contents are higher in the B horizon than either the A or C horizons. On the basis of mineralogical studies and the distribution and composition of the coarse skeleton there is no reason to suspect the presence of a composite profile; it would appear that either the finer fraction has moved down from the A horizon or has been formed in situ at the expense of the fine sand. It is mentioned elsewhere that the fine sand and clay are virtually unweathered;

hence the second hypothesis is untenable.

The eluviation of clay from the A horizon is one of the criteria for identifying a Grey Wooded soil. Its occurrence in the Kinbasket series was noted previously by Lindsay (1954). Visual indications of clay movement down the profiles of some Grey Wooded soils of the Peace River area have been observed by members of the Dominion Soil Survey Division (personal communication). The well marked structural development of the Grey Wooded B horizon obviously provides many fine cracks and channels for the downward movement of clay as a suspension in percolating water.

There also seems to have been some movement of silt and clay in the Podzolized Grey Wooded profile, particularly from the A_{2p} and B_p horizons it appears that most of the silt and clay has moved through to the B_{gw} horizon. Even in this horizon, the accumulation of finer particles of clay is slight compared with the silt and clay contents of the C and the C_{gw} horizons; this can possibly be attributed to a lower initial content of silt and clay in the parent material compared with that of the Kinbasket silt loam.

(5) SOIL STRUCTURE

Field examination of the three profiles showed that maximum structural development was attained in the B horizon of the Kinbasket profile with somewhat less in the A_{2gw} and B_{2gw} horizons of the Yoho soil.

Structural changes in the solum were least pronounced in the Wycliffe profile and most marked in the Yoho; in this profile there was a change in structure from "single grain" in the A_{2p} to "medium to large subangular blocky" in the B_{2gw} (Arscott, 1956).

Total pore space determinations of the A and B horizons down to the horizon of lime accumulation indicated a slight increase (from 51.4 per cent to 62.3 percent) down the solum of the Wycliffe profile although this trend was reversed in the Kinbasket (53.2 per cent to 43.2 per cent). The figures obtained for the A_{2p} and the B_p of the Kinbasket also showed a slight reduction of porosity with depth (76.5 per cent to 63.2 per cent) although there is a sharp change below to the more compact A_{2gw} .

The measurements of total pore space indicate a well marked structure in the solum of the Brown Wooded and Grey Wooded soils and similarly in the Grey Wooded horizons of the Podzolized Grey Wooded soil. The field descriptions are more indicative of the degree of structure development.

It has already been suggested that for closely related soils the stage of maturity of the profile may be related to structure. The

strong structural development in the B_{22} of the Kinbasket and the B_{gw} of the Yoho soil can be regarded, therefore, as additional evidence of the immaturity of the Wycliffe profile because of its relatively weakly developed structure.

(6) WEATHERING OF SAND FRACTION

The weathering of the very fine sand fraction has been shown to be a good index of weathering, particularly in the heavy mineral fraction.

An examination of slides of the heavy minerals (above 2.94 specific gravity) showed that most of the grains were little weathered; even crystals of hornblende, a mineral which has little resistance to weathering, had clean, relatively unweathered surfaces, as already described.

The proportion of magnetite on a basis of the total number of grains of heavy minerals in the very fine sand was fairly constant down the Kinbasket profile indicating relatively little weathering even in the A horizon. Although there was more magnetite in the A_2 of the Wycliffe compared with the B_4 this is probably due to a depositional difference rather than a weathering effect.

More significance has been attached to the difference in magnetite content between the podzolized horizons of the Yoho silt loam and the underlying grey wooded horizons. Titanium, manganese and potassium were also higher in the A_{2p} than the C horizon. The possibility that this may be due to either a depositional effect or to weathering has already been mentioned.

The observation of very little weathering is in agreement with the findings of other mineral studies across Canada. Particularly of interest is the fact that there was very little weathering of soil minerals even in the A_2 horizon of a podzol developed on well-drained

glacial till in Manitoba (Ehlich, Chapman and Rice, 1957). Indeed, no weathering trend could be found even with the feldspars.

(7) WEATHERING OF CLAY

X-ray diffraction patterns show that the clay fractions consist mainly of illite with some quartz and muscovite. The patterns were very similar to that given by a standard sample of illite from Fithian, Illinois.

Some weathering was indicated by the rather diffuse diffraction lines obtained for clay samples from the solum compared with the relatively sharp lines for the till (Jackson, Hseung et al., 1952). However, it is evident that there has been little structural alteration in the clay minerals, even in the acid horizons of the Podzolized Grey Wooded soil. Cation exchange studies indicated that the main effect was an increase in surface area.

This theory is also supported by the finding that there is only a slight loss of combined potassium from the clay of the A and B horizons of the three soils compared with its content in the parent till. Indeed, only minor amounts of potassium have moved into positions available for exchange as indicated by the low values for exchangeable potassium.

However, weathering has resulted in some changes within the clay fraction. Decalcification has obviously occurred resulting in the leaching of calcite from the clay fraction and its secondary deposition lower in the profile, particularly in the Grey Wooded soil.

There are marked changes in the calcium content of the clay down the profile with highest values in the till. Similarly, there is some loss of magnesium but to a lesser extent in accordance with the tightness of binding of the two ions. Lattice iron shows some tendency to be

higher in the B horizon but this may not be significant although it agrees with the finding of Swenson and Riecken (1955) for Loess soils.

The iron oxide coating the clay particles, resistant to attack by 2 N hydrochloric acid, is of some interest. The largest amount (5 per cent to 6 per cent) was found in the B₂₂ horizon of the Grey Wooded soil; lattice iron was also highest in this horizon. This is perhaps related to the suggestion of Jackson and Tyler (1948) that hematite monolayers are formed by the weathering of clay minerals under conditions of good oxidation, particularly with very fine particles. If this occurs in the soils under study it would indicate that there has been some surface weathering of the clay particles, particularly in the B horizon of the Grey Wooded soil. It must be remembered, however, that some of these iron coatings may be iron that has moved towards the clay from the rest of the soil system. There is also the possibility that iron oxide minerals in the clay fraction itself were dissolved by the dithionite treatment.

SECTION IV

CONCLUSIONS

The main conclusions to be drawn from this study are as follows:

(1) Although there are differences in the till underlying the three soils, particularly in mechanical composition, the similarities in carbonate content, mineral composition and general lack of weathering, do not justify the separation of the material into Wycliffe and Cedrus tills.

(2) The till underlying the solum of the Wycliffe silt loam, at least in the profile under study, is a D horizon rather than the parent material. This conclusion is based largely on the wide difference in mechanical composition, the X-ray patterns, composition and exchange capacity of the clay, and the content of heavy minerals. There is some doubt as to the parent material of the podzolized horizons of the Yoho silt loam on the basis of differences in the percentage of magnetite in the heavy mineral fraction of the very fine sand. A more extensive study with other profiles of the same soil is called for to elucidate this problem.

(3) Profile development has been largely restricted to the leaching of carbonates and bases, the movement of iron and the eluviation of fine particles. There has been only slight movement of organic matter except in the podzolized horizons of the Podzolized Grey Wooded profile. Maximum profile development has occurred in the Podzolized Grey Wooded soil and the minimum in the Brown Wooded soil.

