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Clay mineralogy of late Pleistocene sequences in northwestern Washington and southwestern British Columbia

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CLAY MINERALOGY OF LATE PLEISTOCENE SEQUENCES IN NORTHWESTERN WASHINGTON AND SOUTHWESTERN BRITISH COLUMBIA

by

Michael Arthur Hepp

Accepted in Partial Completion

of the Requirements for the Degree

Master of Science

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Michael Hepp
February 14, 2018

CLAY MINERALOGY OF LATE PLEISTOCENE SEQUENCES IN NORTHWESTERN WASHINGTON AND SOUTHWESTERN BRITISH COLUMBIA

A Thesis

Presented to

The Faculty of

Western Washington State College

In Partial Fulfillment

of the Requirements for the Degree

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INTRODUCTION

Pleistocene clay-bearing sediments of parts of northwestern Washington and southwestern British Columbia were studied in an attempt to determine the clay mineral composition of these units; the origin of these clay minerals; and any correlation between clay mineral composition, sediment type, location, or probable geologic history of the sediments.

The Pleistocene stratigraphy of the area is fairly well known, although in some specific locations the stratigraphy has not been determined. Recorded work in the region dates back to Dawson (1887).

The units studied range in age from the greater than 50,000 year old Double Bluff Drift to Holocene (Recent) river sediments. The units are composed of silt, clay, peat, gravel, sand, till and glaciomarine drift.

Previous studies of the clay mineralogy of Pleistocene and Holocene units in the vicinity of the study area and their source rocks are quite limited. Subbarao (1953) found kaolinite, illite and chlorite in glacial clay in Seattle, Washington. Mullineaux, Nichols and Speirer (1964) found a greenish zone of weathered clay on unweathered pre-Vashon Drift on Capitol Hill in Seattle. The clay minerals in the unweathered sample consisted of chlorite, illite and montmorillonite in order of decreasing abundance. In the upper portion of the weathering profile, montmorillonite was the most abundant constituent, chlorite and kaolinite were next most abundant, but illite was not found. Mullineaux (1967) reported nonglacial clay at the same Capitol Hill location to be similar to those in the weathered deposits. Kelly (1970) found illite, chlorite and vermiculite in rocks of the basal Chuckanut For-

mation near Lake Samish. Reynolds (1971) found vermiculite, mixed-layer vermiculite-phlogopite, ferruginous bauxite, and montmorillonite-group minerals to be forming in the northern Cascades at the present time.

Willman, Glass and Frye (1963 and 1966) studied in detail the clay mineralogy of Pleistocene tills and their weathering profiles in Illinois. Distinct differences in the clay mineralogy of the different tills were found. This report is an attempt to do a similar study on the glacial deposits of the north and central Puget Lowland, Fraser Lowland, San Juan Islands and Cascade foothills in Washington and British Columbia.

Samples were collected from sea cliffs, road cuts, gravel pits, river banks and river beds from sea level to an elevation of six hundred feet in the Cascade foothills. The sample sites were chosen because of their known or postulated stratigraphic position. A total of 85 samples were analyzed during the course of this study.

ACKNOWLEDGEMENT

I am grateful for the patient help and guidance given me by Dr. Ada Swineford, Dr. Don J. Easterbrook and Dr. David Pevear during the course of this study. I would like to thank Mr. Barnum and the many other landowners who gave me permission to collect samples of their property. I would also like to thank my wife, Patricia Lynn Hepp, for her encouragement and patience during this study.

Michael Arthur Hepp

REGIONAL SETTING

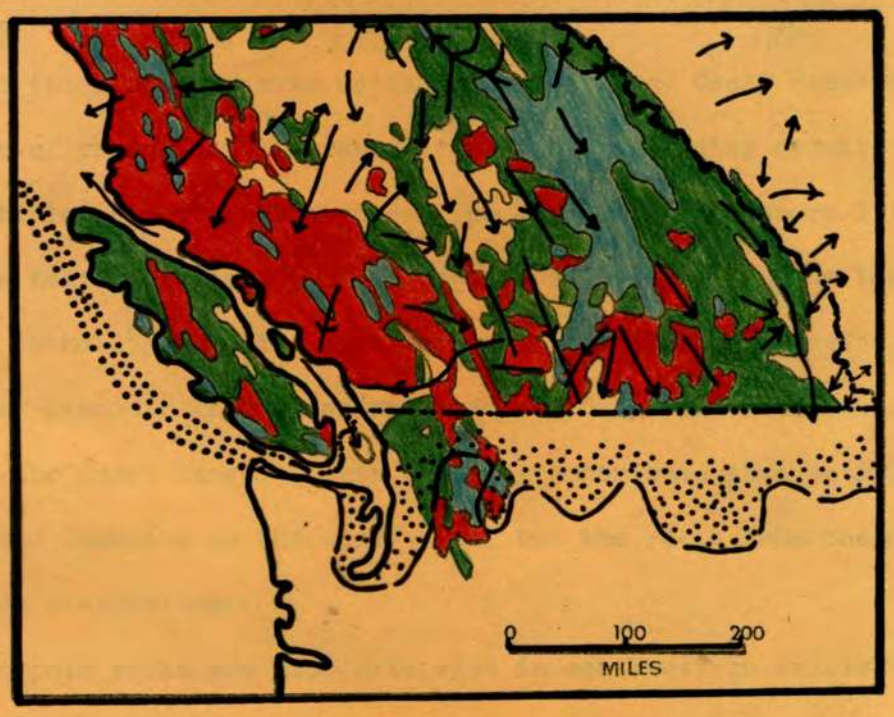
The Pleistocene and Holocene deposits studied occur in the northern and central Puget Lowland, the foothills on the western edge of the Cascade Mountains, the San Juan Islands, and the Fraser Lowland in northwestern Washington and southwestern British Columbia. The area is bordered on the north by the southern edge of the Coast Mountains, on the west by the Olympic Mountains and Vancouver Island, on the east by the Cascade Mountains, and on the south by a line approximating 48°N latitude. The western portion of this area is composed of numerous islands surrounded by salt water. The eastern portion consists of four broad alluvial valleys and the Cascade foothills.

SOURCE AREAS

Three probable sources for the late Pleistocene and Holocene deposits studied are (1) the Cascade Range to the east, (2) southwestern British Columbia, and (3) local units in the lowlands. Easterbrook (1963) found (1) rock typical of a Canadian provenance in the Bellingham Glaciomarine Drift in a deposit near Deming, Washington, (2) sand fragments of local provenance in the Deming Sand at the same location, and (3) rock types from the Cascades in the present Nooksack river at the same location. The large quantity of British Columbia-derived rock fragments found in the glacial deposits indicates that southwestern British Columbia is the principal source of the glacial deposits in the study area (Fig. 1). Easterbrook and Rahm (1970) reported glacial erratics of Canadian rock types as high as 5,700 feet in the Cascades. The rock fragments found in the interglacial and nonglacial deposits studied indicate that the Washington Cascades and local units are major sources

Generalized directions of glacial movements

Border zone of glaciated areas (known, postulated)



High Grade Metamorphic Rocks

Low Grade Metamorphic Rocks

Granitic Rocks

Other Unmetamorphosed Rocks

Fig. 1. Generalized geologic map of southern British Columbia and northwestern Washington (after Monger and Hutchison, 1971) with overlay of glacial features (Stockwell, 1963).

of the material in these deposits.

British Columbia Source Area

Many people have studied the geology of southwestern British Columbia. The following is a summary of work reported by Stockwell (1963) and Monger and Hutchison (1971). Most of the rocks in this area are either granitic intrusive or low-grade metamorphic rocks (Fig. 1). Lesser amounts of sedimentary, high-grade metamorphic and volcanic rocks are present.

One of the more extensive units is the Tertiary Coast Range Batholith, a zone of predominately granodioritic (but including granite to gabbro) multiple intrusions that underlies much of southwestern British Columbia. A coarse-grained, pink feldspar-bearing granite from the Coast Range Batholith is quite distinctive in the glacial deposits.

Smaller granitic intrusions are also found on Vancouver Island and east of the Coast Range. These probably contribute some material to the glacial deposits in the study area, but the rocks from these units are not distinctive.

Metamorphic rocks are also extensive in southwestern British Columbia. These are mainly metasediments and metavolcanics of late Paleozoic age and younger. As with the granitic rocks, fragments of the metamorphic rock types are also abundant in the Pleistocene deposits of the study area. For purposes of this study, the metamorphic rocks have been divided into low-grade metamorphic rocks (greenschist, subgreenschist and blueschist facies) and high-grade metamorphic rocks (amphibolite facies) according to the phyllosilicates present. The low-grade rocks may contain micas. The presence of chlorite in the glacial deposits should be a good indication that their source is,

at least in part, an area of low-grade metamorphic rocks. Most of the metamorphic rocks in southwestern British Columbia are of low grade, but some high-grade metamorphic rocks are also found. Nonfoliated metamorphic rocks in this area include quartzite, metagreywacke and metaconglomerate. The Jackass Mountain metaconglomerate is especially distinctive in the glacial deposits.

Unmetamorphosed sedimentary and volcanic rocks make up the remaining rocks in this area. Most of these are of Carboniferous age or younger. Most of the sedimentary rocks are shale, sandstone and conglomerate, but some limestone, greywacke and argillite are also found. Andesite and basalt are the most abundant volcanic rocks.

Washington Source Area

The following is a summary of work on the geology of northwestern Washington by Misch (1966) and Monger and Hutchison (1971). Most of the rocks in this area are similar to those found in British Columbia, but there are a few obvious differences.

Metamorphic rocks make up most of the pre-Pleistocene deposits. Low-grade metamorphic rocks (phyllites and greenstones) are especially abundant in the lowlands. Both low-grade and high-grade metamorphic rocks (greenschist to amphibolite facies) of the Yellow Aster Complex and Cascade Metamorphic Suite are abundant in the Cascades.

Sedimentary rocks are also abundant in northwestern Washington. Sandstone, shale and conglomerate of the Chuckanut and Huntingdon formations (Cretaceous to early Tertiary) are found in the lowlands and the Cascade foothills. Late Middle Paleozoic to pre-Late Cretaceous eugeosynclinal deposits composed of greywacke, chert, argillite, limestone and volcanic rocks are found along the western flank of the

Cascades. These rocks compose the Chilliwack Group, Nooksack Group, Wells Creek Volcanics and Cultus Formation.

Late Pleistocene glacial and interglacial deposits are abundant in the lowlands and probably contributed much material to later deposits. The reworking of earlier Quaternary deposits by later glaciations has complicated any attempt to use source area as a method of stratigraphic differentiation of the units studied.

Igneous rocks are more common in the Cascades than in the lowlands. Granodioritic rocks are moderately extensive in the north Cascades. The Mt. Baker Andesite is a distinctive unit in the Cascades and rock fragments from it are found in some interglacial deposits in the lowland.

LATE PLEISTOCENE AND HOLOCENE GEOLOGY

Pleistocene deposits in the study area represent at least three periods of glaciation and three interglacial or nonglacial periods (Table 1). The study of these deposits is complicated by the time-transgressive nature of their deposition. Work on the deposits dates back to 1898. Modern studies include particularly Armstrong (1956), Armstrong, Crandell, Easterbrook and Noble (1965), Crandell, Mullineaux and Waldron (1965), Easterbrook (1963, 1966, 1968 and 1969) and Easterbrook, Crandell and Leopold (1967).

