THE GEOLOGY OF THE SAUK RIVER AREA IN THE NORTHERN CASCADES OF WASHINGTON

by

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ABSTRACT

THE GEOLOGY OF THE SAUK RIVER AREA IN THE NORTHERN CASCADES OF WASHINGTON

The Sauk River area comprises about 260 square miles centering around the town of Darrington which lies on the western flank of the Cascades about 60 miles northeast of Seattle. Geologically the area is complex, including a wide variety of igneous, sedimentary, and metamorphic rocks and structures.

Low grade metamorphic rocks in the Sauk River area include the Gold Hill phyllite and the Shuksan greenschist which were produced by low grade isochemical metamorphism of argillaceous sediments and basalts. These rocks form a large thrust sheet (Whitechuck Mtn. overthrust) which moved from east to west and overlies nonmetamorphic upper Paleozoic sediments. The thrust is cut by the later Straight Creek fault.

The eastern part of the Sauk River area consists of medium and, locally, of high grade metamorphic rocks including biotite schists, orthoamphibolites, and less prominently marble and hornblendite among the isochemical rocks, together with more abundant trondhjemitic and quartz dioritic gneisses of metasomatic origin. The higher grade metamorphics are separated from the low grade metamorphic rocks and nonmetamorphic sediments on the west by a major high angle fault, the Straight Creek fault of probable Tertiary age. A small occurrence of higher grade amphibolites and hornblende gneiss on Helena Ridge, 8 miles west of the Straight Creek fault, is interpreted as a klippe.

The age of the main metamorphism in the present area is not known but is earlier than the thrusting and is definitely pre-Tertiary. Regional relationships indicate that the low angle thrusts are of middle to early late

Cretaceous age.

Three units of essentially unmetamorphosed, but strongly deformed sedimentary and volcanic rocks were recognized. They are of upper Paleozoic and possibly in part of lower Mesozoic age. Structurally these units belong beneath the thrusts mentioned above. The uniform structure and nonmetamorphic character of these rocks suggest that they owe their main deformation to a single period of orogeny, which is considered to be pre-middle Jurassic.

Mesozoic sedimentary rocks, principally arkosic siltstones, on Three Fingers may be correlative with the upper Jurassic and lower Cretaceous Nooksack formation. These rocks apparently lie with angular unconformity on strongly folded upper Paleozoic cherts and slates. In middle to early late Cretaceous time the Mesozoic rocks were folded into an open syncline and the underlying Paleozoic rocks were redeformed.

Unconformable continental arkoses, shales, and conglomerates of the Paleocene Swauk formation are preserved in a narrow belt. They were moderately to rather strongly folded before the deposition of the Eocene Barlow Pass volcanics which comprise 4000 feet of gently folded andesitic and basaltic, and subordinately acidic flows, with prominent arkosic interbeds. This sequence is correlated with the Eocene Teanaway and Naches formations.

Basic and ultrabasic igneous rocks are common as dikes and small irregular intrusive bodies in the western part of the area. These intrusive bodies are of several ages, some are pre-thrusting, others are post-Swauk, and at least one is post-Barlow Pass volcanics.

A large quartz diorite stock in the western part of the area is of magmatic origin. It is very uniform in composition, has universally sharp contacts, and is surrounded by an aureole of contact metamorphism. The quartz diorite cuts the Swauk and is of Tertiary age.

A steep-walled pipe of andesitic breccia at Round Lake is a remnant of a late Tertiary volcano. Physiographic evidence indicates that this volcano was built prior to the elevation of the Cascades to their present level, probably at a time when a lower ancestral Cascade Range with several thousand feet of relief was already present.

Two distinct episodes of late Pleistocene glaciation are recognized. The first was alpine glaciation by Cascade valley glaciers which shaped the present river valleys. The second was the advance of Puget Sound ice into the mountain valleys, after the decline of the Cascade glaciers. The Suiattle River is believed to have been diverted during glaciation to its present northward course into the Skagit River. Thick ash fill terraces in the Sauk, Suiattle, and Whitechuck River valleys and an ash layer several inches thick on many of the gentler ridge crests are correlated with a Glacier Peak eruption dated by Rigg and Gould at about 6800 years ago.

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THE GEOLOGY OF THE SAUK RIVER AREA IN THE NORTHERN CASCADES OF WASHINGTON

INTRODUCTION

Location and Access

The area studied centers around the middle course of the Sauk River which flows north some 25 miles west of the Cascade crest. The area covers approximately 260 square miles. It extends about 20 miles from Three Fingers on the west to the eastern boundary on the Whitechuck River just west of Glacier Peak. The western part of the area is bounded on the north and south by the North and South Forks of the Stillaguamish River. The eastern part of the area is bounded on the north by the Suiattle River and on the south by the North Fork of the Sauk River. Darrington, a logging town in the northwestern part of the area, is 75 miles by highway from Seattle. The western part of the area lies in the southeastern part of the United States Geological Survey 30 minute Stillaguamish quadrangle, and the eastern part lies in the southwestern part of the 30 minute Glacier Peak quadrangle. These old topographic maps are considerably in error, especially on some drainage features, and many lakes are omitted. New Forest Service planimetric maps made from aerial photographs show the drainage more accurately and also

indicate new roads. A few square miles in the eastern part of the area are covered by the excellent 1950 U. S. Geological Survey 15 minute Glacier Peak quadrangle. Aerial photographs of the area are available both from the United States Geological Survey and from the Forest Service (some of the Forest Service photos were taken too late in the year and many features at higher elevations are obscured by new snow).

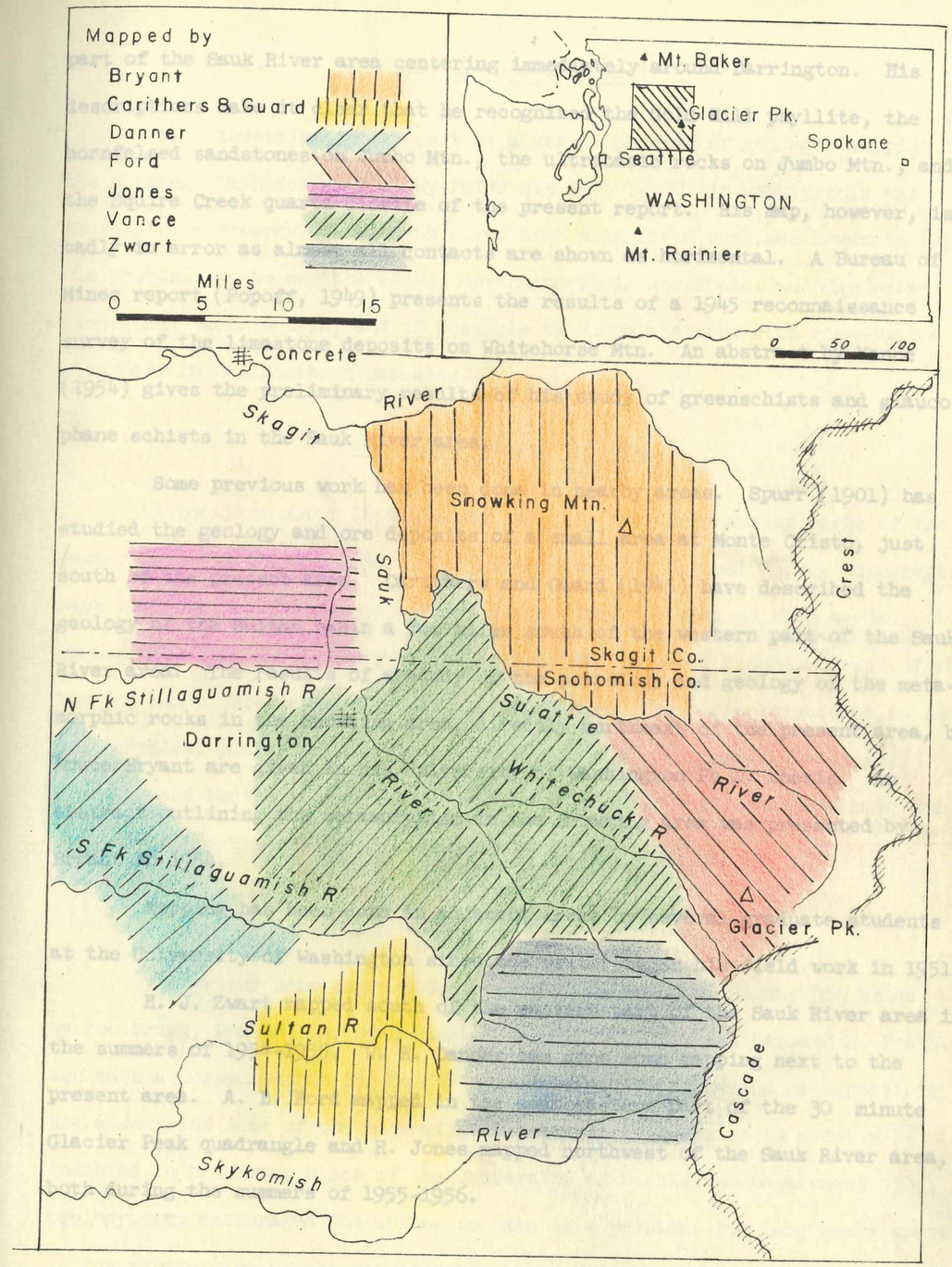
The area is traversed by one good road, the Mountain Loop road, which leads east up the valley of the South Fork of the Stillaguamish River to Barlow Pass and then north along the Sauk River to Darrington. From the Mountain Loop road, good roads extend about 11 miles up the Whitechuck River, 8 miles up the North Fork of the Sauk River, and onto the east side of Gold Hill and the west side of Whitechuck Mtn. in the upper Dan Creek area. A good road leads north from Darrington to the Suiattle River at the north end of the north ridge of Prairie Mtn., and another extends from Straight Creek to Lime Creek on the south side of the Suiattle River. These roads are at low elevations and only exceptionally do they have good outcrops. Shorter branch logging roads up the mountainsides give better exposures. Most of the trails indicated on the old Forest Service maps have been abandoned and are now almost impassable. Among the trails still maintained are the trails to the lookouts on Mt. Pugh and Circle Peak, the Dickerman and Meadow Mtn. trails, the Lost Creek Ridge trail, the Whitechuck River trail, the Canyon Creek, Deer, Coal, Falls, and Perry Creek trails, and the lower parts of the Squire and Clear Creek trails.