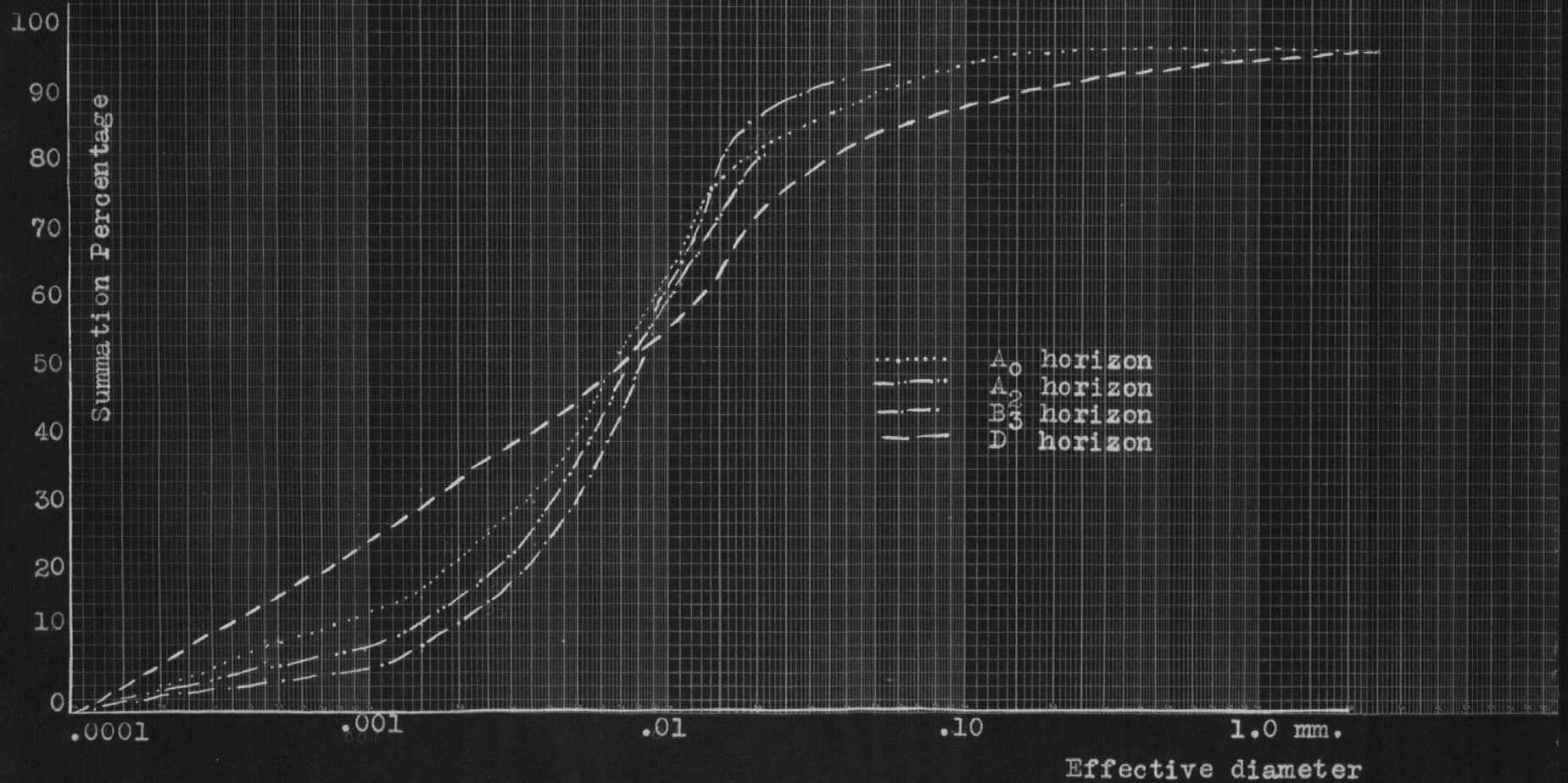
(4) The soil minerals in the very fine sand and clay fractions are relatively unweathered even in the A_{2p} horizon in which the maximum amount of leaching has taken place.

APPENDIX I
I. MECHANICAL COMPOSITION

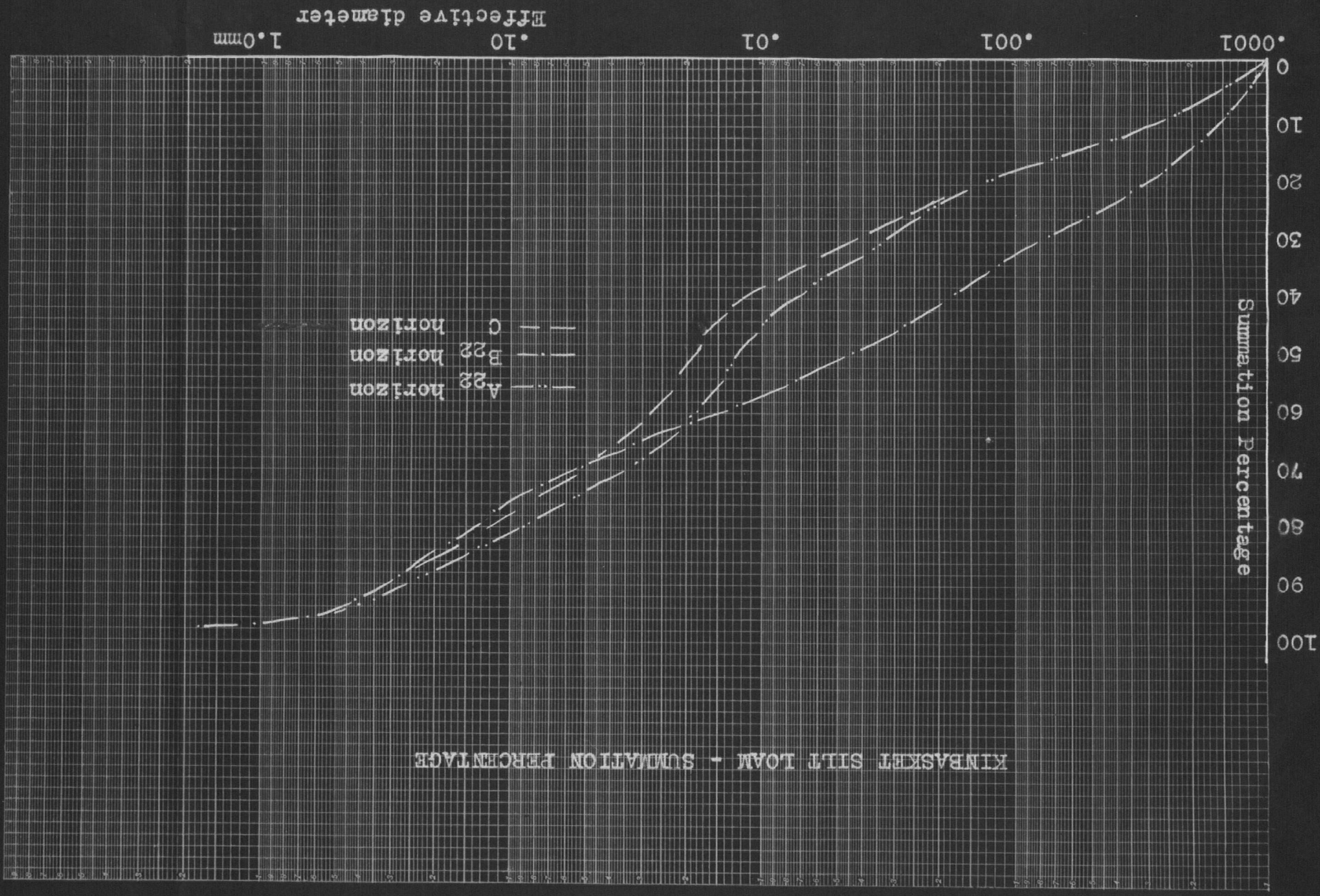
	HORIZON	DEPTH (inches)	COARSE SKELETON (per cent total wt.)	MECHANICAL ANALYSES ★				CALCIUM CARBONATE EQUIVALENT (CO ₂ loss)	ORGANIC MATTER PERCENTAGE oven dry soil
				Percentage organic matter free, acid extracted, oven dry soil.					
				Fractions I & II 2mm - .02mm	Fraction III .02mm - .002mm.	Fraction IV .002mm .001mm			
WYCLIFFE	A ₁₁	½-0	-	12.2	64.8	23.0	13.0	3.71	4.02
	A ₁₂	½-3	3.7	17.5	65.5	17.0	8.8	0.93	1.30
	B ₃	6½-10	1.1	12.8	73.4	13.8	6.5	24.2	1.50
	B ₄	10-14	-	18.0	67.0	15.0	11.5	37.2	1.41
	D ₁	14-19	6.9	14.0	47.0	39.0	27.0	40.5	1.81
	D	19 +	38.8	26.6	39.1	34.3	25.0	36.2	0.72
KINBASKET	A ₂₁	0-3½	11.0	40.5	39.3	20.2	13.5	-	1.73
	A ₂₂	3½-7½	6.8	36.0	38.4	25.6	19.5	-	1.40
	B ₂₁	7½-9½	8.1	36.8	23.2	40.0	31.5	-	1.50
	B ₂₂	9½-11½	6.0	36.2	20.6	43.2	34.0	-	1.47
	B _{Ca}	11½-18	9.5	34.8	30.5	34.7	28.0	16.8	0.99
	C ₁	18-27	4.6	53.8	26.5	19.7	11.0	20.3	1.24
	C	27 +	7.2	47.0	28.5	24.5	18.5	20.6	0.53
YOHO	A _{2p}	0-2½	2.6	39.0	49.6	11.4	9.7	-	0.80
	B _p	2½-11½	8.0	42.2	42.9	14.9	7.6	-	2.02
	A _{2gw}	11½-15	4.3	36.0	46.4	17.6	8.7	-	1.10
	B _{gw}	15-20	6.5	29.0	48.4	22.6	14.2	1.05	1.18
	C _{gw}	20 +	5.3	43.4	35.4	21.2	12.0	41.9	1.89
	C		16.2	34.6	41.7	23.7	13.7	35.1	0.60

★ Size limits using International System.