Double Bluff Drift

The Double Bluff Drift is the oldest Pleistocene deposit recognized in the study area. Material overlying this unit is too old to date by C^{14} methods and no absolute date can yet be assigned to it. The Double Bluff Drift is exposed on Whidbey and Camano Islands and at Point Wilson on the Olympic Peninsula. The samples used in this study are from the

TABLE 1. CORRELATION CHART OF LATE PLEISTOCENE AND HOLOCENE DEPOSITS IN STUDY AREA

GEOLOGIC CLIMATE UNITS Crandell and others (1958) Armstrong and others (1965) Easterbrook (1969)		STRATIGRAPHIC UNITS British Columbia Armstrong and others (1965)	STRATIGRAPHIC UNITS Washington Easterbrook (1963, 1968 and 1969)	C^{14} AGE*
HOLOCENE				10,000
	Sumas Stade	Sumas Drift	Sumas Drift	11,000
FRASER GLACIATION	Everson Interstade	Whatcom Glaciomarine Drift Newton stony clay Cloverdale sediments } Capilano sediments	Bellingham Glaciomarine Drift Deming Sand Kulshan Glaciomarine Drift } Everson Glaciomarine Drift	13,000
			Partridge Gravel	
	Vashon Stade	Surrey Drift	Vashon till Esperance Sand } Vashon Drift	18,000
OLYMPIA NONGLACIAL INTERVAL		Quadra sediments	Olympia sediments	23,000 27,000
SALMON SPRINGS GLACIATION		Semiamu Drift (age unknown)	Possession Drift	35,000 47,000
PUYALLUP INTERGLACIATION			Whidbey Formation	50.000
STUCK (?) GLACIATION			Double Bluff Drift	Older than 50,000

*Because most of the units are time-transgressive the ages shown are approximate.

type locality at Double Bluff on Whidbey Island. This unit contains till, glaciomarine drift, sand and gravel. It has been tentatively correlated with the Stuck Glaciation (Easterbrook and others, 1967).

Whidbey Formation

The next younger unit is the Whidbey Formation. Peat from this unit has yielded C^{14} dates of greater than 47,600 years (Easterbrook, Personal Communication, 1972). Exposures of the Whidbey Formation are reported from Whidbey, Guemes and Camano Islands and from Point Wilson on the Olympic Peninsula (Easterbrook, 1968 and 1969). The samples used in this study are from Double Bluff and other locations on Whidbey Island. The formation consists of sand, silt, clay and peat, which were deposited in a floodplain environment during an interglaciation thought to be equivalent to the Puyallup Interglaciation.

Possession Drift

The next younger unit is the Possession Drift, which is made up of till and lesser amounts of peat, outwash deposits and glaciomarine drift. The Possession Drift has been reported on Whidbey and Guemes Islands and at Point Wilson on the Olympic Peninsula. Carbon 14 dates from Strawberry Point on Whidbey Island have given an age spread from 47,600 years B.P. to sometime between 34,900 and 27,000 years B.P. (Easterbrook, 1969), thus correlating with the Salmon Springs Glaciation.

Olympia Nonglacial Sediments

Olympia nonglacial deposits in the Puget Lowland have been correlated with the Quadra Formation of southwestern British Columbia. Samples were collected from Point Grey in British Columbia and Strawberry Point on Whidbey Island. The formation is made of sand, gravel, silt and peat

that were deposited in swamp, lacustrine and floodplain environments. Carbon 14 ages for the Quadra Formation in British Columbia indicate an interval from at least 36,000 to 24,000 years B.P. In the Seattle area the range of the Olympia nonglacial interval is from 35,000 to 15,000 years B.P. These ages indicate that the Possession Drift was deposited, at least in part, during the latter portion of this interval. Samples of peat from the Olympia sediments at Strawberry Point have given an age spread from $27,200^{+1000}_{-900}$ years B.P. to $22,700 \pm 550$ years B.P. (Easterbrook, 1969).

Fraser Glaciation

The Fraser Glaciation, which was the last major glaciation in the area, has been divided into the following units from oldest to youngest: Vashon Stade, Everson Interstade and Sumas Stade (Armstrong and others, 1965).

Vashon Stade. The Vashon Stade, represented by the Vashon Drift, includes the Esperance Sand and Vashon till. The Esperance Sand is made of sand and gravel deposited as the Vashon glacier advanced. In southwestern British Columbia deposition of the Esperance Sand was ended by advancing ice 20,000 years ago.

The Vashon till, made of compact massive till with minor sand and gravel lenses, is probably the most widespread glacial deposit in the study area. In British Columbia this unit is known as the Surrey till. Deposition of the Vashon till was ended by downwasting and floating of the glacier. In the San Juan Islands deposition ended 12,500 years B.P.

Partridge Gravel. Easterbrook (1968) reported a pebble-to-cobble gravel and sand that was deposited between the Vashon Stade and the

Everson Interstade. It is known as the Partridge Gravel from its type locality at Partridge Point on Whidbey Island. Samples were collected from this location. The Partridge Gravel was probably deposited in water near stagnating ice.

Mary Hill Mudflow. A mudflow of uncertain age was found at the Mary Hill gravel pit in Port Coquitlam, British Columbia. Sample BC-5A was collected from this location. The unit is located near the top of the pit at an elevation of 270±5'. From work by Armstrong (1965), this unit would seem to be post-Vashon Stade (Surrey Drift) and pre-Everson Interstade (Capilano sediments). Its age is about 12,000 years B.P.

The deposit is located above a 20'-thick brown sandy gravel bed (Surrey Drift) and below a 2'-thick brown clayey silt with occasional pebbles (Capilano sediments). The mudflow is composed of a 2" to 2'-thick brown sandy silt with occasional pebbles.

The mudflow was recognized by its tabular nature, diamicton texture and its clay mineral content. The tabular nature of the deposit and its diamicton texture are evidence that this unit is either a thin till, thin glaciomarine drift or a mudflow. It is unlikely for a till or glaciomarine drift to be so thin (2"). The presence of a large amount of soil-type clay mineral (mixed-layer mica-vermiculite) is good evidence of the unit's nonglacial origin. Whether the deposit was deposited subaerially or subaqueously is not known.

Everson Interstade. The Everson Interstade is represented predominantly by glaciomarine drift formed under floating ice. The floating ice resulted from an invasion of the sea as the Vashon glacier retreated and thinned. Minor peat, clay and sand also occur. Along

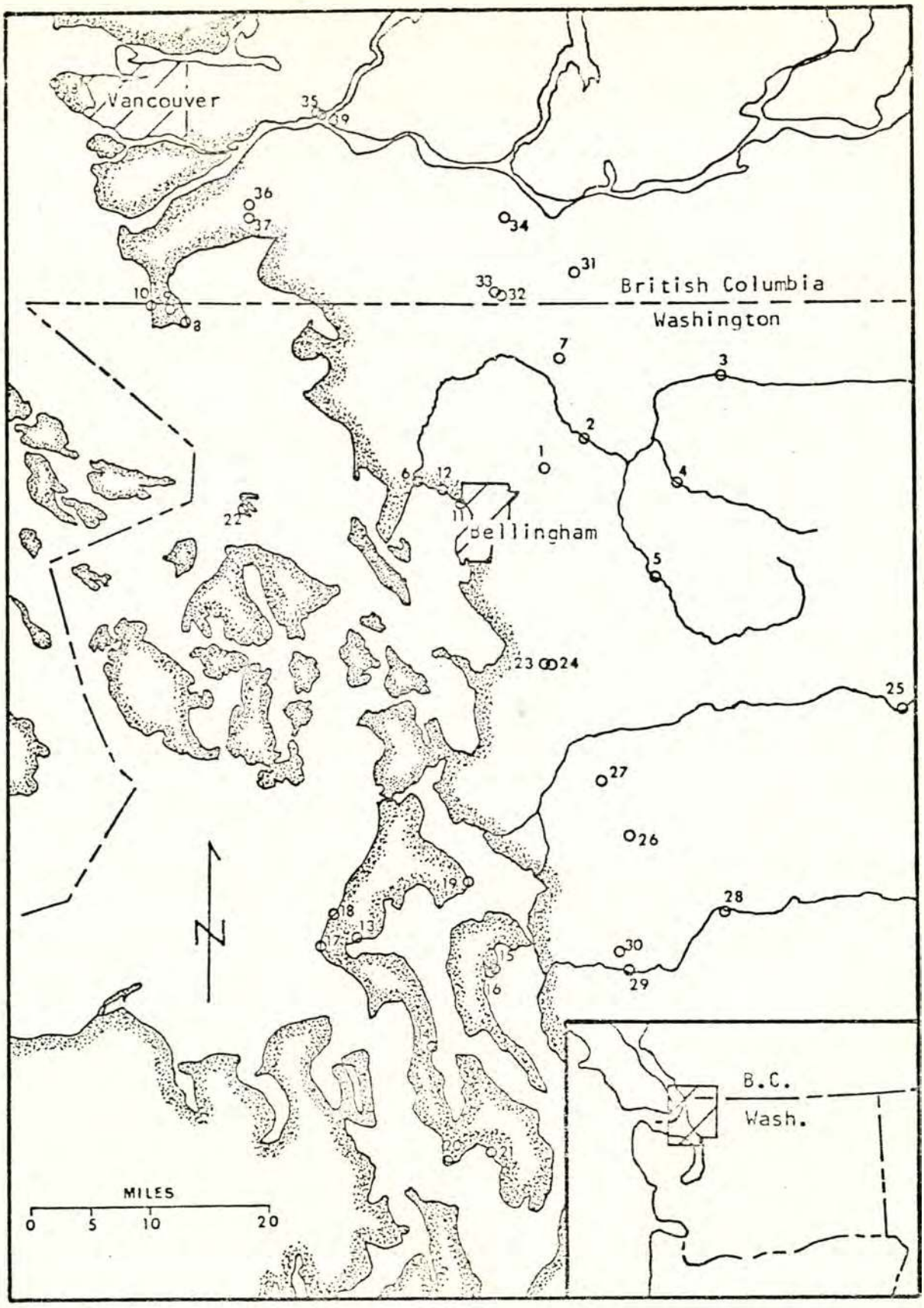


Fig. 2. Sample location map. (For location descriptions see Appendix I)

Bellingham Bay and the Nooksack River at Deming, the Everson Interstade is separated into three rock-stratigraphic units: the Kulshan Glaciomarine Drift, the Deming Sand, and the Bellingham Glaciomarine Drift. The Deming Sand was deposited during a short emergence of the land. A peat found in the Deming Sand gave a C^{14} age of 11,640±275 years B.P. to about 11,000 years B.P. (Easterbrook, 1969).

The Everson Interstade is represented by the Capilano sediments in British Columbia. The Capilano sediments are divided into three rock-stratigraphic units: the Whatcom glaciomarine deposits, the Newton stony clay, and the Cloverdale sediments.

Sumas Stade. The Sumas Stade, represented by the Sumas Drift found in the northern portion of the study area, consists of till, outwash, and ice-contact sediments. The till and outwash sediments were deposited directly on the Everson Glaciomarine Drift. Carbon 14 ages from the Fraser Lowland indicate that the advance of Sumas ice began about 11,000 years B.P. and that the deposition of outwash sediments ended about 10,000 years B.P. (Armstrong and others, 1965; Easterbrook, 1969).

Holocene Sediments

The youngest deposits studied are Recent silt, clay and sand found in transport in the major rivers in the study area. These deposits represent the present Holocene nonglacial period.

CLAY MINERALOGY

Procedures

Samples of Pleistocene sediments were collected from outcrops and streams throughout the study area (Fig. 2). Their location, color, eleva-

tion, stratigraphic location and sediment type were noted (Appendix I&II). The samples were then placed in plastic bags and taken to the laboratory for analysis with an X-ray diffractometer.