Topography and Exposures

The lowest elevation in the area is approximately 400 feet, at the mouth of the Suiattle River. The highest point is Black Mtn. at 7242, followed closely by Mt. Pugh at 7150. Small glaciers occur on the north sides of Whitechuck (6935) and Whitehorse (6820) Mtns. and on the west side of Three Fingers (6854). The Sauk, Whitechuck, and Suiattle Rivers, together with the South Fork of the Stillaguamish River, all flow in deep valleys, the elevation of which remains below 2000 feet throughout most of the area. Steep and often cliffy slopes rise above the valleys to ridges ranging from 5000 to 7000 feet in elevation. The mountains are heavily wooded below 5000 feet, except on the steepest faces. Apart from artificial exposures, the best outcrops are found on the high ridges, above 5000 feet, especially on the steeper north slopes. Lower down, good exposures are found in the beds of the smaller streams. Because of thick brush, stream travel is more difficult than travel in the open timber. Consultation of the air photographs is advisable when planning traverses in order to avoid brush and cliffs.

Previous Work and Recent Work in Adjacent Areas

No detailed previous geologic work has been done in the Sauk River area. I. C. Russell (1900) went down the Sauk River from White Pass at the head of the North Fork of the Sauk River to the Skagit River. His map shows schist along the North Fork of the Sauk River (quartz dioritic hornblende gneiss is actually the major rock type there), and more correctly slate (the Gold Hill phyllite of the present thesis) between the mouth of the Whitechuck River and Darrington. Awoki (1912) in an unpublished University of Washington Bachelor's thesis in mining engineering has described the geology of a small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Sultan R
River
Cascade
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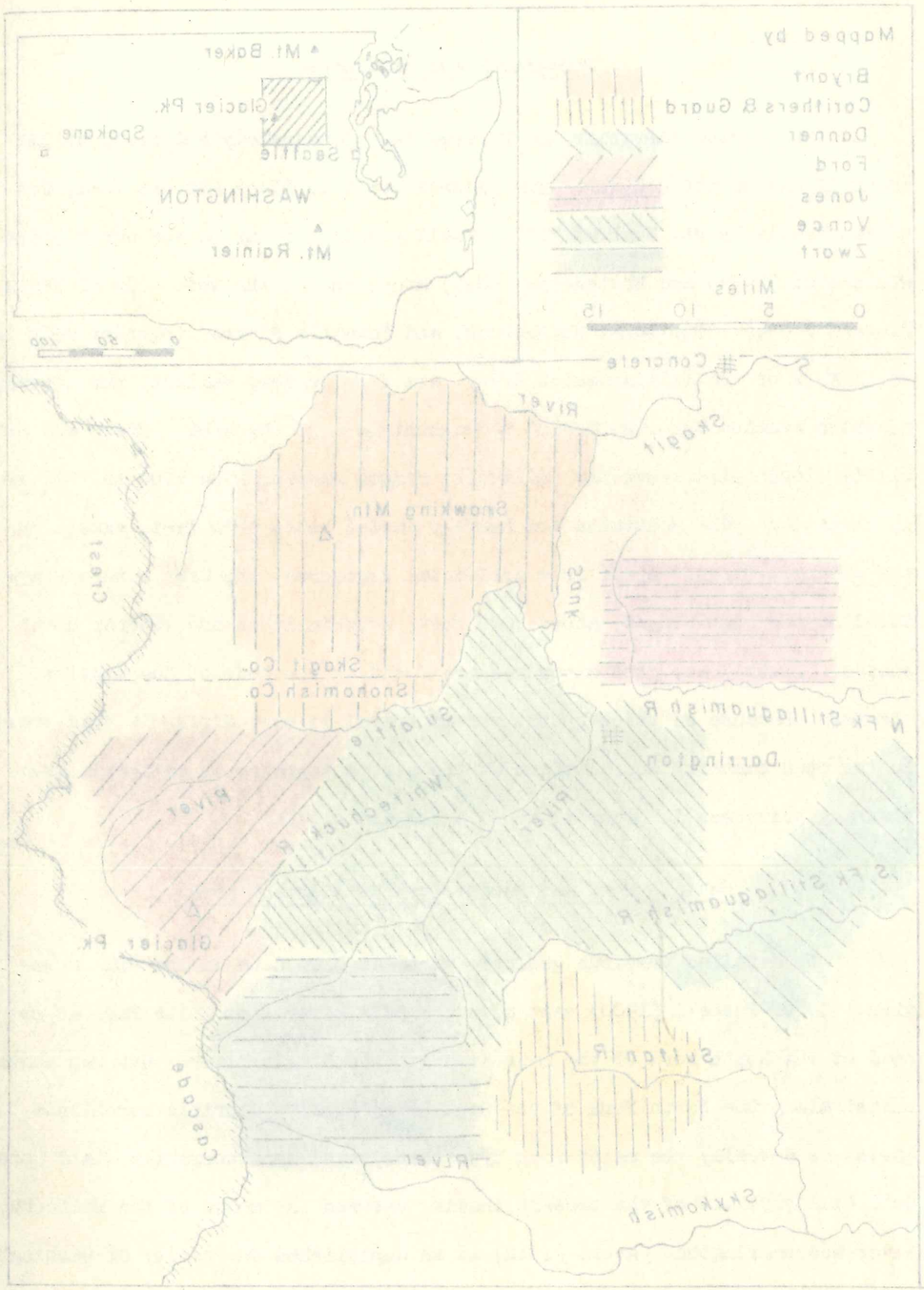
INDEX MAP



part of the Sauk River area centering immediately around Darrington. His descriptions make it clear that he recognized the Gold Hill phyllite, the hornfelsed sandstones on Jumbo Mtn., the ultrabasic rocks on Jumbo Mtn., and the Squire Creek quartz diorite of the present report. His map, however, is badly in error as almost all contacts are shown as horizontal. A Bureau of Mines report (Popoff, 1949) presents the results of a 1945 reconnaissance survey of the limestone deposits on Whitehorse Mtn. An abstract by Vance (1954) gives the preliminary results of his study of greenschists and glaucophane schists in the Sauk River area.