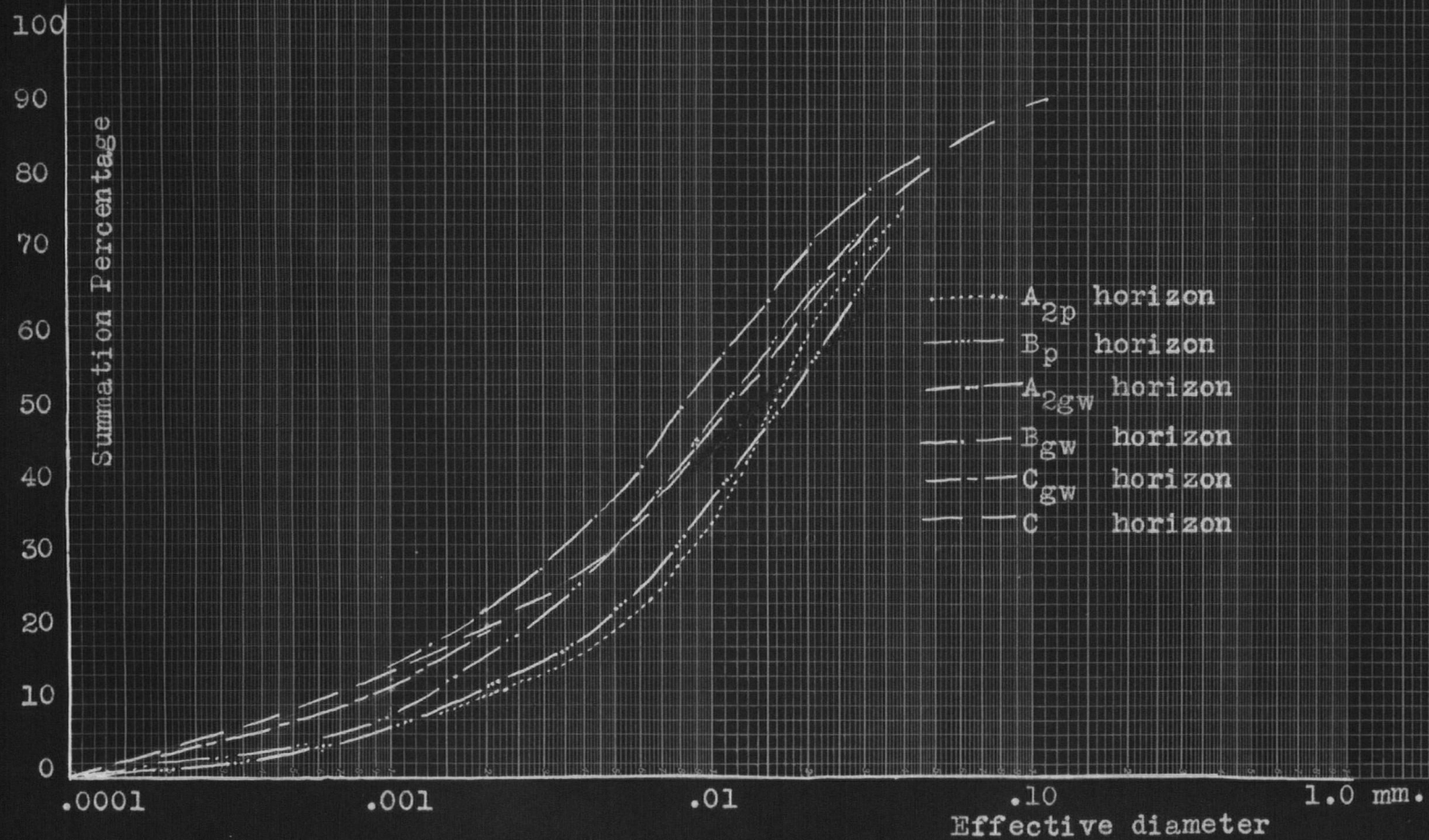
WYCLIFFE SILT LOAM - SUMMATION PERCENTAGE



KINBAKKEH SILL LOAM - SUMMATION PERCENTAGE



YOHO SILT LOAM - SUMMATION PERCENTAGE



III. PHYSICAL AND CHEMICAL PROPERTIES

	HORIZON	pH	AIR-DRY MOISTURE	Plastic limit	PLASTICITY		EXCHANGEABLE BASES Milli-equivalents per 100 grams oven-dry soil.			FREE IRON OXIDE Percent Fe ₂ O ₃ air-dry soil
					Liquid limit	Plastic index	Ca ⁺⁺	Mg ⁺⁺	K ⁺	
WYCLIFFE	A ₁₁	8.1	3.73	46.4	47.0	0.6	(24.4)	2.48	1.50	1.48
	A ₁₂	7.9	2.72	23.3	31.5	4.2	(16.0)	1.85	1.47	1.01
	B ₃	8.1	2.53	33.4	36.3	2.9	(42.1)	2.25	0.43	0.90
	B ₄	8.1	1.71	35.5	42.3	6.8	(42.4)	2.46	0.50	1.33
	D ₁	8.3	1.05	22.9	26.1	3.2	(40.1)	1.85	0.13	0.55
	D	8.2	0.61	10.3	14.1	3.8	(35.5)	1.25	0.08	0.70
KINBASKET	A ₂₁	7.5	2.22	21.6	27.7	6.1	9.04	1.86	0.10	0.83
	A ₂₂	6.4	2.02	18.7	22.6	3.9	9.54	3.62	0.22	1.08
	B ₂₁	6.5	3.05	17.7	25.2	7.5	8.74	3.64	0.35	2.04
	B ₂₂	6.5	2.48	17.1	27.5	10.4	10.15	4.95	0.33	2.01
	B _{Ca}	8.1	1.02	15.2	22.2	7.0	(32.3)	4.14	0.04	1.07
	C ₁	8.1	0.83	13.3	18.6	5.3	(32.0)	4.23	-	0.92
	C	8.1	0.66	6.2	14.6	8.4	(32.0)	4.20	-	0.69
YOHO	A _{2p}	5.1	1.97	4.5	-	-	4.69	1.33	-	0.29
	B _p	5.7	3.42	35.3	37.5	2.2	1.34	2.05	-	1.17
	A _{2gw}	5.9	0.98	18.1	22.9	4.8	4.66	3.34	-	1.08
	B _{gw}	8.1	2.26	14.8	31.0	6.2	(19.6)	3.33	-	1.01
	C _{gw}	8.1	1.00	24.0	29.9	5.9	(34.2)	3.18	-	0.54
	C	8.1	0.49	16.0	21.2	5.2	(33.2)	3.01	-	0.58

NOTE: Figures in parentheses have little meaning owing to solution of calcium carbonate by ammonium acetate.