In the laboratory, the samples were dispersed in distilled water using a few drops of concentrated NH_4OH as a dispersing agent. The fraction finer than two microns was obtained through gravity settling of the slurry. This portion was drawn off by pipette and dropped onto two glass and two Coors porcelain slides which were allowed to dry at room temperature.

Diffractograms were run on an X-ray diffractometer after the slides had undergone the following treatments. Air dried glass and porcelain slides were run on the diffractometer after storage in the laboratory atmosphere. The air-dried porcelain slides were heated to 450°C and allowed to cool to room temperature. These were X-rayed, heated to 575°C for one hour, allowed to cool and X-rayed again. The other glass slides and a few other porcelain slides were exposed to an ethylene glycol atmosphere at 90°C for at least 1 1/2 hours. These slides were stored in an ethylene glycol atmosphere until they were X-rayed.

Some of the samples were also treated with HCl to determine the presence or absence of kaolinite. This treatment involved boiling the less-than-2-micron size fraction in 1N HCl for four hours and then X-raying the air dried samples.

X-ray diffractograms were recorded using a General Electric XRD-5 diffractometer with nickel filtered copper radiation at 40kv and 20ma. The range $2\theta = 2^\circ$ to $2\theta = 35^\circ$ was found to be most useful and least wasteful. A beam slit of 1°, a detector slit of $.1^\circ$ and a goniometer speed of 2° 2θ per minute were used. Range and time constants of

1000CPS/4Sec., 2000/4 and 5000/2 were used.

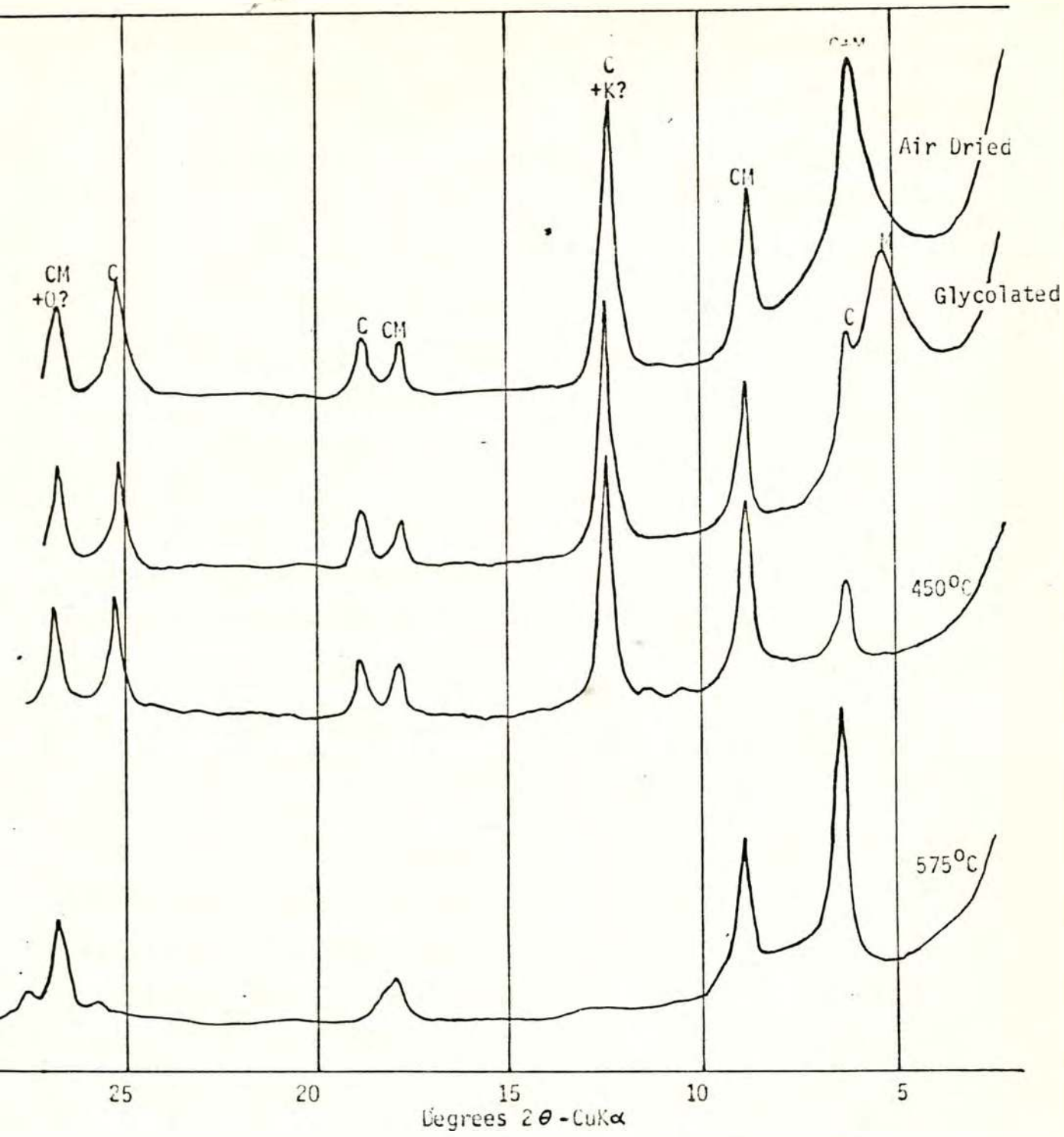
Clay Mineral Identification

The following clay mineral groups were identified by their characteristic 00ℓ reflections: montmorillonite, chlorite, clay sized micas, kaolinite and mixed-layer minerals. The following non-clay minerals were also identified from the X-ray diffractograms: quartz, amphibole and feldspars.

Montmorillonite. Material that shows expansion from about 14A to 17A on glycolation was assigned to the montmorillonite group (Fig. 3). This material could also include swelling chlorites and vermiculites, but is grouped with montmorillonite because of difficulty of positive identification. Montmorillonite group minerals were found in almost all samples. The larger amount of these minerals in the brownish samples would seem to indicate that montmorillonite is forming in the present weathering profile. This conclusion agrees with work by Reynolds (1971) and Mullineaux (1967).

Chlorite. Chlorite was identified from the presence of a 14A peak which intensified after heating to 575°C for one hour and a 7A peak which shrinks or vanishes completely after heating (Fig. 3). Chlorite is present in most of the samples tested.

Clay Micas. Clay micas were identified from a strong 10A peak that intensified on heating (Fig. 3). The minerals in this group are probably a mixture of illite and clay sized muscovite, biotite and phlogopite. There seems to be no reason to attempt to separate the different minerals. Clay mica is abundant in all samples tested and constitutes most of the



C = Chlorite
CM = Clay Mica
Q = Quartz
K = Kaolinite
M = Montmorillonite

Fig. 3. X-ray diffractograms of oriented, < 2 micron, typical sample (SK-1A).

clay fraction of some samples.

Kaolinite. Kaolinite was tentatively identified from the presence of a 7A (001) peak (Fig. 3). Other tests were needed since this peak could also belong to chlorite 002. Brown (1961, p. 85) recommended heating in HCl to destroy the chlorite. This was done with a few samples of till, glaciomarine drift and peat-associated deposits. A small amount of kaolinite was found in all samples tested. More kaolinite was found in the deposits associated with peat than the other deposits. This is typical of underclay-type deposits (Grim, 1968, p. 555-557).

Vermiculite. The presence of vermiculite cannot be determined with the techniques used in this study. The chlorite peaks occur at similar spacings and overlap those of vermiculite. Vermiculite was found in weathered material by Mullineaux (1967) and Reynolds (1971) and is probably present in the weathered material in the study area. Vermiculite is probably one of the first weathering stages of micas.

Mixed-layer Clay Minerals. A mixed-layer clay mineral showing a peak in the area of 12A was found in some of the samples (Fig. 4). This is a randomly interstratified mica-vermiculite. The changes that occur on heating indicate the mica-vermiculite nature of the material. A "shoulder" is found to appear on the low angle side of the 10A peak after heating. This would result from driving out part of the water which had expanded the mica-vermiculite layers. Rich (1958) found a similar mineral in a muscovite weathering profile in Virginia. The best examples of this material were found associated with peat deposits, especially location I-9. The origin of this clay mineral is uncertain. The most probable source is mica altering to vermiculite or vermiculite

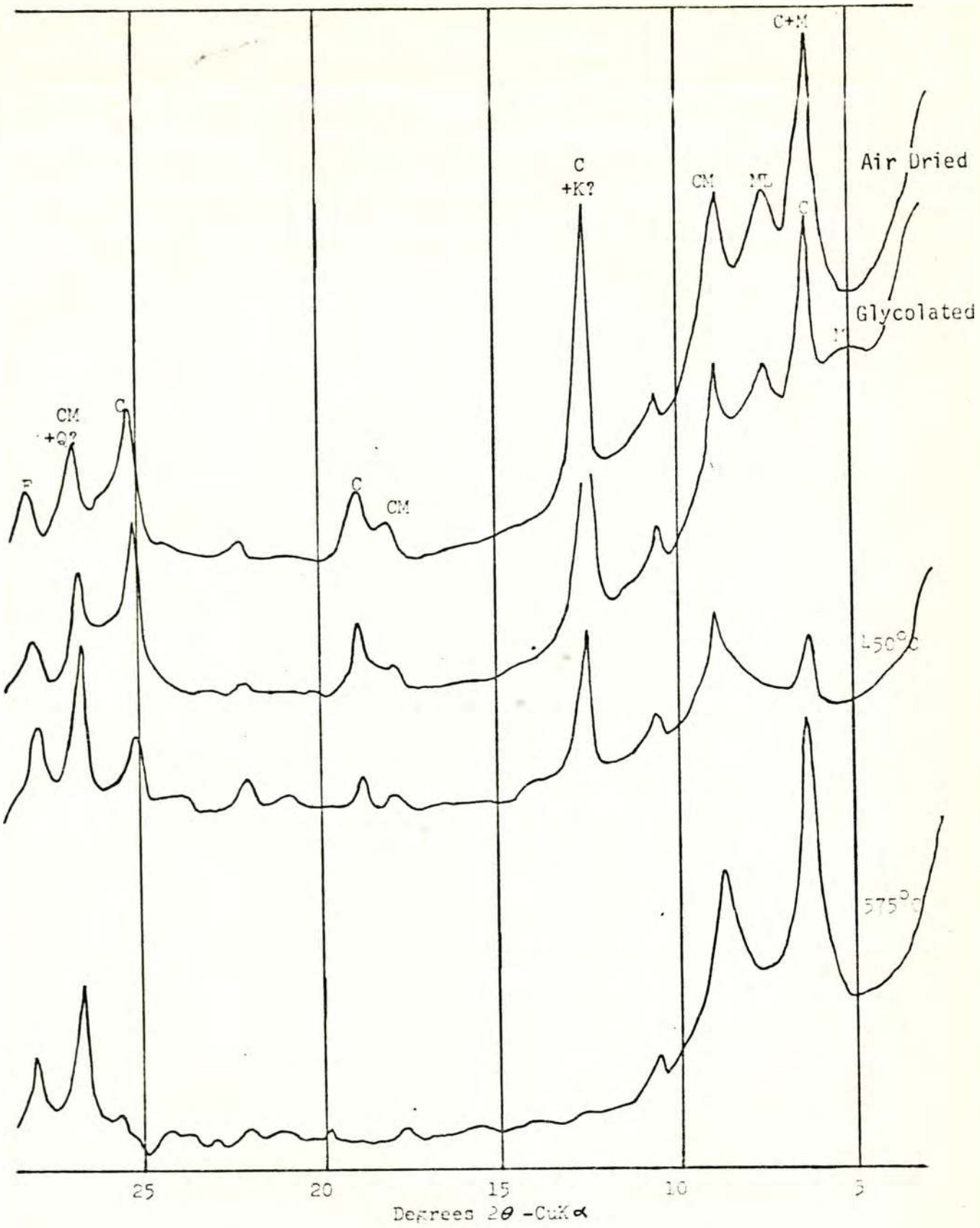


Fig. 4. X-ray diffractograms of oriented, <2 micron, sample containing 12A mixed-layer clay mineral (I-9C).

altering to mica. The former is the most logical, because it is probably easier to replace interlayer cations with water layers in a leaching environment than to introduce cations. Mixed-layer mica-vermiculite is the first weathering stage of micas. The time of formation is also in doubt, but it may be forming at the present time.