Some previous work has been done in nearby areas. Spurr (1901) has studied the geology and ore deposits of a small area at Monte Cristo, just south of the present area. Carithers and Guard (1945) have described the geology of the Sultan basin a few miles south of the western part of the Sauk River area. The results of a study of the petrology and geology of the metamorphic rocks in the Snowking area, directly northeast of the present area, by Bruce Bryant are given in his University of Washington Ph.D. thesis. An abstract outlining the metamorphism in the Snowking area was presented by Bryant in 1954.

Mapping has been done in adjacent areas by several graduate students at the University of Washington since the writer began his field work in 1951.

H. J. Zwart mapped south of the eastern part of the Sauk River area in the summers of 1954-1955. W. R. Danner has done some mapping next to the present area. A. B. Ford mapped in the southeastern part of the 30 minute Glacier Peak quadrangle and R. Jones mapped northwest of the Sauk River area, both during the summers of 1955-1956.

Statement of Purpose

This investigation is part of a larger program of geologic mapping in the Northern Cascades started by Peter Misch in 1949. As very little was known of the geology of the Sauk River area when field work was begun in 1951, the problem was to map the rocks, determine their structural and age relations, and their origin, and if possible to correlate them with rocks units elsewhere in the Northern Cascades.

Field and Laboratory Work

A total of about 18 weeks was spent in the field during parts of the summers of 1951 through 1956. The United States Geological Survey topographic maps were used as field maps, except in the last two seasons when aerial photographs were used. Most of the higher, well-exposed ridges and all of the logging roads were traversed. As time permitted, the poorer exposures in the more critical places were visited. Much time was spent merely in brush fighting and backpacking. Thin sections of 752 rock specimens were made and studied at the University of Washington.

Acknowledgments

The writer here expresses his thanks to Donald M. Ragan, Don Wilde, Warren Drugg, Don Kellum, John Hinkle, Robert S. Yeats, and Richard M. Pratt, who each accompanied him for one or more days in the field and made possible the ascents of some of the more difficult peaks. The writer is greatly indebted to Dr. Peter Misch of the University of Washington Department of Geology, who encouraged the writer to take this problem, for long hours spent in the supervision of the petrographic study and the writing of this thesis,

as well as for discussion of mutual problems and for permission to quote him on unpublished data bearing on the interpretation of several geologic problems in the Sauk River area. For discussion of mutual problems the writer is grateful to the following workers, all of whom are or have been associated with the University of Washington Department of Geology in mapping near or adjacent to the present area: Bruce Bryant, Wilbert R. Danner, H. J. Zwart, Robert S. Yeats, Arthur B. Ford, and Robert Jones. The writer wishes to thank Prof. Howard A. Coombs and Prof. G. E. Goodspeed for critical reading of the manuscript, and Prof. J. Hoover Mackin for his criticism of the chapters of the Round Lake breccias and Quaternary History.

Presentation

The presentation of the various rock units begins with the metamorphic rocks which are of uncertain age, but are presumably among the oldest in the area. First the low grade, then the higher grade rocks are discussed. Thereafter the sequence in general proceeds from oldest to youngest. A summary of the structural and age relations of the different units more detailed than that given in the abstract is found in the concluding chapter.

LOW GRADE METAMORPHIC ROCKS

General Structural Relations and Stratigraphy

The greenschists and associated blue amphibole schists of the Sauk River area are part of a series of low grade metamorphic rocks extending continuously southward from Mt. Shuksan near the Canadian border to the present area, thence with several breaks to southeast of Snoqualmie Pass, a distance of more than 100 miles along the general strike. The lithology of the low grade metamorphics is quite distinctive, comprising well crystallized phyllites and associated greenschists and blue amphibole schists; all showing a characteristically intense deformation. The first reference to rocks of this type is that of Smith (1903) and Smith and Calkins (1905) in the Snoqualmie Pass-Mt. Stuart area; they describe "phyllitic quartz-mica schists" associated with "amphibolites containing both blue and green amphiboles." These rocks, the Easton schist, have been examined by the writer in several outcrops and are very similar to the rocks of the present area and other areas farther north. Between the present area and that of the Easton schist in the Skykomish area, Yeats (oral communication) has recently found blue amphibole schists associated with phyllites. Smith and Calkins (1904) observed glaucophane schists on an early reconnaissance trip in the lower Skagit Valley apparently in the area recently studied by Bryant. Shedd (1922) found glaucophane schists near Hamilton just south of the Skagit River about 20 miles northwest of the present area. I have examined a number of thin sections from this locality and found them to be in part similar to the glaucophane schist-greenschist rocks of my own area. Some of these rocks are different, in that they contain green hornblende and garnet, and are associated with ferruginous

quartzites.

The low grade metamorphics in the Sauk River area comprise two major units, the Gold Hill phyllite (after Gold Hill just east of Darrington in this area) and the Shuksan greenschist (Misch). The Gold Hill phyllite comprises a monotonous sequence of black quartz-sericite phyllites usually characterized by a tight crumpling of the foliation and by abundant quartz veinlets and lenticles. This phyllite sequence contains one major bed of crossite schist about 300 feet thick which has been traced for several miles. This member of the Gold Hill phyllite is well exposed near the mouth of Clear Creek and will here be called the Clear Creek Crossite schist in order to avoid confusion with the Shuksan greenschist. Since it differs from the Shuksan greenschist in several important respects, it will be described separately. Apart from this larger member a number of small greenschist layers, varying from less than a foot to about 100 feet in thickness, were found in the Gold Hill phyllite. Equivalents of the Clear Creek member may also be present northwest of the present area where Robert Jones (currently working on a thesis there) has found blue amphibole schists associated with phyllites of Gold Hill type. H. J. Zwart who has just completed mapping the area directly south of the present area has found a greenschist bed several hundred feet thick in the Gold Hill phyllite. The Shuksan greenschist crops out in a 55-mile long trending belt extending from Mt. Shuksan on the north to the present area where it has its southern limit. In Sauk River area it consists of greenschists (actinolite-epidote-albite-chlorite) intimately associated with glaucophane schists (glaucophane-epidote-chlorite) and crossite schists (crossite-epidote-chlorite); locally phyllite intercalations are important.

Field and petrographic evidence indicate that the Shuksan and Gold Hill units are part of a sequence of basic volcanics and argillaceous

sediments which has been regionally metamorphosed in the greenschist facies. Neither the age of the original rocks nor the time of their metamorphism are definitely known. However, in the present area both are older than the plant bearing arkoses of the Swauk (Chuckanut) formation of upper Cretaceous or lower Tertiary age which overlies the Gold Hill Unit. The regional metamorphism was also earlier than the upper Cretaceous of Succia Island (San Juan Islands) to the northwest in which clastic crossite and glaucophane occur (Weymouth, 1926). The low grade metamorphic rocks are presumably metamorphosed Paleozoic or Mesozoic sediments and basic volcanics, fossiliferous equivalents of which occur to the north and west of the present area. The structural complexity of the metamorphics precludes any determination of the thickness of the original beds. The apparent thickness, however, is great, that of the Shuksan unit, for instance, is more than 3000 feet on Whitechuck Mtn.

In the Sauk River area the low grade metamorphic rocks make up a large thrust sheet, the Whitechuck overthrust. Windows in the thrust occur in the area around the mouth of the Whitechuck River and in the Prairie Mtn. area. Horizontal movement on the thrust has probably been from ENE to WSW and exceeds nine miles in this area. Below the thrust is a thick series of slates associated with nonmetamorphosed basic volcanics, limestone beds, arkosic sandstones and pebble conglomerates, and occasional beds of ribbon chert. These rocks contain many small intrusive bodies of basic, and more locally of ultrabasic and quartz dioritic composition. Three of the limestone beds have yielded large crinoid stems similar to those occurring north of the Skagit River in rocks of probable Permian age. The thrust truncates structures in both the upper and lower plates and is younger, probably much younger than the regional metamorphism. North of the present area, thrusting which is probably

of the same age involves lower Cretaceous rocks (Misch). On the east the low grade metamorphics of the thrust sheet and the underlying little metamorphosed sediments are abruptly separated from medium grade migmatitic gneisses by a high angle fault, the Straight Cr. fault. The original sequence of progressive regional metamorphism is thus broken. However, the fault dies out north of the present area, south of the Skagit River (Bryant, 1955), and here there is a continuous gradation northeastward across the strike from low grade rocks to medium grade rocks of the kyanite zone (Misch, 1952).