APPENDIX II

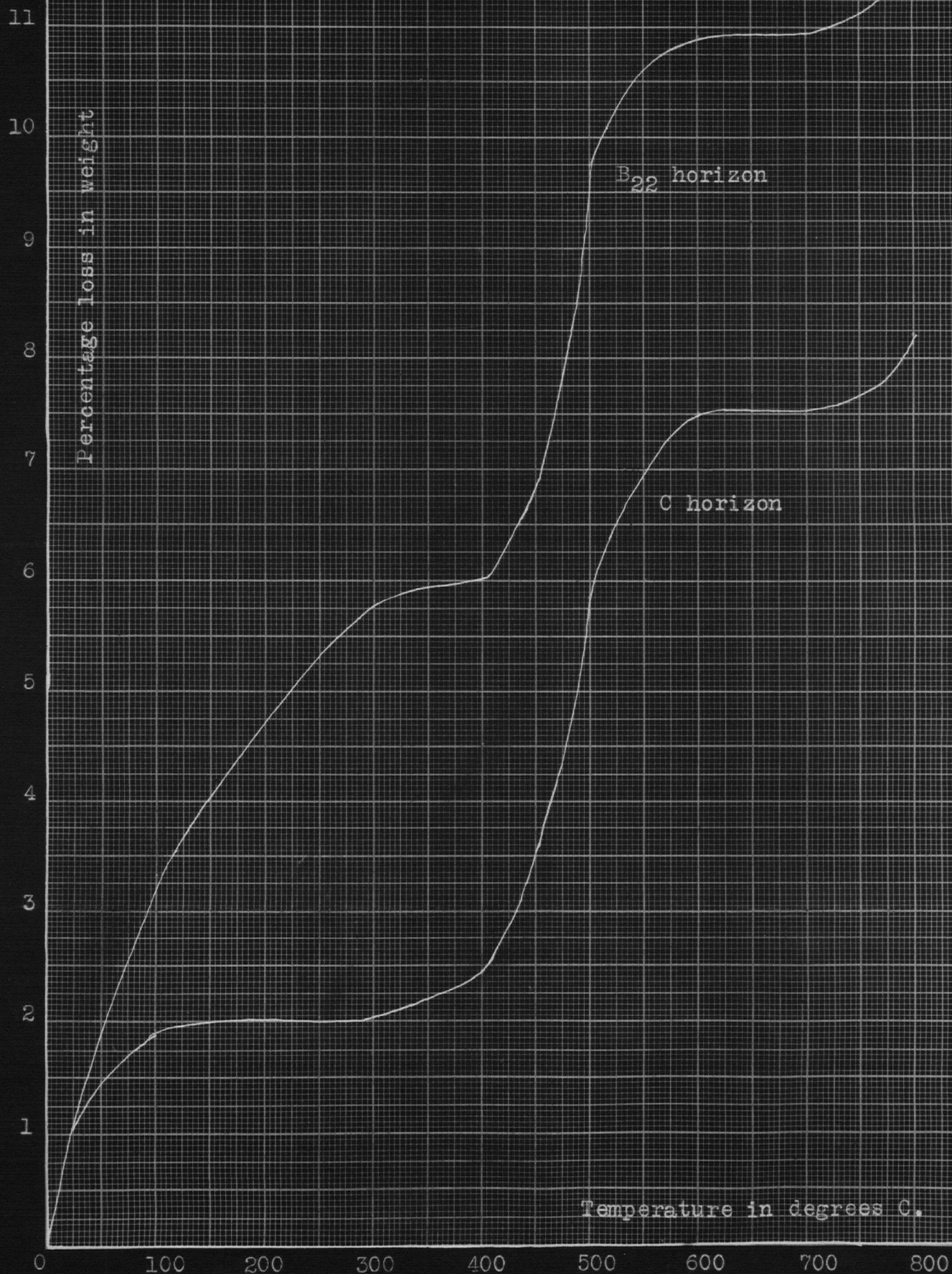
TOTAL CLAY ANALYSIS

	HORIZON	CATION EXCHANGE CAPACITY m.e./100 g.	AIR-DRY MOISTURE per cent oven dry	TOTAL CHEMICAL ANALYSIS (per cent oven-dry soil)							Fe ₂ O ₃ COATING per cent by weight
				SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	TiO ₂	CaO	MgO	K ₂ O	
WYCLIFFE	A ₁₁	41.7	6.5	60.5	4.30	14.7	.29	.33	0.84	3.57	1.43
	A ₁₂	55.6	6.7	53.4	6.41	18.6	.37	.14	2.40	3.40	3.10
	B ₃	54.2	5.4	34.4	7.30	25.8	.25	(13.5)+	2.54	3.07	2.40
	B ₄	57.3	5.4	31.9	6.33	19.3	.26	(15.9)+	3.04	3.48	2.47
	D ₁	16.3	1.9	49.1	5.23	18.0	.24	9.6	4.51	4.52	2.58
	D	23.1	1.1	43.6	5.32	22.1	.17	4.4	4.79	4.52	3.26
KINBASKET	A ₂₁	18.8	1.5	56.6	5.30	25.5	.34	.24	1.68	4.49	3.04
	A ₂₂	29.6	3.5	55.5	7.97	20.1	.40	.14	1.74	4.50	4.36
	B ₂₁	35.9	3.1	51.0	9.22	26.6	.28	.10	2.18	4.57	6.40
	B ₂₂	37.5	3.2	49.9	9.58	28.4	.31	.19	2.44	4.44	5.17
	B _{Ca}	17.7	1.5	38.0	8.00	26.6	.17	.25	3.62	5.74	4.68
	C ₁	17.5	1.7	49.0	8.15	20.8	.42	.40	4.36	5.67	2.30
	C	17.8	1.9	40.8	8.08	25.7	.30	.84	4.33	5.32	3.44
YOHO	A _{2p} ★	21.5									.02
	B _p ★	30.4	2.4	-	4.83	19.1	.58	1.14	3.06	3.85	2.81
	A _{2gw} ★	15.3	1.4	-	6.37	20.5	.49	.35	3.57	5.48	.36
	B _{gw}	28.4	3.1	-	7.78	22.8	.34	.60	2.78	5.65	4.58
	C _{gw}	23.9	1.3	47.7	7.63	23.6	.32	2.68	4.11	5.30	3.64
	C	29.4	2.1	41.1	7.71	25.2	.37	5.51	4.88	4.91	3.66

+ High values may be due to incomplete removal of calcite.

★ Insufficient material for sodium carbonate fusion.