Non-Clay Minerals. Quartz, amphibole and feldspar were identified from the diffractograms. Quartz was identified from 3.35A (101) and 4.27A (100) peaks. Amphibole was identified from a peak in the vicinity of 8.5A (110). Feldspar was identified from one or two peaks in the region 3.17A to 3.22A (040 and 002).

Origin of the Clay-Sized Fraction

There are two probable origins of the clay-sized fraction in the deposits studied. The minerals were formed by mechanical disintegration before deposition or chemical weathering before and after deposition of the sediments. Determination of the most common environment is difficult, since most of the clay minerals could form in both environments, but some of the clay minerals are more indicative of one weathering environment than another. Chlorite and clay mica are indicative of a mechanical disintegration environment, hence glacial deposits in general (Millot, 1970, p. 137), while montmorillonite, kaolinite, vermiculite and the mixed-layer clays are more indicative of chemical weathering.

The extent of clay formation before deposition is more difficult to determine. The deposits, with few exceptions, seem to have undergone both mechanical disintegration and chemical weathering before deposition. The unweathered deposits contain chlorite, clay mica and montmorillonite. These minerals are indicative of both mechanical disintegration and chem-

ical weathering and indicate a complex predeposition history of the clay minerals in the deposits studied. The clay minerals were derived from previously weathered deposits in all source areas and from mechanical action during glacial transport.

The amount of clay mineral formation after deposition is often indeterminable, since the exact original clay mineral composition of these deposits is unknown, but montmorillonite is forming as the deposits weather and mixed-layer clays are probably forming in the deposits associated with peat.

QUANTITATIVE STUDIES

The clay mineralogy of the samples was studied quantitatively in order to gain detailed information about the clay mineral content of these samples. With complex clay mineral suites any quantitative study is at best semiquantitative, but an approximation can be made by using characteristic X-ray peaks. Carroll (1970) summarized the difficulties in quantitative studies caused by the following differences between samples: differences in mass absorption coefficients of individual minerals, orientation of grains, thickness of the mounts, weight of the clay sample used, evenness of spread of the mixed minerals, differences in crystal perfection, polytypism, hydration and chemical composition. It is best to use the same techniques in all instances and note that the values attained are valid only within the scope of these techniques and this study. Any close comparison with values obtained in other studies is at best tenuous.

Under ideal conditions one can use mixtures of standard clay minerals to form calibration curves to determine weight percentages of the

minerals present. This is impossible with samples studied in this report. Standard clay minerals for the specific minerals that occur in the samples studied do not exist. Some comparison of the amounts of the various minerals can be made by measuring the peak areas of the various basal reflections. That semiquantitative method is used here.

No attempt at a detailed statistical study of the values obtained was made. The values overlap too much for a useful separation to be made, but trends can be identified directly from the graphs. A line of separation drawn statistically would not have a practical use.

Methods Used

Biscaye's (1965) weighting factors were applied to the areas of the basal peaks (glycolated) of the various clay minerals in order to make this semiquantitative analysis more realistic. The factors used are as follows: the area of the 17A peak for the montmorillonite content (possibly includes expandable chlorite and vermiculite), four times the 10A peak for the clay mica content and twice the 7A peak area for the kaolinite and chlorite content. For these calculations the 10A peak also includes the mixed-layer peak. The peak areas were calculated by tracing the peaks on tracing vellum, cutting them out and weighing them on a Mettler balance. The peak areas (weights) were multiplied by the appropriate weighting factors, totaled, and used to calculate "percentages" for the various clay mineral groups (Appendix III). All values have been rounded to the nearest five percent. These "percentages" are real only within the scope of this report, but they are at least approximations of reality.

There is some disagreement as to which method of sample slide preparation is best. Gibbs (1965) reported error in quantitative clay

mineral studies caused by segregation of montmorillonite due to its smaller size and therefore lower settling velocity than kaolinite or illite, thus resulting in apparent montmorillonite contents that are higher than the actual values. The following techniques were recommended by Gibbs: the smear-on-glass, suction on ceramic tile and powder press techniques. The pipette-on-glass method used in this report was not recommended. The smear-on-glass and powder press techniques were rejected because of the large amount of sample needed. A method similar to the suction on porcelain slide technique was tried. This involved using a dry porcelain slide to produce a suction effect. Fifteen samples were analyzed using both glass and porcelain slide techniques. There is an apparent increase in montmorillonite content from using the pipette-on-glass technique (Fig. 5). This report does not purport to give "real" percentages of clay mineral content. The values given have meaning only within the scope of the techniques used in this report. There are some real objections to using porcelain slides in a general study such as this. The most important objection is that quartz, mullite and corundum peaks show through the clay peaks and confuse their identification and intensities. Another objection is that the use of settling in water to obtain the less-than-two-micron fraction already involves a segregation of montmorillonite. Therefore, the values obtained are different from the "real" values no matter which method of slide manufacture is used.

Results

General Conclusions. The only general conclusion that can be made from the quantitative data is that chlorite and kaolinite are never abundant in the samples tested and rarely make up more than one-third

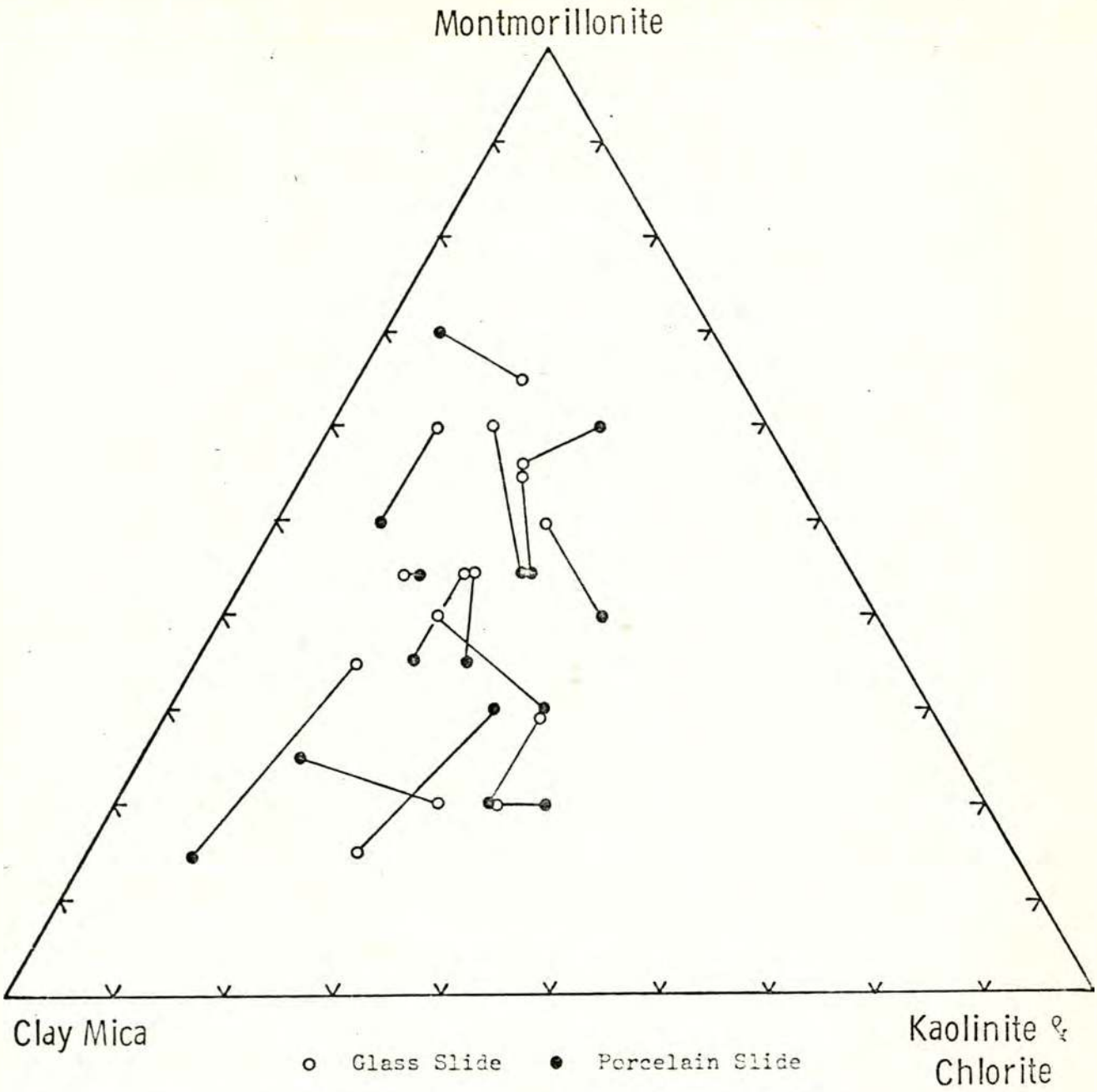


Fig. 5. Comparison of glass and porcelain slides from the same samples.

of the sample (Figs. 6,7&8). Chlorite is not the principal clay-type mineral in the source areas and weathering might have destroyed much of whatever chlorite was present, since chlorite is very easily weathered. No correlation between sample location and clay mineral content could be made.

Weathered Zones. More montmorillonite is present in the oxidized (brown) glacial deposits than in the unoxidized (grey) deposits (Figs. 6&7). In the nonglacial deposits there is poor correlation between color and clay mineral content (Fig. 8) as a result of the varied predepositional and outcrop conditions. On the other hand, the glacial deposits show definite weathering horizons. Montmorillonite (expandable clays) and probably vermiculite as well, are being formed from micas and chlorite by leaching in the weathering zone. This is obvious from Figure 9. Willman, Glass and Frye (1966) found similar results in Illinois glacial deposits. Evidence of weathering and the formation of new clay minerals was observed even in the younger deposits.

A study of the chlorite 7A and 14A peaks also indicates that weathering has occurred in the oxidized deposits. A larger 14A peak, in the absence of kaolinite, is indicative of Mg-rich chlorite or the presence of vermiculite and chlorite (Grim, 1968, p. 147-153). In samples from location BC-4, the non-weathered sample contains Fe-rich chlorite. The weathered sample contains Mg-rich chlorite or vermiculite. Destruction of Fe-rich chlorite and the formation of vermiculite probably accompany weathering of the glacial deposits. This may indicate that the source of the brown color in the weathered material is, at least in part, iron from weathered Fe-rich chlorite.