On the summit of Helena Ridge, just west of the Sauk River, a klippe of medium grade amphibolites overlies the Gold Hill phyllites. This is believed to be a remnant of a higher thrust sheet the root of which must lie in the gneisses somewhere to the east. If, as mapping by Misch (oral communication) suggests, the root zone lies just southeast of Cascade Pass, then horizontal movement of over 25 miles is indicated. This upper thrust is probably of about the same age as the lower thrust.

The Gold Hill and Shuksan units were subjected to intense deformation during their metamorphism. This is shown by their pronounced crystallization foliation which parallels the bedding where the latter could be determined. Tight or isoclinal folding of the foliation planes (s_1) characterizes many of the rocks, in particular the phyllites. Often this folding produces a second, coarser, superposed foliation (s_2) which occasionally becomes so pronounced that the earlier foliation (s_1) is entirely eliminated. This same foliation on a very minute scale commonly produces an extremely fine striation (b lineation) on the foliation planes of the phyllites and the greenschists and blue amphibole schists. The general tectonic strike of these rocks is NNW.

The Shuksan Greenschist

On the basis of mineral composition the rocks of the Shuksan unit fall into two major groups: (1) the greenschists, characterized by a tremolitic or actinolitic amphibole, abundant epidote and albite, and minor chlorite; and (2) the blue amphibole schists in which albite is present in lesser amount and may even be absent and in which glaucophane or crossite and epidote are the major constituents and chlorite a minor constituent. These two types are intimately associated throughout the area and are mutually intercalated dozens and apparently hundreds of times in the section. Since distinction between the blue amphibole schists and greenschists is not always possible in the field, no exact figures can be given as to the quantity of blue amphibole schists compared to greenschists or on the average thickness of individual layers of the two rock types. In general, however, the greenschists predominate over the blue amphibole schists and individual layers may have thicknesses from as little as a few inches to as much as several tens of feet. Individual layers seem to be lenticular and of limited horizontal extent.

The greenschists and blue amphibole schists show the same structural features, both in hand specimen and under the microscope. All these rocks are strongly foliated. The schistosity is usually quite pronounced and the rocks split into slabs along somewhat uneven surfaces. The amphiboles show a very strong tendency to be oriented parallel to the foliation (s) and very frequently show a linear parallelism as well. This linear element is interpreted as b lineation, as it usually closely parallels the strike and is always parallel to the axes of observed minor folds. Schists in which this b lineation is strongly developed split into rough, elongate, rodlike fragments. Most of these rocks are very fine-grained.

Petrography of the Greenschists of the Shuksan Unit

Twenty-two thin sections of greenschists of the Shuksan unit were studied. Most of these schists have a rather simple mineral composition, the essential minerals being epidote, albite, tremolite-actinolite, and chlorite. The average estimated mode of five greenschists is:

Epidote	37%
Albite	29%
Tremolite-Actinolite	23%
Chlorite	5%
Quartz	4%
Sphene	2%

A colorless tremolite or a pale green actinolite is almost always present. It occurs as tiny acicular prisms most of which show sharp parallel alignment in sections cut parallel to b and perpendicular to s. Apart from their color, the pale actinolite and the tremolite do not seem to differ in their optical properties. The optic plane is 010 and the extinction angle Z:c is about 19°-20° on 010. The birefringence ranges from 0.022 to 0.024. In several of the greenschists a strongly colored actinolite was found. This actinolite is identical to the sodic actinolite (a name Misch has applied to bluish-green amphibole intermediate between crossite or glaucophane and actinolite in optical properties and composition, which frequently occurs as rims and tips on zoned glaucophane and crossite crystals, in the blue amphibole schists. Its pleochroism is X very pale yellow to colorless, Y greenish, and Z greenish blue to bluish green, X<Y=Z. The extinction angle Z:c on 010 is usually around 15°-18°, that is smaller than the paler actinolites, and the birefringence is lower about 0.019 to 0.021. Some of the sodic actinolite is itself zoned, grading into paler actinolite or tremolite on its tips. Retrogressive stilpnomelane was found in one of the greenschists containing sodic actinolite. In only one of the greenschists was amphibole entirely lacking.

Epidote is generally a major constituent of the greenschists. It occurs as rounded and irregular grains which often show a wide range in size in the same thin section. The epidote generally shows a lemon yellow pleochroism, but the pleochroism is weak or absent in the epidotes of some greenschists and the birefringence approaches that of clinozoisite. This iron-poor epidote typically occurs in greenschists which show other indications of low iron content, such as pale, iron-poor chlorite, iron-free tremolite, etc.

Albite is almost always present, usually in large amount. Often it is concentrated in albite-rich layers, individual grains joining as an interlocking mosaic or as a pavement, but it also occurs as scattered grains in a matrix of epidote and actinolite. Twinning is often but not always present. Where twinning and cleavage were not conspicuous, it was found necessary to take a large number of interference figures in order to distinguish albite and quartz and to determine their relative amounts. Extinction angles indicate a very pure albite, the anorthite content of which does not seem to exceed about An_3.

Chlorite was found in small amounts in all the greenschists. The pleochroism of the chlorite is X and Y green, and Z pale yellow or pale greenish yellow X=Y>Z. The intensity of absorption is variable, ranging from very weak to moderately strong. The interference colors are grays of the first order. In the more strongly colored chlorites the interference color is usually masked by brownish to reddish brown color, resulting apparently from the dispersion of the mineral.

Accessory sphene is generally present in amounts up to 2 or 3%. Minor apatite may also occur. Some of the greenschists contain considerable sericite. Late carbonate is sometimes present spreading through the rock without regard for the foliation or occurring in crosscutting veinlets.

Pumpellyite was found in six of the greenschists. The pumpellyite is generally very fine grained and it was not possible to determine all its properties in every case. It occurs as narrow columns which are elongate parallel to the crystallographic b-axis, and simulate the habit of the tremolite with which it is usually associated. The optic plane 010 is transverse to the elongation. Cross sections are squarish and show the highest interference colors, generally 0.015 to 0.016. Since Y is parallel to the elongation, some longitudinal sections are length-fast and some length-slow. It is further distinguished from tremolite by a higher relief, lower birefringence and a pale green pleochroism (Y). In several rocks clusters of coarser-grained pumpellyite crystals were found; in these Y has a strong blue-green absorption; the intensity of the absorption may vary within a single crystal in an irregular, patchy manner. The pumpellyite, especially the more strongly pleochroic variety, shows somewhat anomalous bluish and yellowish interference colors apparently reflecting its dispersion. There is a very fine 001 cleavage, and also a rough transverse parting across b and the elongation. In one rock the pumpellyite shows simple twins parallel to 001; on the twins a maximum extinction angle of 10° X:a, was measured. This same pumpellyite gave an interference figure with positive sign, 2V about 20°-25° and distinct dispersion of the optic axes r<v.

Lawsonite occurs in two of the greenschists containing pumpellyite. Both contain about 10% lawsonite. The lawsonite occurs as large idioblasts most of which show lathlike, rectangular outlines, but a few of which are rhombic in cross section. The crystals are tablets, flattened parallel to (001), and since Z=c, all the crystals are length fast. The birefringence is near 0.019. All crystals show parallel extinction. 2V is large, the sign is positive, and there is distinct dispersion of the optic axes r>v. Most of the

lawsonite tablets lie in the foliation plane (s), but a few have transverse positions indicating that their time of growth was somewhat later than that of the pumpellyite and tremolite both of which are always oriented parallel to the schistosity. There is a good 001 cleavage and a distinct 010 cleavage. In one of these rocks the lawsonite shows all stages of replacement by albite. Replacement proceeds along and is rigidly controlled by the two cleavage directions. In the final stage of replacement, a lawsonite grain is completely pseudomorphed by several small albite grains and only the preservation of its lathlike form makes its identification possible. The replacement of lawsonite by albite was accompanied by the formation of many small crosscutting albite veinlets in the rock. In the other lawsonite-bearing specimen some of the lawsonite has been replaced by a yellow chlorite-like mineral.