DEHYDRATION CURVES
KINBASKET SILT LOAM



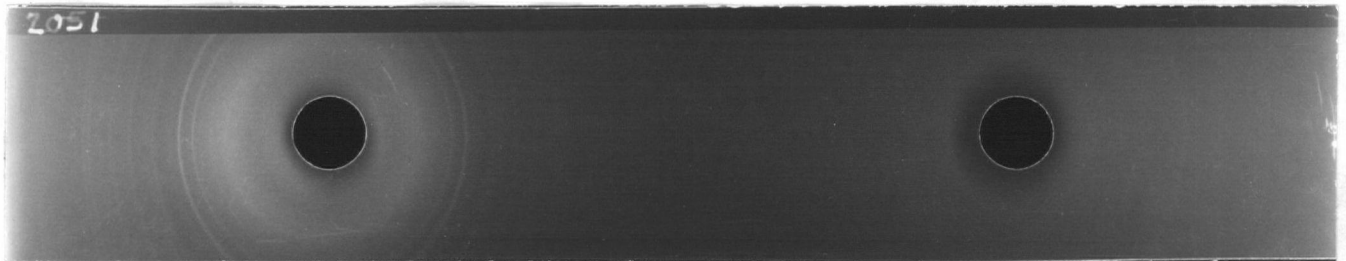
APPENDIX II

X-RAY DIFFRACTION PATTERNS

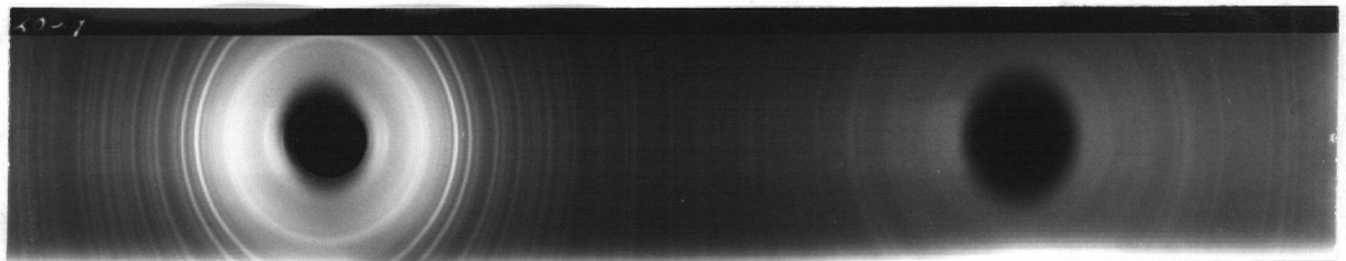
(1) WYCLIFFE A₁₂ HORIZON



(2) WYCLIFFE B₄ HORIZON

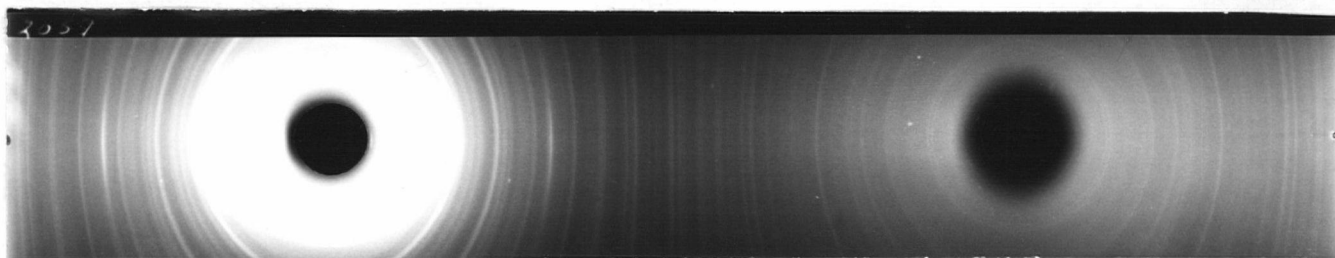


(3) WYCLIFFE D₁ HORIZON

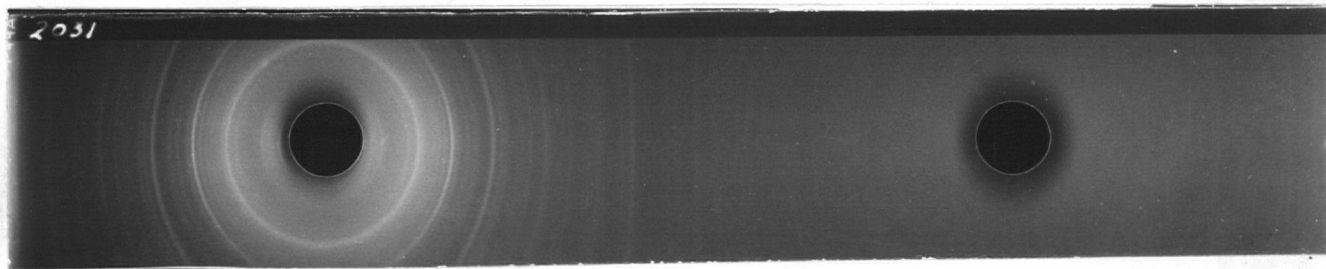


X-RAY DIFFRACTION PATTERNS

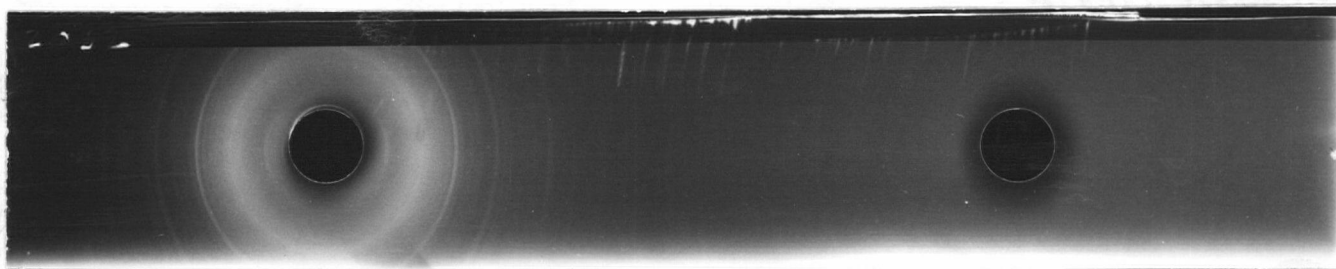
(4) KINBASKET A₂₁ HORIZON



(5) KINBASKET B₂₂ HORIZON

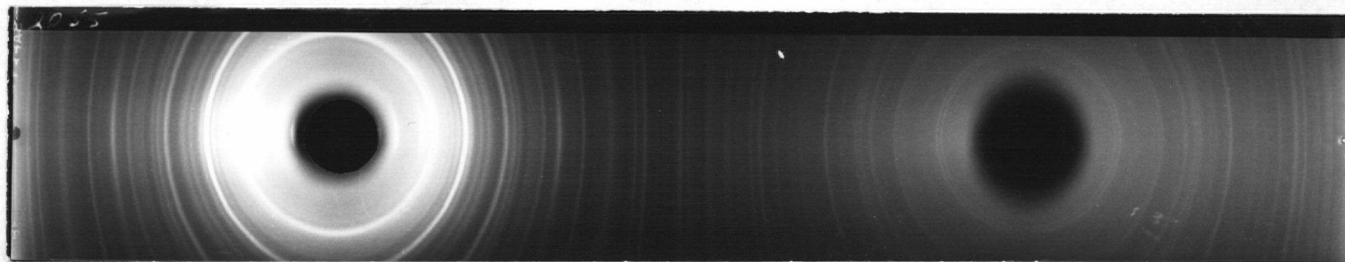


(6) KINBASKET C HORIZON

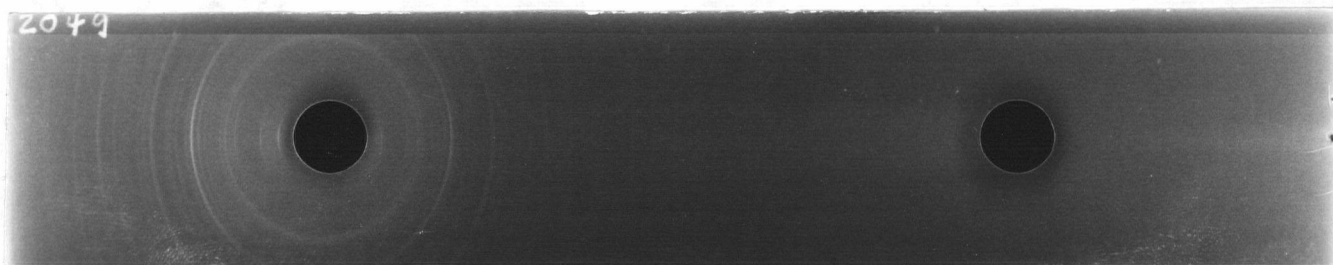


X-RAY DIFFRACTION PATTERNS

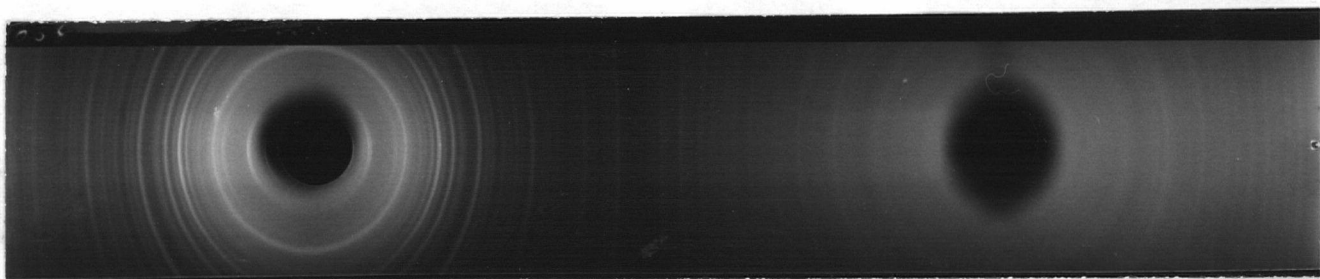
(7) YOHO A_{2p} HORIZON



(8) YOHO A_{2gw} HORIZON

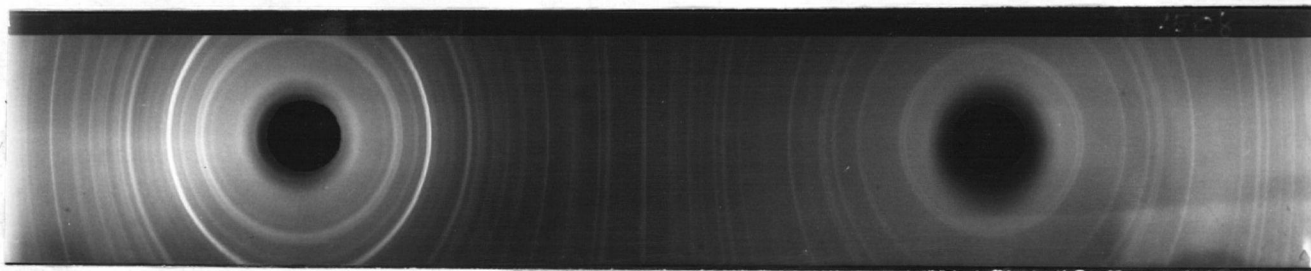


(9) YOHO C HORIZON

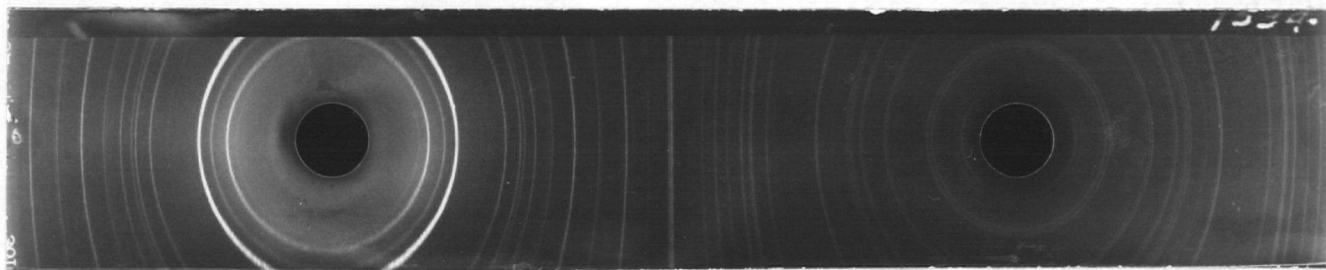


X-RAY DIFFRACTION PATTERNS

(10) FITHIAN ILLITE



(11) QUARTZ



APPENDIX III

DISTRIBUTION OF MAGNETITE IN THE HEAVY MINERAL FRACTION OF THE
VERY FINE SAND.