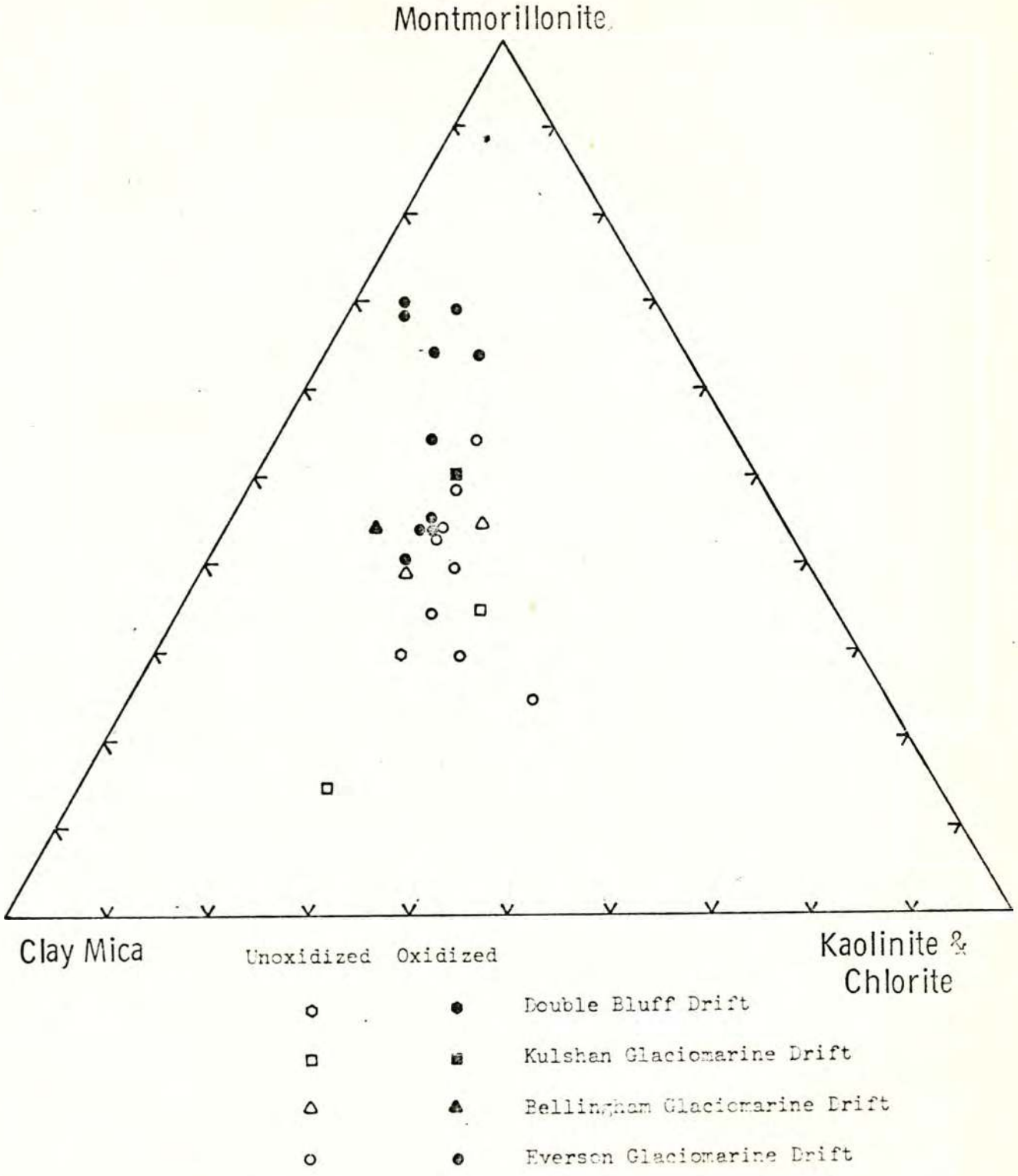


Fig. 6. Three component diagram showing clay-mineral composition of glaciomarine drift.

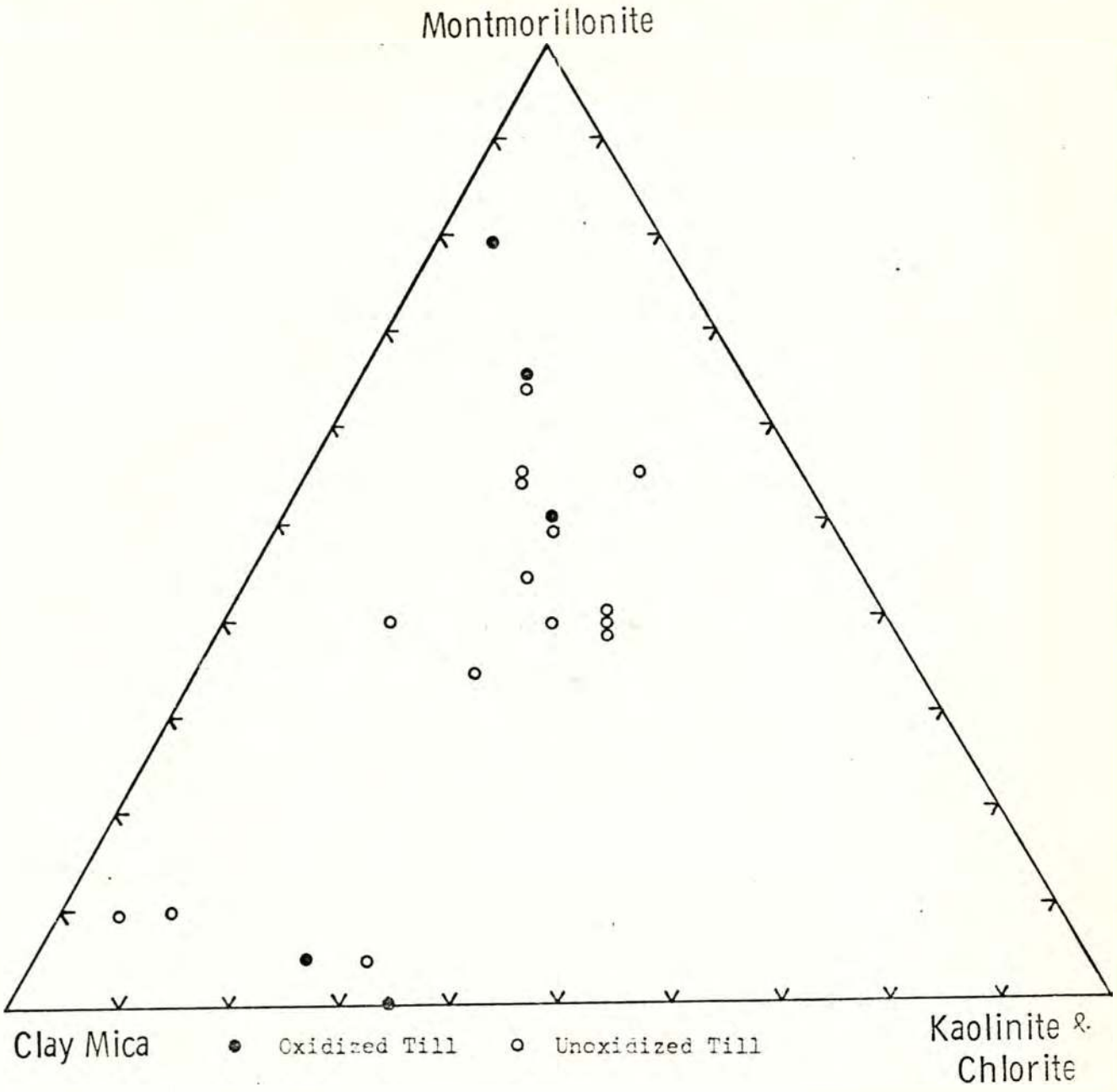


Fig. 7. Three component diagram showing clay-mineral composition of tills.

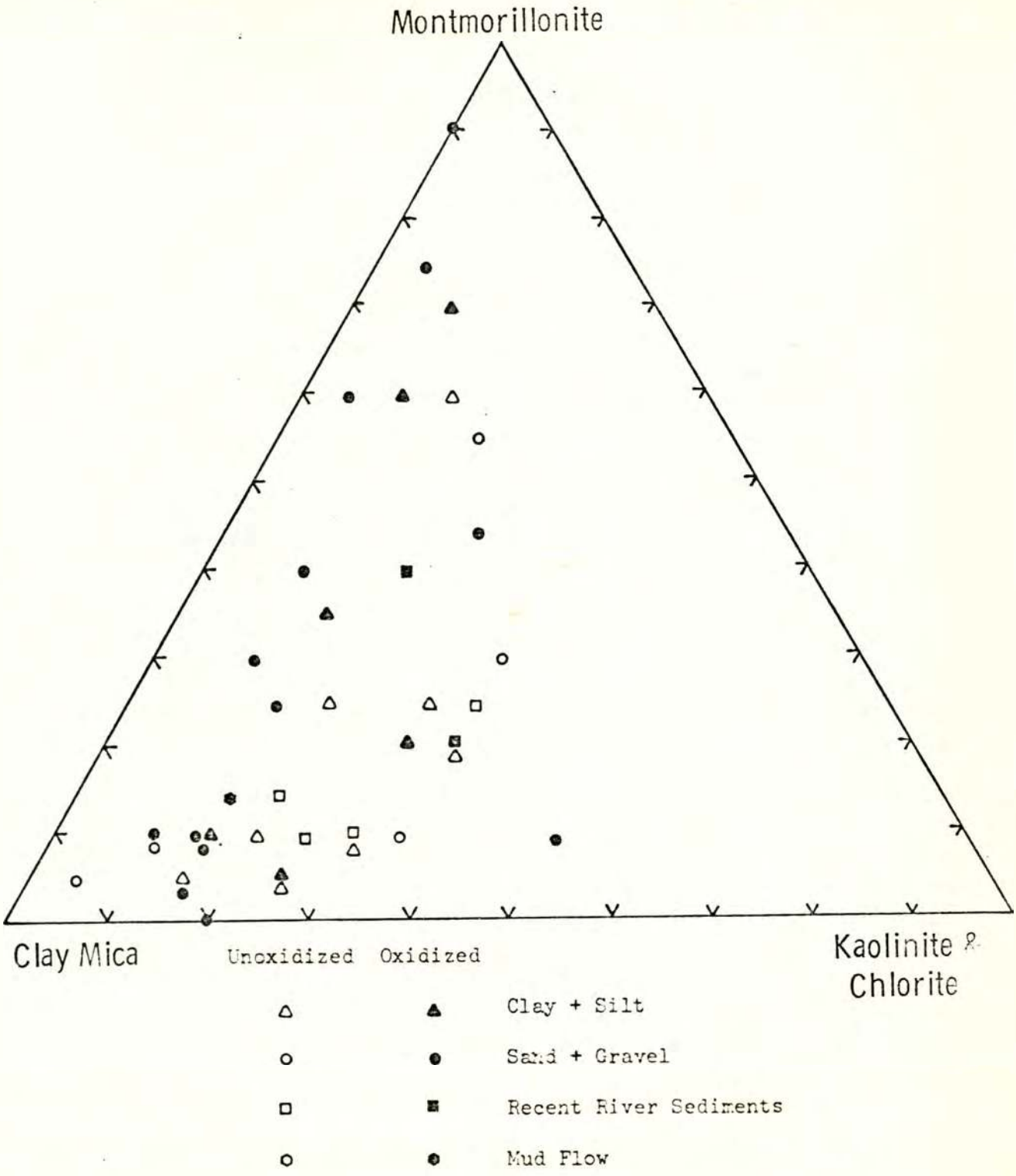
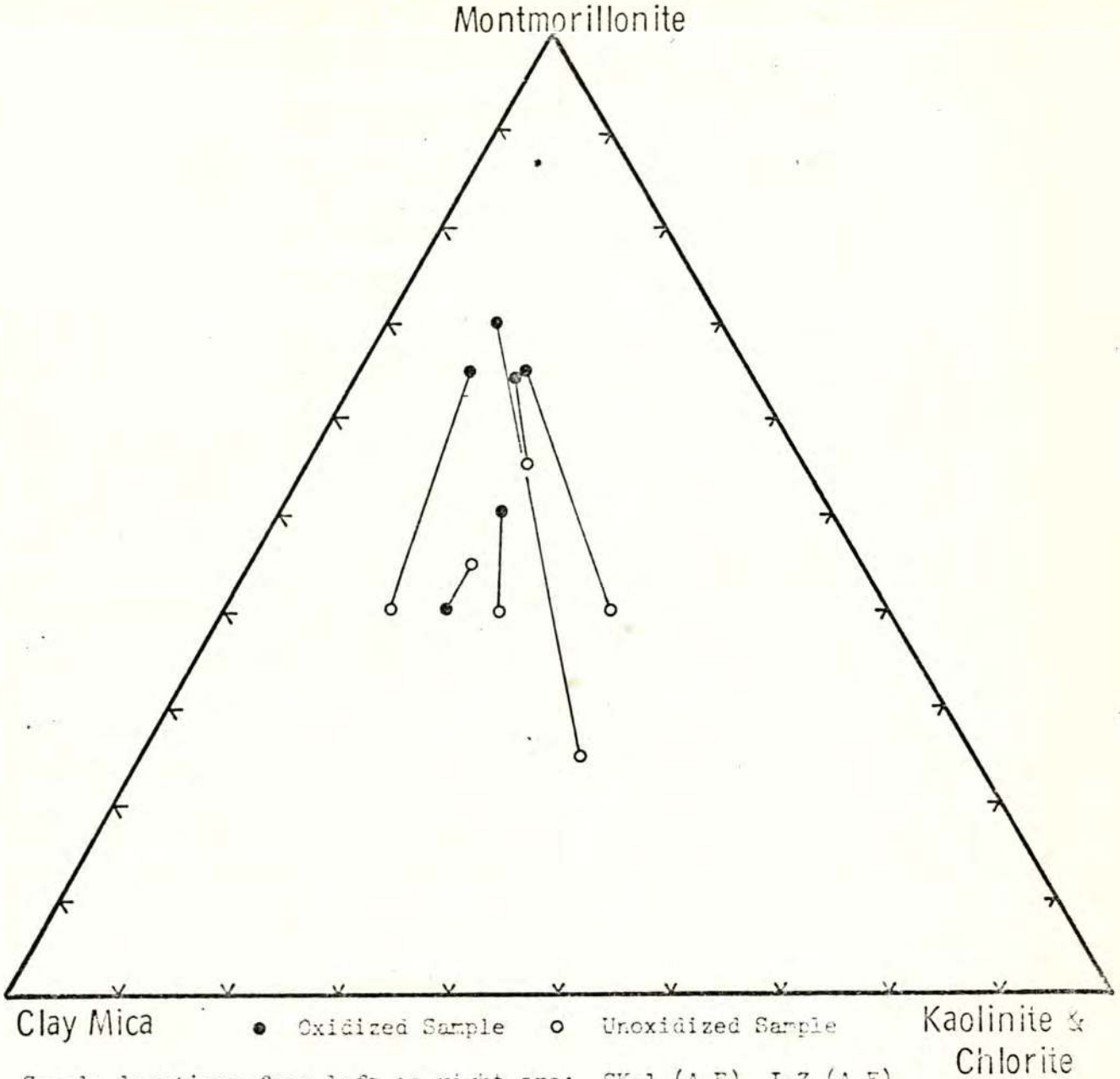