Five of the greenschists containing pumpellyite were collected on Whitechuck Mtn., and the sixth near the north end of the north ridge of Prairie Mtn. just south of the Suiattle River. These rocks occur with the ordinary greenschists and the intercalated blue amphibole schists. In all these rocks, except one, pumpellyite is a major constituent and usually makes up about 30%-35% of the rock. The typical pumpellyite greenschists consist of albite, tremolite, and pumpellyite, together with minor chlorite and iron-poor epidote. In mineral composition they do not differ significantly from the more common variety of greenschist except in that the anorthite component of the rock is bound in pumpellyite, rather than in epidote, and in that lawsonite occurs in two of these rocks. Chemically they seem to differ from the ordinary greenschists by having an even lower iron content. These rocks contain an almost colorless chlorite, iron-free tremolite and iron-poor epidote. The development of pumpellyite rather than epidote may in some way be related to the low iron content of these rocks. If this is so, it is still not clear

why pumpellyite should form instead of an iron-free clinozoisite. It may be noted, however, that none of the greenschists contain true clinozoisite; the iron-poorest epidote found had a -2V near 90° and a birefringence of about 0.017.

According to Quitzow (1936) there are two common modes of occurrence of pumpellyite: one is as a secondary mineral forming after the anorthite component of basic plagioclase in hydrothermally altered basic volcanic rocks; the other is with lawsonite in certain glaucophane rocks where it occurs both in veinlets and as nonoriented crystals in the rock itself. Rocks of the latter kind have been described by Quitzow (1935) in Calabria, and by Irving, Vonsen, and Gonyer (1932) in California. From Celebes de Roever (1947, 1950) has described pumpellyite associated with blue, green, and colorless amphiboles in various low grade metamorphic rocks derived from basic igneous rocks; in these rocks pumpellyite seems to have grown during a late stage in crystallization, its growth being contemporaneous with that of colorless amphibole and albite. In New Zealand Hutton (1937) has found pumpellyite to be a common minor constituent in graywackes metamorphosed in the chlorite zone. Bryant (1955) has described two rocks from the Shuksan greenschist which are very similar to the present pumpellyite greenschists. The present pumpellyite rocks are of interest in that the pumpellyite is a major constituent; it is also synkinematic being marked by a sharp parallel orientation in contrast to its apparently more usual postkinematic crystallization. Actually the present rocks differ from the associated tremolite greenschists only in the presence of pumpellyite instead of epidote. Probably pumpellyite is more common in greenschists than has been supposed, for due to its elongate habit it is easily mistaken for the tremolite with which it is usually associated.

In two of the rocks, one a common greenschist, the other a pumpellyite greenschist, a mineral was found which seems to be a pyroxene although it could not be positively identified. In the greenschist the mineral makes up about 10% of the rock. In the pumpellyite greenschist the mineral is restricted to one layer very rich in pumpellyite. The mineral occurs as rounded grains and stubby prisms which show a wide variation in grain size in the same rock. The birefringence is 0.024-0.025 and the relief is high. There is a distinct cleavage in two directions. In a few crystals these cleavages were seen to intersect nearly at right angles as in pyroxene, but the cleavage lacks the sharpness usually found in the latter. Z makes an angle of 41°-42° with the cleavage in sections showing the maximum birefringence. The mineral seems to have a faint yellowish-green color. The sign is positive and the 2V close to 50°. This mineral resembles very closely a colorless pyroxene occurring in certain epidote-pyroxene rocks which are described below. Textural evidence suggests that the mineral is a stable constituent in both rocks.

Petrography of the Blue Amphibole Schists of the Shuksan Unit

In the present area, as farther north, the Shuksan greenschist comprises glaucophane schists and crossite schists in addition to the more abundant greenschists. Of 24 thin sections studied, half were crossite schists and half glaucophane schists. Apart from the complexity of the amphiboles which are various members of the isomorphous group riebeckite-glaucophane-actinolite, the blue amphibole schists have a rather simple mineral composition. Essential minerals are crossite or glaucophane and epidote as major constituents and chlorite and sphene as minor ones. Quartz, sericite and albite are frequently present in varying, but generally small,

amounts. Below are the average estimated modes of

	5 glaucophane schists	5 crossite schists
Glaucophane	37%	-
Crossite	-	40%
Epidote	45%	41%
Chlorite	4%	4%
Sericite	4%	5%
Quartz-Albite	8%	6%
Sphene	1-2%	2%
Iron Ores	-	1%

The epidote of the blue amphibole schists is of the iron-rich variety pistacite and usually has a strong lemon yellow or yellowish-green pleochroism. It commonly shows a wide range in grain size in a single thin section. Unlike the epidote of the greenschists it often forms porphyroblasts. The larger grains tend to interrupt the sharp preferred orientation of the glaucophane and crossite prisms. Most of the epidote is anhedral, idioblasts are less common. Glomeroblasts consisting of clusters of epidote grains are very common. Occasionally individual epidote grains or glomeroblasts of epidote form odd circular, ball-like structures. These "epidote balls" consist of a spherical central portion of clear epidote separated from a rim of dusty, turbid epidote. Some of the dusty material seems to be finely divided hematite. The rim is generally in optical continuity with the crystals comprising the core. The outer boundary of the dusty rim is usually irregular in outline, but a few instances of spherical outline were observed. In one rock several of the clear cores were observed, each containing within it a small concentric sphere of chlorite; these epidote balls are doughnutlike in cross section. The spherical cores of clear epidote seem to have formed by pushing out the dusty included material. This is indicated by several epidote balls in which there is a concentration of the dusty material at the outer margin of the clear cores. Various epidote balls show successive stages of development

from tiny incipient clear cores to cores making up almost the entire epidote grain or glomeroblast. Why the clearing has proceeded concentrically without regard for crystallographic directions remains a mystery. The origin of the chlorite cores is also unclear.

As in the greenschists, chlorite is always present in small amount. The chlorite is moderately to strongly pleochroic. X green, Y green, Z yellowish to greenish-yellow, X=Y>Z. In most of the blue amphibole schists the chlorite shows abnormal brownish, brownish-red, or purple interference colors due to dispersion. As a rule the absorption of the chlorite is stronger in the blue amphibole schists than in the greenschists.

The blue amphibole schists commonly contain minor quartz or albite or both of these. As in the greenschists the anorthite component of the albite does not exceed about 3%. Often sericite is present, sometimes in considerable amount. Sphene is generally present as an accessory. Iron ore is common, especially in the crossite schists. Late carbonate and late stilpnomelane are sometimes present. Brownish-green synkinematic biotite was found in one glaucophane schist and in one crossite schist.

The blue amphiboles occur as narrow prisms which are sharply oriented parallel to the schistosity. The amphiboles are generally very fine grained, although crossite sometimes occurs in more coarsely crystallized layers. Amphibole cleavage and the prismatic zone are well developed and there is usually a transverse parting. Terminations of the prisms tend to be fibrous and ragged. The amphibole is zoned in almost all the glaucophane and crossite schists. The zoned amphiboles are members of a complex isomorphous series involving substitution of cations of the riebeckite (Na, Fe^{III}, Fe^{II}), glaucophane (Na, Al, Mg, Fe^{II}) and actinolite (Ca, Mg, Fe^{II}) molecules. There are two common sequences of zoning, one is crossite-uniaxial blue

amphibole-glaucophane-sodic actinolite-actinolite, the other is crossite-uniaxial blue amphibole-sodic actinolite-actinolite. Misch has studied in detail the variations in optical properties of these zoned amphiboles. Since optical data from the present area are in accord with Misch's findings, only a general outline of the optical properties of the present amphiboles will be presented here. The main emphasis is placed on those features which bear directly on the genetic interpretation of the rocks.