	HORIZON	NO. MAGNETITE GRAINS	NO. GRAINS COUNTED	PERCENTAGE OF MAGNETITE
WYCLIFFE	A ₁₂	83	1802	4.61
	B ₄	26	1974	1.32
	D	66	1564	5.55
KINBASKET	A ₂₁	57	2023	2.81
	B ₂₂	48	1636	2.94
	C	41	1564	2.62
YOHO	A _{2p}	114	1324	8.62
	B _p	281	2470	11.4
	B _{gw}	11	743	1.48
	C	8	773	1.03

LITERATURE CITED.

1. Aarnio, B. 1913 The precipitation of iron in podzol soils. Inst. Mitt. Bodenk 3: 131.
2. Adams, J. E. ; Matelski, R. T. 1955 Distribution of heavy minerals and soil development in Scott silt loam. Soil Sci. 79: 59-69.
3. Aguilera, N. H. ; Jackson, M. L. 1953 Iron oxide removal from soils and clays. Soil Sci. Soc. Amer. Proc. 17: 359-364.
4. Ambroz, H. 1955 (The composition and changes of humus in some forest soils). Fol. Biol. 1: 48-53.
5. American Petroleum Institute 1950 Analytical data on reference clay materials. Amer. Petroleum Inst. Project 49, Prelim. Rept. No. 7, Columbia University, New York.
6. American Society for Testing Materials 1950 Procedures for Testing Soils.
7. Antevs, E. 1945 Correlation of Wisconsin glacial maxima. Amer. J. Sci. 243-A: 1-39.
8. Arscott, T. G. 1956 Moisture studies on some soils of the Rocky Mountain Trench. Graduate Essay; Department of Soil Science, The University of British Columbia.
9. Barshad, I. 1948 Vermiculite and its relation to biotite as revealed by base exchange reactions, X-ray analysis, differential thermal curves and water content. Amer. Mineralogist 33: 655-678.
10. Bell, G. M. 1952 The Structure of the Clay Minerals. D. Sc. Thesis Mass. Inst. Tech.
11. Bloomfield, C. 1953 A study of podzolization. Pt. I. The mobilization of iron and aluminium by Scots pine needles. J. Soil Sci. 4: 5-16.
12. _____ 1954a A study of podzolization. Pt. III. The mobilization of iron and aluminium by rimu. ibid 5: 39-45.
13. _____ 1954b IV The mobilization of iron and aluminium by picked and fallen larch needles. ibid 5: 46-49.
14. _____ 1954c V The mobilization of iron and aluminium by aspen and ash leaves. ibid 5: 50-56.
15. _____ 1955 Experimental production of podzolization. Chem. and Indust. 1596-1597 Abstr. Soils and Fert. 29 (1591).
16. _____ 1956 The movement of sesquioxides and clay in the soil. Afr. Soils 3: 488-506 Abstr. Soils and Fert. 29 (1592).

17. Boekel, P. ; Peerlkamp, P. L. 1956 Soil consistency as a factor determining the structure of clay soils. Netherlands J. Agric. Sci. 4: 122-125.
18. Bower, C. A. ; Reitemeier, R. F. ; Fireman, M. 1952 Exchangeable cation analysis of saline and alkali soils. Soil Sci. 73: 251-261.
19. Bremner, J. M. 1956 Some soil organic matter problems. Soils and Fert. 29: 115-123.
20. Brewer, R. 1956 A petrographic study of two soils in relation to their origin and classification. J. Soil Sci. 7: 268-279.
21. Brink, V. C. 1948 Climates of British Columbia for Agrologists. Pt. I. Tech. Comm. Agronomy Dept., The University of British Columbia.
22. Brown, G. 1953 A semi-micro method for the preparation of soil clays for X-ray diffraction studies. J. Soil Sci. 4: 229-232.
23. Burmister, D. M. 1950 Identification and Classification of Soils - An Appraisal and Statement of Principles. Special Tech. Publ. No. 113. Amer. Soc. Testing Materials.
24. _____ 1954 Principles of Permeability Testing. Symposium on Permeability of Soils. A. S. T. M. Spec. Publ. 163.
25. Carroll, D. 1944 Mineralogical examination of some soils from Southwestern Australia. J. Dept. Agr. West. Aust. 21: 85-93.
26. Casagrande, A. 1947 Classification and identification of soils. Proc. Amer. Soc. Civil Eng. June, 1947.
27. Chapman, H. D. ; Kelley, W. P. 1930 The determination of the replaceable bases and the base exchange capacity of soils. Soil Sci. 30: 391-406.
28. Cheng, K. L. ; Bray, R. H. 1951 Determination of calcium and magnesium in soil and plant materials. Soil Sci. 72: 449-458.
29. _____ ; Melsted, S. W. ; Bray, R. H. 1953 Removing interfering metals in the versenate determinations of calcium and magnesium. Soil Sci. 75: 37-40.
30. Chillingar, G. V. 1956 Relationship between Ca/Mg ratio and geologic age. Bull. Amer. Ass. of Petroleum Geologists 40: 2256-2266.
31. Cline, M. G. 1949 Profile studies of normal soils of New York I. Soil Sci. 68: 259-272.
32. Coleman, R. ; Jackson, M. L. 1946 Mineral composition of clay factor of several coastal plain soils of southeastern United States.

33. Coleman, N. T. ; Jackson, M. L. ; Mehlich, A. 1950 Mineral composition of the clay fraction II. Soil Sci. Soc. Amer. Proc. 14: 81-85.
34. Connor, A. J. 1949 The frost-free season in British Columbia. Meteorological Div., Dept. of Transport, Toronto, Ontario.
35. Coppenet, M. ; Helias, M. Le fer et le manganese dans quelques profils caracteristiques du Finistere. Bull. Ass. franc Et. Sol No. 76: 476-483.
36. Corey, R. B. ; Jackson, M. L. 1953 Rapid silicate analysis for Si, Al, Fe, Ti, Ca, Mg, Na, K. Anal. Chem. 25: 624-628.
37. Davenport, W. H. 1949 Determination of aluminum in the presence of iron. Anal. Chem. 21: 710-711.
38. Day, P. R. 1950 Physical basis of particle size analysis by the hydrometer method. Soil Sci. 70: 363-374.
39. DeLong, W. A. ; Schnitzer, M. 1955 Investigation on the mobilization and transport of iron in forested soils: I. The capacities of leaf extracts and leachates to react with iron. Soil Sci. Soc. Amer. Proc. 19: 360-363.
40. Duchaufour, P. 1955 (Note on the mineralogical analysis of sands, in pedology). Bull. Ass. franc Et Sol. 70: 318-323.
41. Ehrlich, W. A. ; Chapman, L. J. ; Rice, H. M. 1957 (Unpublished Report).
42. _____ ; Rice, H. M. 1955 Postglacial weathering of Mankato till in Manitoba. J. Geol. 63: 527-537.
43. _____ ; _____ ; Ellis, J. H. 1955 Influence of the composition of parent materials on soil formation in Manitoba. Canad. J. Agric. Sci. 35: 407-421.
44. Ellis, J. H. 1938 The Soils of Manitoba. Manitoba Economic Survey Board, Province of Manitoba.
45. Farstad, L. ; Laird, D. G. 1954 Soil Survey of the Quesnel, Nechako, Francois Lake and Bulkley - Terrace Areas in the Central Interior of British Columbia. Rept. No. 4, B. C. Soil Survey.
46. _____ ; Leahey, A. 1949 Soils of the Canadian Cordillera in British Columbia. Proc. 7th Pac. Sci. Congr. 6: 10-16.
47. Flint, R. F. 1947 Glacial Geology and the Pleistocene Epoch. John Wiley and Sons, New York.
48. Frei, E. 1950 Genesis of various types of soil structure. 4th Int. Congr. Soil Sci. 1: 46-48.