Fig. 8. Three component diagram showing clay-mineral composition of nonglacial deposits.



Sample locations from left to right are: SK-1 (A,B), I-7 (A,B), BC-4 (A,C), SK-4 (B,C), W-1 (D,E), and I (5A,6B).

Fig. 9. Oxidized vs. nonoxidized samples from the same locations.

Comparison of Tills and Glaciomarine Drift. An attempt to differentiate between tills and glaciomarine drift on the basis of clay mineralogy was made. The samples from the glaciomarine drift seem to contain more clay mica than samples from tills (Fig. 10). The mean of the clay mica content of the twelve normal unweathered till samples is 28% (σ=8%), while the mean of the clay mica content of the thirteen unweathered glaciomarine drift samples is 38% (σ=8%). The clay-mica-rich tills of British Columbia (Fig. 10) are an apparent contradiction to this trend, but their clay mineral content is the result of unusual particle size distribution and will be discussed later. The difference in clay mica content of the tills and glaciomarine drift may be significant, but it is not great enough to differentiate till from glaciomarine drift by clay mineralogy alone. Differentiation between different glaciomarine units on the basis of clay mineralogy was also attempted (Fig. 6), but no correlations could be made.

There are two probable reasons for the larger amount of clay mica in the glaciomarine drift. The higher clay mica content could be caused by variation in settling rates of the various clay mineral types in sea water. Grim (1968, p. 538) reported differentiation of clay minerals caused by flocculation of illite in the near-shore environment. This flocculation could help to account for the lower bulk density of the glaciomarine drift reported by Easterbrook (1964). The reformation of clay mica from degraded illite in the area of deposition could also cause the difference in the clay mica content in the different deposits. Both factors could and probably do account for the difference in the clay mica content of the deposits. More work is needed to determine how much effect each has. The comparison of potassium-argon age determina-

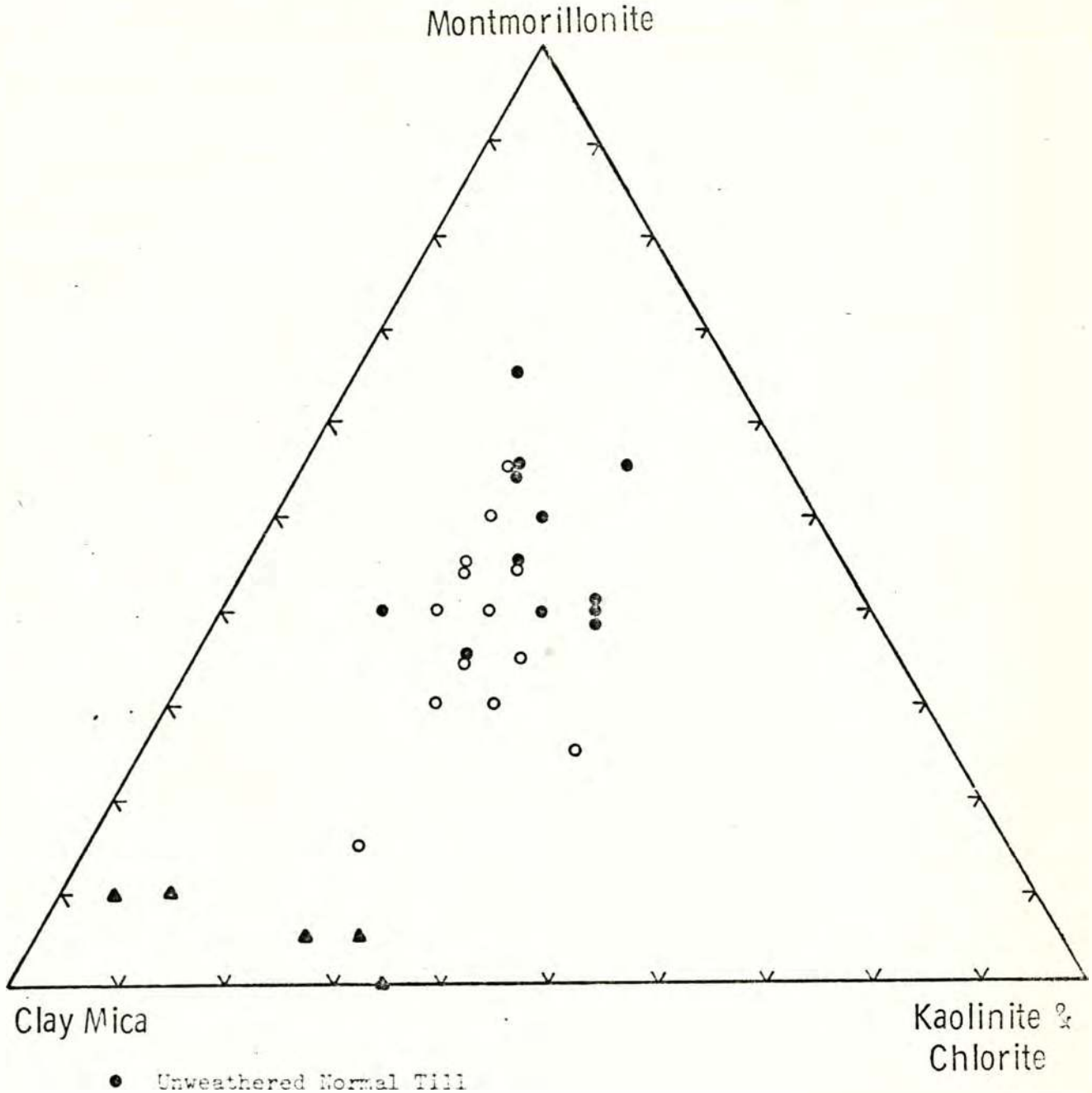


Fig. 10. Comparison of unweathered normal tills, unweathered glaciomarine drift and high clay mica content British Columbia till.

tions of the clay micas in the tills and glaciomarine drifts might be of use in determining how much new clay mica was formed in the glaciomarine deposits. This may not work if much of the clay mica was formed by feldspar weathering in the source areas.

High Clay Mica Content of British Columbia Tills. The high clay mica content of certain British Columbia tills (Fig. 10) is the result of an unusual particle size distribution in these tills. The five samples which gave the high clay mica contents all contain very little clay-sized material. A small amount of clay mica can give unrealistic "percentages" since so little clay is present. The clay mica probably resulted from mechanical disintegration of the relatively unweathered granitic rock which is abundant to the north. This disintegration would result in ground mica being the only abundant clay mineral present.

Origin of Montmorillonite in the "Unweathered" Glacial Deposits. The amount of montmorillonite (15%-65%) present in the "unweathered" glacial deposits indicates that weathering took place in the source areas for these deposits. A large amount of this montmorillonite probably formed in the mountains of southwestern British Columbia. This suggestion agrees with work by Reynolds (1971), who reported rapid clay mineral (vermiculite, mixed-layer vermiculite-phlogopite and montmorillonite minerals) formation in the Cascades at the present time. Some of the montorillonite probably formed by weathering of the older glacial deposits and was later incorporated into the younger deposits with reglaciation.

Nonglacial Deposits. The clay mineralogy of the nonglacial deposits is complicated because of their varied histories. The sands and

gravels seem to contain less chlorite than the silts and clays (Fig. 8) This is probably caused by greater weathering of chlorite in the permeable sands and gravels than in the impermeable clays and silts. No other conclusions about the nonglacial material were made.

CONCLUSIONS AND SUMMARY

1. The clay minerals in the late Pleistocene and Recent deposits of northwestern Washington and southwestern British Columbia were formed by mechanical disintegration before deposition and chemical weathering before and after deposition.

2. Montmorillonite, chlorite and clay mica are the most abundant clay minerals in the samples studied. Kaolinite and mixed-layer vermiculite-mica were found in some of the samples studied. The presence or absence of vermiculite could not be determined with the methods used in this study.

3. The late Pleistocene glaciations of the north and central Puget Lowland and the Fraser Lowland cannot yet be distinguished on the basis of their clay mineralogy alone.

4. There are apparent differences between the clay mineral contents of tills and glaciomarine drifts. The glaciomarine drifts seem to contain more clay mica. The difference in clay mica content may have been caused by the flocculation of clay mica in sea water and/or the formation of clay mica (illite) in the sea water by absorption of potassium ions.