Orientation. Considerable care must be exercised in the identification of the various amphiboles. Positive identification often can be made only when the orientation of the optic plane is known. In crossite the optic plane is normal to 010 and near 001; X=b. In glaucophane the optic plane is 010 and Y=b. In crossite Y is nearest c, while in glaucophane Z is nearest c. In the isomorphous series crossite-uniaxial blue amphibole-glaucophane the 2V of crossite decreases gradually, passing through 0° in the uniaxial transition member to glaucophane; away from the uniaxial transition member the 2V of glaucophane gradually increases again. Passing through the uniaxial member the positions of Y and Z of crossite are exchanged for Z, and Y of glaucophane respectively. Crossites and glaucophanes near the uniaxial member may be indistinguishable except for their optic orientation; for their axial angle, character and orientation of pleochroism, extinction angle, and birefringence may be identical. The position of the optic plane is best determined by an interference figure. Where the amphibole grains are too small to give a figure, an examination of grains cut parallel to 100 showing both the blue and violet rays will often permit identification of the longitudinal blue ray as Y or Z. Both crossite and glaucophane commonly form isomorphous mixtures with actinolite. The pleochroism and other optical properties of these sodic actinolites are intermediate between those of crossite and glaucophane and

actinolite. In sodic actinolite the optic plane is 010, Y=b, and Z is nearest c, as in ordinary actinolite. In the series crossite-actinolite there is a transitional uniaxial blue amphibole member, similar to that in the crossite-glaucophane series, within which the optic plane changes position. In a number of crossite schists Misch has found a greenish-blue to bluish-green amphibole with the birefringence and pleochroism of sodic actinolite, but with the optic orientation and dispersion of crossite. This "crossactinolite" occurs as tips on cores of crossite. This "crossactinolite" often passes into greenish-blue or bluish-green uniaxial amphibole which may in turn pass into sodic actinolite with normal orientation. The optic orientation must again be determined in order to distinguish sodic actinolite from "crossactinolite." "Crossactinolite" is present as tips on riebeckite-rich crossite cores in one of the crossite schists in the present area; most of the crossite grains in this rock, however, have tips of normal sodic actinolite.

Pleochroism. The intensity of pleochroism of crossite varies from moderate to strong. In zoned crystals the strongest absorption in this material was always found in the riebeckite-rich cores. X<Y=Z.

X colorless, yellowish in the darker crossites

Y bright sky blue, dark inky blue in the darker crossites

Z violet, deep blackish violet in the darker crossites

The pleochroism of glaucophane varies from moderate to rather weak in intensity. The intensity of absorption of the darkest glaucophanes is about the same as that of the lightest crossites. X<Y=Z

X colorless

Y pale to medium violet

Z pale blue to bright blue

The pleochroism of sodic actinolite is intermediate in character between crossite or glaucophane on the one hand and actinolite on the other. The intensity of absorption is moderate to weak, being stronger where crossite passes into sodic actinolite. X<Y≈Z.

X colorless, sometimes faintly yellowish

Y violet-gray in members very close to glaucophane or crossite, but mostly gray-green, becoming green near actinolite

Z greenish-blue near glaucophane or crossite, and bluish-green near actinolite

The pleochroism of "crossactinolite" is as in sodic actinolite, but the positions of Y and Z are exchanged for those of Z and Y of sodic actinolite respectively. The absorption is moderate to weak.

2V. The optic sign of all these amphiboles is negative. The largest -2V of crossite was measured in the darkest cores and is about 55°. In zoned crystals the 2V decreases gradually outward from the dark cores to the lighter rims approaching 0° near the uniaxial transition member to glaucophane or sodic actinolite. Values between 40° and 5° are all very common. Dispersion of the optic axes r<v is strong in the darker crossites but becomes weaker in the paler ones. In glaucophane the -2V increases from very small near the uniaxial transition member to a maximum measured value of about 45° passing into sodic actinolite. Optic angles from 5°-20° are very common. -2V increases rapidly to about 60° in sodic actinolite, and then increases further passing into ordinary actinolite. Dispersion of the optic axes r<v was observed in "crossactinolite" and r>v in a few sodic actinolites zoned with crossite and uniaxial blue amphibole.

Birefringence. The birefringence of crossite ranges from about 0.008 in the darker riebeckite-rich varieties to about 0.012 in the lighter

crossites close to the uniaxial blue amphibole. The birefringence of glaucophane increases further from near 0.015 to around 0.019 at the transition to sodic actinolite.

Extinction angle. All extinction angles were measured on 010. In glaucophane and actinolite extinction angles Z:c were measured on grains showing the maximum interference colors; where possible the orientation was checked by an interference figure. In measuring the extinction angle Y:c in crossite, only those crystals showing both a pure Y (blue) and a pure X (colorless to yellowish) were used. As Misch and others have pointed out, the maximum extinction angle in the prismatic zone may not coincide with the true extinction angle Z:c or Y:c measured on 010. This is especially true of crossite. One dark crossite from the present area shows a maximum extinction angle Y:c of 4° on 010, whereas the maximum extinction angle Y:c in the prismatic zone is 21°. The extinction angles of crossite vary widely among crossites of otherwise similar optical properties (2V and pleochroism). However, in all the zoned crystals examined, the angle decreases from a maximum value in the riebeckite-rich cores to a minimum near the riebeckite-poor uniaxial blue amphibole. One zoned crossite has an extinction angle of 5° in the dark core (2V 55°) and of 2° near the uniaxial blue amphibole (2V 5°). In another zoned crossite the extinction angle varies from 17° in the dark core (2V 45°) to 13° at the rim (2V 5°). These angles were the extreme values measured in zoned crystals, intermediate angles are very common. The regular decrease in extinction angle from the dark crossite cores to the lighter rims reflects a decrease in the amount of the riebeckite molecule. Misch has shown that the larger extinction angles are probably due to admixture of the actinolite molecule, for in "crossactinolite" an isomorphous mixture of riebeckite-rich crossite and actinolite the extinction angle is large. Crossite generally

shows dispersion of extinction r<v. In the darker crossites this dispersion is very strong. The extinction angle Z:c of glaucophane is also somewhat variable. The smallest angle measured was 2°. The largest angle 12° was measured where glaucophane passes into sodic actinolite. The initial extinction angle of glaucophane near the uniaxial transition member from crossite varies in different glaucophanes, depending on the extinction angle of the uniaxial amphibole itself. After the uniaxial amphibole the extinction angle of the glaucophane may either drop further, if zoning progresses toward a pure glaucophane, or may increase with zonal growth toward sodic actinolite.

The zoned amphiboles. Zoned amphibole is present in all the crossite schists and glaucophane schists studied. The different zones comprise various members in the isomorphous group riebeckite-glaucophane-actinolite. The trend in zoning is uniform in all the rocks examined. There are two broad sequences of zoning, one is: riebeckite-rich crossite - riebeckite-poor crossite - uniaxial blue amphibole-glaucophane - sodic actinolite - actinolite; the other is riebeckite-rich crossite - riebeckite-poor crossite - uniaxial blue amphibole - sodic actinolite - actinolite. Misch has observed a third type of sequence in a number of rocks, represented by zoning from riebeckite-rich crossite through "crossactinolite" to uniaxial green amphibole and then to sodic actinolite. In my material the first two sequences seem to be much more common than the third. The trend in zoning is uniform in all the zoned crystals observed. Crystallization may begin with any member in the sequence and then progresses in the order given. That these different zoned crystals represent different compositions is clear from their optical properties. That is, minerals defined on the basis of specific optical properties (e.g., pleochroism, 2V, or optic orientation) may differ in their other optical properties. The uniaxial blue amphibole, for instance, shows varying properties in

different zoned crystals observed in different rocks; this is true even for different zoned crystals all of which lie within one of the broader zoning sequences (e.g., crossite-uniaxial blue amphibole-sodic actinolite-actinolite).

In the zoning sequence crossite-uniaxial blue amphibole-glaucophane-sodic actinolite-actinolite the full range of zoning is generally not observed in any one single rock. More often the zoning comprises only a part of the whole series, for instance, crossite-uniaxial blue amphibole-glaucophane, or glaucophane-sodic actinolite; not infrequently the range of zoning lies entirely within the composition of crossite or glaucophane alone. In the sequence crossite-uniaxial blue amphibole-sodic actinolite-actinolite the full range of zoning is more often observed in a single rock, but individual members also occur on their own.

It is usual to find that individual crystals within a single rock differ widely among themselves in the range of their zoning; some crystals show the entire range of zoning in the rock, others only a small part of it. It is also generally true that zoned crystals in a single rock differ widely among themselves in the width of individual zones. The uniaxial blue amphibole is in most cases represented by a very narrow zone, reflecting its very restricted compositional range. Commonly sodic actinolite or sodic actionlite and actinolite are present only as very tiny tips on zoned crystals of crossite or glaucophane.