49. Gallagher, P. H. ; Walsh, T. 1943 The solubility of soil constituents in oxalic acid as an index to the effects of weathering. Proc. Roy. Irish Acad. 49: B. I.
50. Gardner, W. R. 1956 Representation of soil aggregate - size distribution by a logarithmic - normal distribution. Soil Sci. Soc. Amer. Proc. 20: 151-153.
51. Graham, E. R. 1953 Soil mineralogy as an index to the trace element status of some Australian soils. Soil Sci. 75: 333-340.
52. Greene - Kelley, R. 1953 The identification of montmorillonoids in clays. J. Soil Sci. 4: 233-237.
53. Grim, R. E. 1953 Clay Mineralogy, McGraw Hill Company.
54. _____ ; Bray, R. H. ; Bradley, W. F. 1937 The mica in argillaceous sediments. Amer. Mineralogist 22: 813-829.
55. _____ ; Lamar, J. E. ; Bradley, W. F. 1937 The clay minerals in Illinois limestones and dolomites. J. Geol. 45: 829-843.
56. _____ ; Rowland, P. A. 1941 Amer. Mineralogist 27: 746-761.
57. Hallsworth, E. G. ; Costin, A. B. ; Gibbons, F. R. 1953 Studies in pedogenesis in New South Wales VI. On the classification of soils showing features of podzol morphology. J. Soil Sci. 4: 240-256.
58. Handley, W. R. C. 1954 Mull and Mor Formation in Relation to Forest Soils. Forestry Commission Bull. No. 23. H. M. S. O.
59. Hansen, H. P. 1947 Post-glacial Forest Succession, Climate and Chronology in the Pacific Northwest. Trans. Amer. Phil. Soc. 37, Part I (New Series).
60. _____ 1955 Post-glacial forests in South - Central and Central British Columbia. Amer. J. Sci. 253: 640-658.
61. Holt, R. F. ; McMillar, P. R. 1956 Characteristics of some forest soils from the gray - brown podzolic - podzol transition zone in Northeastern Minnesota. Soil Sci. Soc. Amer. Proc. 20: 84-87.
62. Jackson, M. L. ; Hellman, N. N. 1942 X-ray diffraction procedure for positive differentiation of montmorillonite from hydrous mica. Soil Sci. Soc. Amer. Proc. 6: 133-145.
63. _____ ; Hseung, Y. ; Corey, R. B. ; Evans, E. J. ; Van der Heuvel, R. C. 1952 Weathering sequence of clay-size minerals in soils and sediments II. Chemical weathering of layer silicates. Soil Sci. Soc. Amer. Proc. 16: 3-6.
64. _____ ; Tyler, S. A. ; Willis, A. L. ; Bourbeau, G. A. ; Tennington, R. P. 1948 Weathering sequence of clay-size minerals in soils and sediments I. J. Phys. Colloid Chem. 52: 1237-1260.

65. Jeffries, C. D. 1937 Mineralogical composition of the very fine sands of some Pennsylvania soils. Soil Sci. 43: 357-366.
66. _____ 1947 A rapid method for the removal of free iron oxides prior to petrographic analysis. Soil Sci. Soc. Amer. Proc. 11: 211-212.
67. _____ ; Jackson, M. L. 1949 Mineralogical analysis of soils. Soil Sci. 68: 57-74.
68. _____ ; Marshall, C. E. 1946 Mineralogical methods in soil research. Soil Sci. Soc. Amer. Proc. 10: 397-405.
69. Joffe, J. S. 1937 A pedological study of some soils in New Jersey. Soil Sci. 43: 221-238.
70. _____ 1949 Pedology. Pedology Publications. New Brunswick, New Jersey.
71. Keller, W. D. 1956 Clay minerals as influenced by environments of their formation. Bull. Amer. Ass. Petroleum Geologists 40: 2689-2710.
72. Kelley, C. C. 1955 Soil Survey of the Upper Kootenay and Elk River Valley, British Columbia. B. C. Soil Survey; Report No. 5.
73. _____ 1956 Draft description of certain soil types (Unpublished) Soil Survey of the Upper Columbia River Valley.
74. _____ ; Farstad, L. 1946 Soil Survey of Prince George Area, B. C. Soil Survey - para. No. 2.
75. _____ ; Sprout, P. N. 1955 Soils of the East Kootenay District. Agronomists Conference, Vancouver, B. C. January 1955.
76. Kilmer, V. J. ; Alexander, L. T. 1949 Methods of making mechanical analyses of soils. Soil Sci. 68: 15-24.
77. Kononova, M. M. 1956 (The humus of the most important soil types of the U.S.S.R., its nature and methods of formation). Pochvovedenie No. 3: 18-30.
78. Krusekopf, H. H. 1925 The Brown Soils of the North-Central States. Amer. Soil Survey Assn. Bull. 62: 146-148.
79. Lambe, T. W. 1954 The permeability of fine grained soils. Amer. Soc. Testing Mat. Proc. 59.
80. Leahey, A. 1946 The agricultural soil resources of Canada. Agric. Inst. Review 1: 285.

81. Leahey, A. 1953 Preliminary soil survey of lands adjacent to the MacKenzie Highway in the Northwest Territories. Expt. Farms Services, Ottawa.
82. Lindsay, J. D. 1954 A comparative study of five soil profiles from the East Kootenay District of British Columbia. M. S. A. Thesis, The University of British Columbia.
83. Low, A. J. 1954 The study of soil structure in the field and the laboratory. J. Soil Sci. 5: 57-74.
84. Lundblad, K. 1934 Studies on podzols and brown forest soils I. Soil Sci. 37: 137-155.
85. _____ 1936 Studies on podzols and brown forest soils II and III
ibid 41: 295-313, 318-394.
86. Lutwick, L. E. ; Coldwell, B. B. ; DeLong, W. A. 1952 Leachates from decomposing leaves - Part I. Some general characteristics. Sci. Agric. 32: 603.
87. MacEwan, D. M. C. 1949 Some notes on the recording and interpretation of X-ray diagrams of soil clays. J. Soil Sci. 1: 90-103.
88. MacKenzie, R. C. 1951 A micro-method for determination of cation exchange capacity of clay. Clay Miner. Bull. 1: 203.
Jour. Colloid Sc. 6: 219-222.
89. _____ 1954 Free iron oxide removal from soils. J. Soil Sci. 5: 167-175.
90. _____ et al. 1947 Mineralogy Mag. 28: 704-713.
91. Marshall, C. E. 1940 A petrographic method for the study of soil formation processes. Soil Sci. Soc. Amer. Proc. 5: 100-103.
92. Martin, A. E. ; Reeve, R. 1955 A rapid manometric method for determining soil carbonate. Soil Sci. 79: 187-197.
93. _____ ; Torrence, R. ; Bushnell, M. B. 1952 Clay minerals of four Southern New York soils. Soil Sci. 74: 267-279.
94. Matelski, R. P. 1951 Separation of minerals by subdividing solidified bromoform after separation. Soil Sci. 71: 269-272.
95. McHenry, J. R. 1952 Clay mineralogy of recent glacial alluvium soils of Western Washington. Soil Sci. 74: 281-285.
96. McKeague, J. A. 1955 Soil Moisture Studies on Some Soils of the Rocky Mountain Trench. B. S. A. Essays. 1955.
97. Mehlich, A. 1948 Determination of cation and anion exchange properties of soils. Soil Sci. 66: 429-445.