5. Weathering and the formation of new clay minerals is occurring in late Pleistocene and Recent deposits in northwestern Washington and southwestern British Columbia.

6. A randomly interstratified vermiculite-mica is associated with some of the peat deposits. This mineral was probably formed from mica altering to vermiculite.

7. A previously unreported post-Vashon mudflow was found at the Mary Hill gravel pit in Port Coquitlam, British Columbia.

PROBLEMS REMAINING

1. What is the rate of weathering and new clay mineral formation in the late Pleistocene deposits of the Puget Lowland?

2. More work is needed on the clay mineralogy of the pre-Olympia deposits in the Puget Lowland.

3. What is the age, size and source of the mudflow at Port Coquitlam?

4. How much vermiculite and kaolinite are present in the deposits studied?

5. What is the relationship between particle size and clay mineral composition of the glacial deposits?

6. What is the origin and rate of formation of the mixed-layer mica-vermiculite?

7. Is the higher clay mica content of the glaciomarine drift real or apparent?

8. How much of the glaciomarine drift is authigenic and how much is detrital?

REFERENCES CITED

Armstrong, J. E., 1956, Surficial geology of the Vancouver area, British Columbia: Canada Geol. Survey Paper 55-40, 16p.

_____ 1965, in Guidebook for Field Conference J., Pacific Northwest, VIIth INQUA Congress, p. 105-108.

Armstrong, J. E., Crandell, D. R., Easterbrook, D. J., and Noble, J. B., 1965, Late Pleistocene stratigraphy and chronology in southwestern British Columbia and northwestern Washington: Geol. Soc. America Bull., v. 76, p. 321-330.

Biscaye, P. E., 1965, Mineralogy and sedimentation of Recent deep-sea clay in the Atlantic Ocean and adjacent seas and oceans: Geol. Soc. America Bull., v. 76, p. 803-832.

Brown, G. (ed.), 1961, X-ray Identification and Crystal Structures of Clay Minerals: London, Mineral. Soc. London, 544p.

Carroll, D., 1970, Clay Minerals: A Guide to Their X-ray Identification: Geol. Soc. America Spec. Paper 126, 80p.

Crandell, D. R., Mullineaux, D. R., and Waldron, H. H., 1958, Pleistocene sequence in southeastern part of the Puget Sound Lowland, Washington: Am. Jour. Sci., v. 256, p. 384-397.

_____ 1965, Age and origin of the Puget Sound trough in western Washington: U.S. Geol. Survey Prof. Paper 525-B, p. B132-B136.

Dawson, G. M., 1887, Report on a geological examination of the northern part of Vancouver Island and adjacent coasts: Canada Geol. Survey Ann. Rept. 1886, v. 2, pt. B, 107p.

Easterbrook, D. J., 1963, Late Pleistocene glacial events and relative sea level changes in northern Puget Lowland, Washington: Geol. Soc. America Bull., v. 74, p. 1465-1484.

_____ 1964, Void ratios and bulk densities as means of identifying Pleistocene tills: Geol. Soc. America Bull., v. 75, p. 745-750.

_____ 1966, Glaciomarine environments and the Fraser Glaciation in northwest Washington: Guidebook for First Annual Field Conf., Pacific Coast Section Friends of the Pleistocene, 52p.

_____ 1968, Pleistocene stratigraphy of Island County, Washington: Washington Dept. Water Resources, Water Supply Bull. 25, p. 1-35.

_____ 1969, Pleistocene chronology of the Puget Lowland and San Juan Islands, Washington: Geol. Soc. America Bull., v. 80, p. 2273-2286.

_____ 1971, Geology and Geomorphology of Western Whatcom County: Dept. of Geology, Western Washington State College, 68p.

Easterbrook, D. J., Crandell, D. R., and Leopold, E. B., 1967, Pre-Olympia Pleistocene stratigraphy and chronology in the Central Puget Lowland, Washington: Geol. Soc. America Bull., v. 78, p. 13-20.

Easterbrook, D. J. and Rahm, D. A., 1970, Landforms of Washington: Bellingham, Union Printing Co., 156p.

Gibbs, R. J., 1965, Error due to segregation in quantitative clay mineral X-ray diffraction mounting techniques: Am. Mineralogist, v. 50, p. 741-751.

Grim, R. E., 1968, Clay Mineralogy: New York, McGraw-Hill Book Co., Inc., 596p.

Kelly, J. M., 1970, Mineralogy and petrography of the basal Chuckanut Formation in the vicinity of Lake Samish, Washington: Western Washington State College M.S. thesis, 63p.

Millot, G., 1970, Geology of Clays: New York, Springer-Verlag, 429p.

Misch, P., 1966, Tectonic evolution of the northern Cascades of Washington State: Sympos. on Tect. Hist. and Min. Dep. of W. Cordillera in B.C. and Neighb. Pts. of U.S., Can. Inst. Min. Met. Spec. Vol. 8, p. 101-148.

Monger, J. W. H., and Hutchison, W. W., 1971, Simplified Metamorphic Map of the Canadian Cordillera, in Metamorphism in the Canadian Cordillera: Cordilleran Section - The Geol. Association of Canada - Programme and Abstracts, Vancouver, B.C., p. 16-17.

Mullineaux, D. R., 1967, Gross composition of Pleistocene clays in Seattle, Washington: U.S. Geol. Survey Prof. Paper 575-B, p. B69-B76.

Mullineaux, D. R., Nichols, T. C., and Speirer, R. A., 1964, A zone of montmorillonitic weathered clay in Pleistocene deposits at Seattle, Washington, in Geological Survey Research 1964: U.S. Geol. Survey Prof. Paper 501-D, p. D99-D103.

Reynolds, R. C., 1971, Clay mineral formation in an alpine environment: Clays and Clay Minerals, v. 19, p. 361-374.

Rich, C. I., 1958, Muscovite weathering in a soil developed in the Virginia Piedmont: in Clays and Clay Minerals, Natl. Acad. Sci.-Natl. Res. Council, pub. 566, p. 203-212.

Stockwell, C. H., (Ed.), 1963, Pleistocene glaciation in northern North America: in Geology and Economic Minerals of Canada, Geological Survey of Canada, Economic Geology Series No. 1, 517p.

Subbarao, E. C., 1953, A study of the fundamental properties of Puget Sound glacial clays: University of Washington M.S. thesis, 74p.

Willman, H. B., Glass, H. D., and Frye, J. D., 1963, Mineralogy of glacial tills and their weathering profiles in Illinois, Part I. Glacial tills: Illinois Geol. Survey Circ. 347, 55p.

_____ 1966, Mineralogy of glacial tills and their weathering profiles in Illinois: Part II. Weathering profiles: Illinois Geol. Survey Circ. 400, 76p.

APPENDIX I

SAMPLE LOCATIONS

Whatcom County

1. Sample Numbers: W-1 B, C, D, E
   Location: Y Road and Mt. Baker Highway
   Longitude and Latitude: 122°21'2"W 48°48'15"N
   Topographic Situation: Road Cut
   Sample Elevations: 470'-480'

2. Sample Numbers: W-2 A, C; W-3 A, B, C, D, E; W-4 B, C; W-5 A, B, C, D
   Location: Cedarville
   Longitude and Latitude: 122°16'0"W 48°49'40"N
   Topographic Situation: River Bank
   Sample Elevations: 190'-245'

3. Sample Number: W-6B
   Location: North Fork Nooksack River 2 miles east of Maple Falls
   Longitude and Latitude: 122°1'46"W 48°55'29"N
   Topographic Situation: River Sand Bar
   Sample Elevation: 590'

4. Sample Number: W-7B
   Location: Middle Fork Nooksack River, Heisler's Ranch
   Longitude and Latitude: 122°6'42"W 48°46'39"N
   Topographic Situation: River Sand Bar
   Sample Elevation: 520'

5. Sample Number: W-8A
   Location: South Fork Nooksack River, Saxson Bridge
   Longitude and Latitude: 122°9'45"W 48°40'40"N
   Topographic Situation: River Bank
   Sample Elevation: 350'

6. Sample Number: W-9B
   Location: Nooksack River, Marietta Bridge
   Longitude and Latitude: 122°34'55"W 48°47'27"N
   Topographic Situation: River Bank
   Sample Elevation: 3'

7. Sample Number: W-10A
   Location: Everson
   Longitude and Latitude: 122°21'5"W 48°56'48"N
   Topographic Situation: Road Cut
   Sample Elevation: 70'

8. Sample Number: W-11A
   Location: Southeast corner Point Roberts
   Longitude and Latitude: 123°1'34"W 48°59'13"N
   Topographic Situation: Sea Cliff
   Sample Elevation: 5'

SAMPLE LOCATIONS
(continued)

9. Sample Number: W-12A
Location: Point Roberts
Longitude and Latitude: 123°3'28"W 48°59'59"N
Topographic Situation: Gravel Pit
Sample Elevation: 130'

10. Sample Number: W-13B
Location: Boundry Bluff, Point Roberts
Longitude and Latitude: 123°5'11"W 48°59'42"N
Topographic Situation: Road Cut
Sample Elevation: 95'

11. Sample Numbers: W-14 B, C
Location: East Shore of Bellingham Bay
Longitude and Latitude: 122°31'29"W 48°46'4"N
Topographic Situation: Sea Cliff
Sample Elevations: 5'-20'

12. Sample Number: W-15C
Location: East Shore of Bellingham Bay
Longitude and Latitude: 122°32'16"W 48°46'38"N
Topographic Situation: Sea Cliff
Sample Elevation: 100'

Island County

13. Sample Numbers: I-1A; I-2 A, B
Location: North side of Penn Cove
Longitude and Latitude: 122°42'25"W 48°14'18"N
Topographic Situation: Sea Cliff
Sample Elevations: 5'-25'

14. Sample Number: I-3B
Location: Greenbank
Longitude and Latitude: 122°33'52"W 48°6'44"N
Topographic Situation: Road Cut
Sample Elevation: 70'

15. Sample Numbers: I-4B, I-5A
Location: Barnum Point
Longitude and Latitude: 122°27'2"W 48°11'45"N
Topographic Situation: Sea Cliff
Sample Elevations: 115'-130'

16. Sample Numbers: I-6 A, B
Location: Barnum Point
Longitude and Latitude: 122°27'41"W 48°11'35"N
Topographic Situation: Sea Cliff
Sample Elevations: 5'-10'

SAMPLE LOCATIONS
(continued)

17. Sample Numbers: I-7 A, C, E
Location: West Beach, Whidbey Island
Longitude and Latitude: 122°45'57"W 48°13'55"N
Topographic Situation: Sea Cliff
Sample Elevations: 5'-15'

18. Sample Numbers: I-8 B, C; I-9 A, B, C, D
Location: 2½ miles north of West Beach
Longitude and Latitude: 122°45'0"W 48°15'40"N
Topographic Situation: Sea Cliff
Sample Elevations: 3'-10'

19. Sample Numbers: I-10 A, B, C, D, E, F
Location: Strawberry Point
Longitude and Latitude: 122°30'20"W 48°18'35"N
Topographic Situation: Sea Cliff
Sample Elevations: 3'-30'

20. Sample Numbers: I-11 A, C, D
Location: Double Bluff
Longitude and Latitude: 122°32'40"W 47°58'5"N
Topographic Situation: Sea Cliff
Sample Elevations: 5-25'

21. Sample Number: I-13B
Location: West side of Useless Bay
Longitude and Latitude: 122°27'32"W 47°58'34"N
Topographic Situation: Sea Cliff
Sample Elevation: 100'