In a great many of the individual zoned crystals gradual transitions in optical properties can be followed through from core to tip. These transitions demonstrate continuous growth of the zoned crystals. That the growth of even the outer zones was contemporaneous with rock deformation is illustrated by a feature common in some of the blue amphibole schists. This is the

occurrence of long thin blue amphibole prisms which have been stretched, broken, and then drawn apart parallel to their length as two, three, or even four separate pieces. In the resulting gaps between the separated pieces of individual blue amphibole crystals and on the two ends of the original crystal identical zonal growth has occurred. Continuous growth during deformation is shown by gradual changes in the composition of the zoned amphibole, and it is probable that there never were any wide gaps between the separated parts of an amphibole crystal.

In the absence of exact chemical data on the amphiboles, the contrasts in chemical composition between core and rim in the various zoned amphibole crystals can be described only in a very general way. Two zoned crystals showing a comparable range of zoning, one in the sequence crossite-uniaxial blue amphibole-glaucophane-sodic actinolite-actinolite, and one in the sequence crossite-uniaxial blue amphibole-sodic actinolite-actinolite may be compared. The two zoned amphibole crystals both show a general progressive decrease in Fe^{III} and Fe^{II} and an increase in Mg and Ca; Al increases to a maximum and then decreases; Na remains constant and then decreases. However, the two zoned crystals here considered differ in composition in optically comparable zones, such as the uniaxial blue amphibole variety; further, the various cations may reach their highest concentration in different mineral varieties or in different parts of the same mineral variety in the two zoned crystals. Other zoned crystals could be chosen which show greater or lesser contrasts in the composition of comparable zones.

The uniform trend in zoning must reflect a uniform progressive change in physical and/or chemical conditions during the crystallization of the amphibole. The progressive change in composition of the amphibole may have occurred either during a process of isochemical metamorphism without

significant change in composition of the rock, or in connection with metasomatism, involving a change in the bulk composition of the whole rock. That metasomatism is responsible for the zoning is unlikely, for Misch's chemical analyses show that the blue amphibole schists of the Shuksan unit are very close to ordinary olivine-free basalts or basaltic andesites in composition. That metasomatism should produce just this particular composition in all the blue amphibole schists seems improbable. Actually the only systematic compositional difference between the blue amphibole schists and an ordinary olivine-free basalt is their high iron content, but since the cores of the zoned amphiboles have the highest iron content, iron-introduction obviously cannot have caused the zoning. Further, the metasomatism would have to have been an extremely complex process, for not only would the added substances (Al, Mg, Ca) have to have changed progressively in composition (as the compositional zoning shows), but they would have to have been of different compositions in different rocks at the same time (as the different compositions of various zoned amphibole crystals show). For these reasons the zoning is believed to have developed without significant change in the composition of the rocks.

The cause of the zoning must, then, lie in a change of physical conditions. Since all the rocks are uniformly sharply foliated, shearing stress cannot have varied systematically in time, nor does it seem probable that depth of burial and confining pressure varied during the formation of these rocks. And, as Misch has pointed out, it is extremely unlikely that either of these conditions has changed uniformly throughout the entire 55-mile-long outcrop belt of the Shuksan greenschist which includes the areas of Misch and Bryant as well as the present area. Thus, a progressive change in temperature appears to be the probable physical control for the zoning of the amphibole.

That this change was a decrease in temperature seems very probable, for general petrographic experience indicates that in metamorphic rocks the record of falling temperature is much more frequently preserved than that of rising temperature. Further, in two of the blue amphibole schists a brownish-green biotite occurs. This biotite which seems to mark a temperature optimum has been in part replaced by chlorite at a time of lower temperature.

Misch has described several crossite schists in which the amphibole shows oscillatory zoning with a core of sodic actinolite which passes into crossite and then into sodic actinolite at the rim. In these rocks biotite formed for a time at the expense of chlorite and then stopped growing. This supports his interpretation that the zoning from sodic actinolite to crossite represents a time of rising temperature and that the more common zoning from blue amphibole to sodic actinolite represents a time of falling temperature.

If control by falling temperature is accepted, the control of the kind and range of zoning of the amphibole in a given rock remains to be examined. In his chemical study of blue amphibole schists and greenschists similar in mineral composition to schists of the present area, Misch has shown that there is a systematic variation in iron-content between the blue amphibole schists and greenschists. The blue amphibole schists are very iron-rich and the tremolite greenschists very iron-poor. The sodic actinolite greenschists and the actinolite greenschists are intermediate in iron content. Further, the crossite schists and sodic actinolite schists show a much higher $Fe^{III}:Fe^{II}$ ratio than the glaucophane schists, actinolite greenschists and tremolite greenschists. It is further true that rocks of different compositions have different types of zoning; and rocks of like composition have the same zoning. This suggests that the kind of amphibole formed and its zonal range in composition are an expression of the chemical composition of the rock and in

particular of its iron content and $Fe^{III}:Fe^{II}$ ratio. At the time of optimum temperature represented by the cores a maximum amount of iron (as riebeckite molecule) has entered into the amphibole. The composition of this initially-formed amphibole depends upon the iron content and the state of oxidation of the iron in the rock; thus in one rock a riebeckite-rich crossite may crystallize at the same time that glaucophane is crystallizing in another rock and actinolite in still another rock. With progressive zoning, the amphibole in each rock accommodates progressively less iron and the observed compositional changes in the zoned amphibole are produced.

The zoned amphibole in a given rock thus seems to preserve the record of a range of temperature during the crystallization of the rock. Although the zoning is believed to reflect temperature, a certain type of amphibole taken alone does not necessarily indicate a certain temperature, for this same amphibole may form at different temperatures as a zone in rocks of differing composition. Whereas the amphiboles of the iron-rich crossite and glaucophane schists, by virtue of their zoning, are very sensitive indicators of slight temperature variations in the greenschist facies, the iron-poor greenschists are very insensitive. For the greenschists intercalated with the blue amphibole schists have obviously gone through the same sequence of physical conditions as the latter, yet the tremolite shows no obvious zoning of any kind.

Although temperature probably determines the composition of the amphibole crystallizing at a given time in a rock of a particular composition, within the area of a thin section a modifying factor may enter in. This is the influence of minor, very local differences in chemical composition in the immediate area around individual amphibole grains. Misch has found, by very detailed petrographic work, that the ranges of composition of individual zoned amphibole crystals in single rocks often do not exactly coincide in one curve

when plotted on a composition diagram as they should in a rock of uniform composition throughout. Similar relations probably also occur in the present rocks. In a number of the blue amphibole schists, for instance, the zoned blue amphibole crystals have tiny tips of sodic actinolite. In many cases the sodic actinolite tips are present on only a small fraction of the total blue amphibole crystals in the rock. The reason why only a few crystals have developed the tips seems to be that there was only a small amount of the necessary material in the rock and that this was only locally available.

Since metasomatism has not produced the zoned amphiboles in the blue amphibole schists, it follows that the material necessary for zoned-amphibole growth was already present in the rock itself. There is no evidence in the rocks to indicate in what form the materials used in the growth of the zoned amphiboles and the other minerals in the blue amphibole schists were bound. This, however, in no way alters the conclusions reached here, for the same observation also applies to most crystalline schists which consist of a stable mineral assemblage and have been produced by isochemical metamorphism. While the isochemical nature of the rocks of the Shuksan unit as a whole is clear, this does not mean that there has been no redistribution of materials already present in the rocks. Such local transfer is, in fact, very common in these rocks. These processes, however, are probably best included under the term metamorphic differentiation and are discussed under this heading below.

The Epidote-Pyroxene Rocks

Five rocks consisting chiefly of epidote and pyroxene were found in the Shuksan greenschist. Four of the specimens were collected on Whitechuck Mtn., the fifth in the western part of the area studied by Bryant. These rocks occur in narrow layers intercalated in the blue amphibole schists.