98. Mehlich, A. 1953 Rapid determination of cation and anion exchange properties and pH of soils. J. Ass. Off. Agric. Chem. 36: 445-457.
99. Metson, A. J. 1956 Methods of Chemical Analysis for Soil Survey Samples. N. Z. Dept. Scientific and Industrial Research. Soil Bureau Bull. 12.
100. Miller, R. W. 1956 The fertility of Western Washington soils with respect to potassium. Project 92, Dept. Agron. Wash. Agric. Exp. Stations.
101. Milne, I. H. ; Warshaw, C. M. 1956 Methods of preparation and control of clay mineral specimens in X-ray diffraction analysis. Proc. 4th Nat. Conf. on Clays and Clay Minerals. Nat. Acad. Sci. Publ. 456.
102. Moss, H. C. 1938 The morphology and composition of Saskatchewan podzolic soils. Sci. Agric. 18: 708.
103. _____ ; St. Arnauld, R. J. 1955 Gray-wooded (podzolic) soils of Saskatchewan, Canada. J. Soil Sci. 6: 293-310.
104. Murray, H. H. ; Leininger, R. K. 1956 Effect of weathering of clay minerals. Proc. 4th Nat. Conf. on Clays and Clay Minerals. Nat. Acad. Sci. Publ. 456.
105. Nagelschmidt, G. 1944 Min. Mag. 27: 59.
106. National Soil Survey Committee 1955 Report on the Third Conference of the National Soil Survey Committee.
107. Nelson, B. W. 1956 The illites of some Northern Illinois shales. 4th Nat. Conf. on Clays and Clay Minerals. Nat. Acad. Sciences, Publ. 456.
108. Nikiforoff, C. C. ; Drosdoff, M. 1943 Genesis of a clay pan soil. Soil Sci. 56: 43.
109. Nygard, I. J. ; McMillar, P. R. ; Holt, F. D. 1952 Characteristics of some podzolic brown forest and chernozem soils of the northern portion of the Lake States. Soil Sci. Soc. Amer. Proc. 16: 123.
110. Odynsky, W. ; Newton, J. D. 1950 Soil Survey of the Rycroft and Watino Sheets. Rept. No. 15, Alberta Soil Survey, University Alberta Bull. No. 53.
111. Palache, C. ; Berman, H. ; Frondel, C. 1944 Dana's System of Mineralogy. Vol. I, John Wiley and Sons.
112. Pauling, L. 1930 Proc. Nat. Acad. Sci. U. S. 16: 578.

113. Pienaar, W. J. ; Lotz, E. S. V. ; Pigget, J. E. H. 1955 A few observations in connection with the flame photometric determination of potassium, calcium and sodium in plant materials with the aid of the Beckman flame spectrophotometer. S. Agr. Dept. Agric. Sci. Bull. 362, pp. 23 Abstr. Soils and Fert. 29 (1896).
114. Piper, C. S. 1950 Soil and Plant Analysis, Interscientific Publishers Inc., New York.
115. Ramann, E. 1928 The Evolution and Classification of Soils. (English Translation). W. Heffer and Sons, Cambridge.
116. Rice, H. M. A. 1936 Glacial phenomena near Cranbrook, British Columbia. J. Geol. 44: 68-73.
117. _____ 1937 Can. Geog. Soc. Mem. 207.
118. Robbins, C. ; Keller, W. D. 1952 Clay and other noncarbonate minerals in some limestones. J. Sed. Petrology 22: 146-152.
119. Robichet, O. 1955 The action of the method of extraction of free iron oxides in soils on certain ferruginous products. Compt. rend. 240: 1354-1355. Chem. Abstr. 49, No. 20 (14243).
120. Rolfe, B. N. ; Jeffries, C. D. 1952 A new criterion for weathering in soils. Science 116: 599-600.
121. Rowles, C. A. ; Farstad, L. ; Laird, D. G. 1956 Soil resources of British Columbia. 9th B. C. Nat. Resources Conf. 84-112.
122. Roy, R. 1949 Decomposition and resynthesis of the micas. J. Amer. Ceram. Soc. 32: 202-210.
123. Schnitzer, M. ; DeLong, W. A. 1955 Investigation on the mobilization and transport of iron in forested soils II. The nature of the reaction of leaf extracts and leachates with iron. Soil Sci. Soc. Amer. Proc. 19: 363-368.
124. Schofield, S. J. 1920 The origin of the Rocky Mountain Trench. Trans. Roy. Soc. Can. 14: 61-97.
125. Smithson, F. 1950 Mineralogy of Arenaceous deposits. Sci. Prog. 38: 1021.
126. _____ 1953 The micro-mineralogy of North Wales Soils. J. Soil Sci. 4: 194-211.
127. _____ 1956 Silica particles in some British soils. J. Soil Sci. 7: 122-129.
128. Stace, H. C. T. 1956 The use of sodium dithionite for the removal of free ferric oxides from soils and clays. C.S.I.R.O. (Australia) Soils Div. Rept. 3/56 pp7. Abstr. Soils and Fert. 29 (1905).

129. Stobbe, P. C. ; Leahey, A. 1944 Guide for the Selection of Agricultural Soils. Dominion of Canada, Dept. of Agriculture, Publ. 748.
130. Swenson, R. M. ; Riecken, F. F. 1955 Movement of iron in the development of loess-derived Brunizem soils. Soil Sci. 79: 177-186.
131. Tamm, O. 1930 The brown forest soils in Sweden. Ztsch. Schwed. Forstvereins 28: 1-41.
132. ——— 1932 Der braune waldboden in Scheden. Proc. and Papers, Second Int. Congr. Soil Sci. 5: 178-189.
133. ——— 1950 Northern Coniferous Forest Soils. Translated by M. L. Anderson. Scrivenor Press, Oxford.
134. Tamura, T. 1956 Mixed layer clays in New England Soils. Proc. 4th Nat. Conf. on Clays and Clay Minerals. Nat. Acad. Sci. Publ. 456.
135. Tedrow, J. C. F. 1954 Clay minerals in three podzol profiles. Soil Sci. Soc. Amer. Proc. 18: 479-481.
136. Thompson, J. Goldsmith 1953 Preliminary note on a suggested new method for exchangeable bases in calcareous soils. J. Soil Sci. 4: 238-240.
137. Thorp, J. ; Smith, G. D. 1949 Higher categories of soil classification. Soil Sci. 67: 117-126.
138. Tobia, S. K. ; Milad, N. E. 1956 Determination of exchangeable calcium in soils containing calcium carbonate. J. Sci. Food Agric. 7: 314-319.
139. Toth, S. J. ; Prince, A. L. 1945 Estimation of cation exchange capacity and exchangeable Ca, K and Na contents of soil by flame photometer techniques. Soil Sci. 67: 439-445.
140. Tucker, B. M. 1954 The determination of exchangeable calcium and magnesium in carbonate soils. Aust. J. Agric. Res. 5: 706-715.
141. Turekian, K. K. 1956 Rapid technique for determination of carbonate content of deep sea cores. Bull. Am. Ass. Petr. Geol. 40: 2507-2509.
142. Turner, R. C. ; Clark, J. S. 1956 The pH of calcareous soils. Soil Sci. 82: 337-341.
143. Twenhofel, W. H. ; Tyler, S. A. 1941 Methods of Study of Sediments. McGraw Hill Inc.

144. Tyurin, I. V. 1930 Genesis and classification of forest-steppe and forest soils. *Pedology* 25, No.5: 104-141.
145. United States Army Corps of Engineers 1953 The Unified Soil Classification System. Tech. Mem. 3-357.
146. United States Department of Agriculture 1954 Diagnosis and Improvement of Saline and Alkali Soils. Agriculture Handbook No. 60.
147. Walker, J. F. 1926 Geology and Mineral Deposits of the Windermere Map Area. G. S. C. Memoir 148.
148. Walkley, A. A. 1947 A critical examination of a rapid method for determining organic carbon in soils - effect of variations in digestion conditions and inorganic soil constituents. *Soil Sci.* 63: 251-264.
149. Warder, F. G. ; Dion, H. G. 1952 The nature of the clay minerals in Saskatchewan soils. *Sci. Agriculture* 32: 535-547.
150. White, W. A. 1949 Atterburg plastic limits of clay minerals. *Am. Mineralogist* 34: 508-512.
151. Wilde, S. A. ; Voight, G. K. ; Pierce, R. S. 1954 The relationship of soils and forest growth in the Algoma District of Ontario, Canada. *J. Soil Sci.* 5: 22-38.
152. Williams, B. H. ; Bowser, W. E. 1952 Gray-wooded soils in parts of Alberta and Montana. *Soil Sci. Soc. Amer. Proc.* 16: 130-133.
153. Winters, E. 1938 Ferromanganiferous concretions from some podzol soils. *Soil Sci.* 46: 33-40.
154. Whittig, L. D. ; Jackson, M. L. 1956 Proc. 4th Nat. Conf. on Clays and Clay Minerals. *Nat. Acad. Sci. Publ.* 456.
155. Wyatt, F. A. ; Newton, J. D. 1928 Proc. 1st Int. Congr. Soil Sci. Comm. V: 358.
156. Yaalon, D. H. 1955 Clays and some non-carbonate minerals in limestones and associated soils of Israel. *Bull. Res. Coun. Israel* 5B: 161-167.
157. Yoe, J. H. ; Armstrong, A. R. 1947 Colorimetric determination of titanium with disodium - 1,2 dihydroxybenzene 3,5 disulphonate. *Anal. Chem.* 19: 100-102.