San Juan County

22. Sample Number: SA-1A
Location: South side of Sucia Island
Longitude and Latitude: 122°54'11W 48°45'0"N
Topographic Situation: Sea Cliff
Sample Elevation: 15'

Skagit County

23. Sample Number: SK-1A
Location: Bow Hill Road and I-5 Freeway
Longitude and Latitude: 122°21'0"W 48°33'30"N
Topographic Situation: Road Cut
Sample Elevation: 300'

SAMPLE LOCATIONS
(continued)

24. Sample Number: SK-1E
Location: Bow Hill Road and I-5 Freeway
Longitude and Latitude: 122°20'27"W 48°33'25"N
Topographic Situation: Road Cut
Sample Elevation: 255'

25. Sample Number: SK-2A
Location: Skagit River 3 miles north of Concrete
Longitude and Latitude: 121°42'20"W 48°30'20"N
Topographic Situation: River Bar
Sample Elevation: 195'

26. Sample Number: SK-3A
Location: Southeast end Big Lake
Longitude and Latitude: 122°12'20"W 48°21'55"N
Topographic Situation: Road Cut
Sample Elevation: 125'

27. Sample Numbers: SK-4 B, C
Location: Nookachamps Creek and Highway 1A near Clear Lake
Longitude and Latitude: 122°15'17"W 48°25'46"N
Topographic Situation: River Bank
Sample Elevations: 70'-75'

28. Sample Number: SN-1A
Location: North Fork Stillaguamish River, Cicero
Longitude and Latitude: 122°0'34"W 48°16'4"N
Topographic Situation: River Bar
Sample Elevation: 130'

29. Sample Numbers: SN-2 A, B, D
Location: I-5 Freeway and Stillaguamish River
Longitude and Latitude: 122°12'35"W 48°12'0"N
Topographic Situation: Road Cut
Sample Elevations: 90'-135'

30. Sample Number: SN-3A
Location: I-5 Freeway 1 2/3 miles north of the Stillaguamish River
Longitude and Latitude: 122°13'20"W 48°13'20"N
Topographic Situation: Road Cut
Sample Elevation: 180'

British Columbia

31. Sample Number: BC-1A
Location: Northwest corner Centennial Park, Abbotsford
Longitude and Latitude: 122°19'2"W 49°2'50"N
Topographic Situation: Road Cut
Sample Elevation: 220'

SAMPLE LOCATIONS
(continued)

32. Sample Numbers: BC-2 A, B
Location: Huntingdon Road 1 mile west of Peardonville
Longitude and Latitude: 122°25'50"W 49°1'2"N
Topographic Situation: Road Cut
Sample Elevations: 265'-275'

33. Sample Numbers: BC-3 A, C
Location: Matsqui municipal gravel pit on Lefeuvre Road
Longitude and Latitude: 122°26'45"W 49°1'20"N
Topographic Situation: Gravel Pit
Sample Elevations: 275'-310'

34. Sample Numbers: BC-4 A, C
Location: Nathan creek 1/4 mile north of B.C. Electric R.R. tracks
Longitude and Latitude: 122°26'43"W 49°6'22"N
Topographic Situation: Road Cut
Sample Elevations: 260'-275'

35. Sample Number: BC-5A
Location: Mary Hill gravel pit, Port Coquitlam
Longitude and Latitude: 122°46'55"W 49°14'17"N
Topographic Situation: Gravel Pit
Sample Elevation: 270'

36. Sample Numbers: BC-6 C, E, F, G
Location: Linton gravel pit, Surrey
Longitude and Latitude: 122°54'0"W 49°7'35"N
Topographic Situation: Gravel Pit
Sample Elevations: 225'-270'

37. Sample Numbers: BC-7 A, B
Location: Highway 10 1/4 mile west of Scott Road, Surrey
Longitude and Latitude: 122°53'30"W 49°6'32"N
Topographic Situation: Road Cut
Sample Elevations: 145'-150'

38. Sample Numbers: BC-8 A, D, G, H
Location: Point Grey, Vancouver
Longitude and Latitude: 123°15'36"W 49°16'17"N
Topographic Situation: Sea Cliff
Sample Elevations: 60'-195'

39. Sample Number: BC-12A
Location: Junction Pitt River and Fraser River, Port Coquitlam
Longitude and Latitude: 122°46'10"W 49°13'53"N
Topographic Situation: River Bank
Sample Elevation: 3'

APPENDIX II

STRATIGRAPHIC INFORMATION

Sample Number	Stratigtaphic Unit	Sediment Type	Color
W-1B	Vashon till	Till	Grey
C	" "	"	"
D	Everson Glaciomarine Drift	Glaciomarine Drift	Light brown
E	" " "	" "	Dark Grey
W-2A	Bellingham Glaciomarine Drift	" "	Light Grey
C	" " "	" "	Grey
W-3A	Deming Sand	Clay	Brown
B	" "	Sand	"
C	" "	"	"
D	" "	Silt	"
E	" "	Sand	"
W-4B	Kulshan Glaciomarine Drift	Glaciomarine Drift	Grey
C	" " "	" "	"
W-5A	Deming Sand	Sand	"
B	" "	Peat - Clay	Dark brown
C	" "	Sand	Grey
D	" "	Clay	Dark grey
W-6B	Recent stream sediments	Sand	Grey
W-7B	" " "	"	Dark brown
W-8A	" " "	"	Grey
W-9B	" " "	Silt	Brown
W-10A	Everson Glaciomarine Drift	Glaciomarine Drift	"
W-11A	Quadra sediments	Clay	Grey
W-12A	Everson Glaciomarine Drift	Glaciomarine Drift	"
W-13B	" " "	" "	Brown
W-14B	Kulshan Glaciomarine Drift	" "	Grey
D	Deming Sand	Silt	Brown
W-15C	Bellingham Glaciomarine Drift	Glaciomarine Drift	"
I-1A	Whidbey Formation	Clay	Grey
I-2A	Everson Glaciomarine Drift	Glaciomarine Drift	Brown
B	" " "	" "	"
I-3B	Vashon till	Till	Grey
I-4B	Esperance Sand	Sand	Brown
I-5A	Vashon till	Till	Light grey
I-6A	Everson Glaciomarine Drift	Glaciomarine Drift	Brown
B	Vashon till	Till	"
I-7A	Everson Glaciomarine Drift	Glaciomarine Drift	Light brown
C	Partridge Gravel	Sand	Brown
E	Everson Glaciomarine Drift	Glaciomarine Drift	Dark grey
I-8B	Whidbey Formation	Sand	Grey
C	Vashon till	Till	"
I-9A	Whidbey Formation	Clay	"
B	" "	Peat - Silt	Brown
C	" "	Clay	Grey
D	" "	"	"
I-10A	Early Possession Drift	Till	Brown
B	Whidbey Formation	Sand	Light brown
C	Middle Possession Drift	"	Dark brown

STRATIGRAPHIC INFORMATION
(continued)

Sample Number	Stratigraphic Unit	Sediment Type	Color
I-10D	Middle Possession Drift	Sand	Brown
E	Olympia sediments	Clay	Grey
F	Upper Possession Drift	Till	Dark brown
I-11A	Double Bluff Drift	Glaciomarine Drift	Dark grey
C	Whidbey Formation	Sand	Brown
D	Double Bluff Drift	Till	Grey
I-13B	Whidbey Formation	Silt	"
SA-1A	Everson Glaciomarine Drift	Glaciomarine Drift	Brown
SK-1A	Vashon till	Till	Grey
E	Everson Glaciomarine Drift	Glaciomarine Drift	Brown
SK-2A	Recent river sediments	Sand	Dark grey
SK-3A	Vashon till	Till	Grey
SK-4B	Everson Glaciomarine Drift	Glaciomarine Drift	"
C	" " "	" "	Brown
SN-1A	Recent river sediments	Sand	Grey
SN-2A	Vashon recessional outwash	"	Brown
B	Vashon till	Till	Grey
D	" "	"	"
SN-3A	" "	"	"
BC-1A	Sumas till	"	Brown
BC-2A	" "	"	"
B	Advance Sumas outwash	Gravel	"
BC-3A	Everson Glaciomarine Drift	Glaciomarine Drift	Grey
C	Recessional Sumas outwash	Sand	Brown
BC-4A	Everson Glaciomarine Drift	Glaciomarine Drift	"
C	" " "	" "	Grey
BC-5A	Mary Hill mudflow	Diamicton	Brown
BC-6C	Quadra sediments	Sand	"
E	Surrey Drift	Till	Grey
F	Capilano sediments	Glaciomarine Drift	"
G	Capilano bar sand	Sand	Brown
BC-7A	Surrey Drift	Till	Grey
B	" "	"	"
BC-8A	Quadra sediments	Sand	"
D	" "	Silt	"
G	" "	Sand	"
H	Surrey Drift	Till	"
BC-12A	Recent river sediments	Sand	Brown

APPENDIX III

CLAY MINERAL CONTENT

Sample Number	% Montmorillonite	% Clay Mica	% Kaolinite & Chlorite
W-1B	50	25	25
C	55	15	30
D	65	20	15
E	55	25	20
W-2A	45	30	25
C	40	40	20
W-3A	35	50	15
B	10	75	15
D	60	30	10
E	5	80	15
W-4B	15	60	25
C	50	30	20
W-5A	55	25	20
B	20	50	30
C	30	35	35
D	20	45	35
W-6B	25	40	35
W-7B	95	0	5
W-8A	10	65	25
W-9B	20	45	35
W-10A	70	25	5
W-11A	25	55	20
W-12A	35	40	25
W-13B	45	35	20
W-14B	35	35	30
D	70	20	10
W-15C	45	40	15
I-1A	60	25	15
I-2A	45	35	20
B	45	35	20
I-3B	65	20	15
I-4B	45	30	25
I-5A	40	25	35
I-6A	70	25	5
B	65	20	15
I-7A	40	40	20
C	10	40	50
E	45	35	20

Sample Number	% Montmorillonite	% Clay Mica	% Kaolinite & Chlorite
I-8B	10	55	35
C	55	25	20
I-9A	10	70	20
B	5	70	25
C	5	70	25
D	10	75	15
I-10A	80	15	5
B	90	10	0
C	60	35	5
D	40	50	10
E	25	45	30
F	50	25	25
I-11A	30	45	25
C	30	60	10
D	35	40	25
I-13B	5	80	15
SA-1A	55	30	15
SK-1A	40	45	15
E	65	25	10
SK-2A	15	65	20
SK-3A	45	30	25
SK-4B	25	35	40
C	70	20	10
SN-1A	10	60	30
SN-2A	0	80	20
B	40	25	35
D	55	25	20
SN-3A	40	30	30
BC-1A	0	65	25
BC-2A	5	70	25
B	25	60	15
BC-3A	30	40	30
C	10	75	15
BC-4A	50	30	20
C	40	35	25
BC-5A	15	70	15
BC-6C	75	20	5
E	5	65	30

Sample Number	% Montmorillonite	% Clay Mica	% Kaolinite & Chlorite
BC-6F	45	35	20
G	10	80	10
BC-7A	10	85	5
B	10	80	10
BC-8A	5	90	5
D	10	60	30
G	10	80	10
H	40	25	35
BC-12A	40	40	20
porcelain slides			
W-1B	40	25	35
E	45	30	25
W-2C	30	35	35
W-3A	15	75	10
D	50	40	10
W-4B	30	40	30
W-5A	60	15	25
B	25	60	15
C	20	45	35
D	20	40	40
W-13B	35	45	20
W-15C	45	40	15
I-1A	45	30	25
I-2B	35	40	25
I-3B	70	25	5