Three were found interbedded in glaucophane schist and the other two adjacent to layers of relatively coarse-grained riebeckite-rich crossite schist. The thickness of the individual epidote-pyroxene layers varies from a maximum of 3 inches to less than half an inch in my specimens. The average estimated mode of four of these rocks is:

Epidote	38%
Pyroxene	32%
Quartz	16%
Albite	9%
Glaucophane (or sodic actinolite)	4%
Chlorite	1%

The epidote and pyroxene generally occur as a fine-grained, matted, felty, intergrown aggregate and only when a larger amount of quartz and albite are present do they occur as well defined grains. Both the epidote and the pyroxene usually have a dusty appearance due to included finely-divided opaque matter. The epidote forms irregular rounded grains, and the pyroxene stubby prisms. Due to the equigranular habit of the minerals there is generally no pronounced schistosity, but when small glaucophane or sodic actinolite needles are present, these show excellent parallel alignment. The epidote is of a distinctly pleochroic, iron-rich variety.

The pyroxene displays the typical cleavage and is moderately to strongly pleochroic with X grass green, Y green, Z brownish-yellow, X>Y>Z. The extinction angle X:c on 010 varies from 32° to 34°; there seems to be some dispersion of extinction, but its character could not be determined. The optic plane is 010. The optic sign is positive and the estimated 2V is around 60° or 65°. The birefringence is around 0.025-0.026. The optic properties of the pyroxene, especially its pleochroism, indicate that a considerable amount of aegirine molecule is present. In all five of the rocks the green pyroxene is zoned, having cores of a colorless pyroxene. However, not every green

pyroxene crystal contains a colorless pyroxene core and where present, the cores are usually rather small. Generally the transition from core to rim is rather abrupt and it is not possible to determine the optic properties of the transition zone. The colorless pyroxene also has a birefringence of 0.025-0.026. Its extinction angle Z:c on 010 is generally about 42° or 43°, but 51° was measured in one rock. The optic plane is 010, the optic sign is positive, and 2V is variable; in 2 rocks 2V was estimated to be about 45°, in another 50° to 55°, and in still another 60° to 65°. This colorless pyroxene resembles very closely the colorless pyroxene occurring in two of the greenschists described above. Unfortunately present data on the chemical composition of the pyroxenes of low grade metamorphic rocks is very meager and the composition of the colorless pyroxene of the present rocks is uncertain. However, since along with aegerine-bearing pyroxenes, jadeite-bearing pyroxenes seem to be the only common pyroxenes of low grade rocks, it is possible that this pyroxene contains a considerable amount of jadeite molecule.

In addition to epidote and pyroxene, quartz and albite are generally present in varying proportions. Usually a few per cent of amphibole is present, either glaucophane, or sodic actinolite, or glaucophane zoned with sodic actinolite. Chlorite is usually present in very minor amount. Late carbonate and minor late stilpnomelane were observed in a few of these rocks.

The epidote-pyroxene rocks are in stable association with the blue amphibole schists with which they occur. This is indicated by the occurrence of rock types transitional in mineral composition between blue amphibole schist and epidote-pyroxene rock at the contact of these two rock types, and also by the occurrence of contemporaneous glaucophane or sodic actinolite in the epidote-pyroxene rock itself. In one epidote-pyroxene rock a replacement veinlet of riebeckite-rich crossite has formed; within and adjacent to the

vein the green pyroxene and epidote have grown to large clear crystals which do not differ optically from the smaller dusty crystals of the epidote-pyroxene rock. In this case the epidote and pyroxene of the crossite veinlet have grown slightly later than the main epidote pyroxene rock, but apparently under the same physical conditions.

The colorless pyroxene in the cores of the zoned pyroxene crystals seems to be the earliest mineral phase in the rock. A very few colorless pyroxene crystals without green pyroxene rims were observed. These crystals seem to be in stable association with epidote. The abrupt transition from colorless to green pyroxene in the zoned crystals indicates an abrupt change of either physical or chemical conditions or both. Unfortunately the present data do not permit an evaluation of these factors. It is possible, however, that the colorless pyroxene cores represent an earlier metamorphic subfacies not preserved elsewhere in the rocks. That the colorless pyroxenes are relicts of an earlier igneous pyroxene seems unlikely, since thus far no relict igneous minerals or textures of any kind have been recognized in the Shuksan unit in the present area. The occurrence of stable colorless pyroxene of similar optical properties in two of the greenschists also counts against this possibility.

Having no chemical analyses of the epidote-pyroxene rocks and since the exact composition of the pyroxenes is unknown, only a few general observations may be made about the chemistry of these rocks. In epidote-content they are closely comparable to the blue amphibole schists and greenschists. The Na-content of the epidote-pyroxene rocks is probably also similar to that of the blue amphibole schists and greenschists, since albite is present as well as an aegirine component and probably also a jadeite component in the pyroxene. Iron-rich epidote and aegirine suggest at least a moderately high

iron-content. Abundant quartz indicates a considerable silica-content. Since the amounts of Ca, Mg, and Al in the pyroxene are not known, their relative amounts in the rocks cannot be determined. Possibly, however, high silica, perhaps combined with low Mg, may characterize the epidote-pyroxene rocks. It may be here mentioned that sodic pyroxenes are very commonly associated with blue amphibole rocks in a number of areas (Quitzow, 1935), (de Roever, 1947), (Brouwer and Egeler, 1952).

Metamorphic Differentiation

Apart from the large scale interlayering of blue amphibole schists and greenschists many of the rocks of the Shuksan greenschist sequence are characterized by a thin banding. The degree of development of this banding varies considerably from place to place, and sometimes it is entirely absent. The banding parallels the foliation and is compositional, consisting of layers which vary principally in the proportion and partly in the kinds of minerals present. The thickness of individual layers ranges from less than a millimeter to as much as several centimeters. The layers are generally of limited lateral extent. Any one mineral or a combination of minerals may predominate in one layer. In the blue amphibole schists, the layering generally consists of glaucophane- or crossite-rich bands alternating with epidote-rich bands. In the greenschists layers rich in epidote (pumpellyite in the pumpellyite greenschists) and tremolite or actinolite alternate with albite-rich layers. Concordant quartz segregations are also common in some of the greenschists. Banded rocks of one type (e.g., greenschist) do not seem to differ in over-all mineral, and therefore in chemical composition, from nonbanded rocks of the same type. The contrast is entirely due to concentration of the constituent minerals in layers, as opposed to their even distribution throughout the rock.

This fine banding may be either inherited from compositional layering of the original rocks or the result of metamorphic differentiation. For several reasons the latter origin is preferred for the rocks here described. First, various rocks show different degrees of banding, some are nonbanded, others are weakly banded, and still others are very sharply banded. These seem to represent all stages of metamorphic differentiation of an originally uniform rock. Further, the striking contrast in composition between adjacent bands, part of which are almost monomineralic, taken together with the extremely small thickness of the individual bands, is too pronounced to represent primary compositional layering in volcanic rocks. In view of the isochemical nature of the rocks as a whole, metamorphic differentiation seems the only adequate explanation for the banding. Banding of this kind is, of course, widespread in synkinematic metamorphic rocks. In the present rocks the differentiation has involved local chemical transfer of various constituents and their concentration in certain layers. Active penetrative movement has controlled the development of the compositional bands parallel to the schistosity.

In a number of the blue amphibole schists small tension joints have opened up normal to the b lineation and the schistosity. Generally these joints are less than a millimeter wide and are filled with a retrogressive mineral assemblage which may include an extremely fine-grained colorless amphibole, a yellowish chlorite, albite, and quartz or a combination of these. A somewhat similar feature, though contemporaneous with the main period of crystallization of the rock, is a tension joint which has opened up normal to b to a width of more than a centimeter (marked by the parallel alignment of the amphibole). This feature was observed in a glaucophane schist in which the earliest-formed amphibole is glaucophane. In this rock

the glaucophane crystals are zoned with sodic actinolite rims and some sodic actinolite has grown independently in the rock. Sodic actinolite and albite have grown in the joint, the former perpendicular to the joint walls and parallel to the aligned amphiboles of the host rock itself. Many of the sodic actinolite crystals of the joint filling are in optical continuity with glaucophane crystals in the host rock and can be followed back into these through a continuous transition in optical properties; these sodic actinolite crystals are nothing more than tips of exaggerated length of zoned glaucophane crystals of the wall rock. Since the sodic actinolite in the joint is not zoned, but is of uniform composition, its growth must have been rapid and may have kept pace with the opening of the joint. The time of growth of the sodic actinolite in the joint can, it is believed, be correlated with the growth of optically identical sodic actinolite as tips on glaucophane crystals and as independent crystals in the glaucophane schist. It is also probable that the growth of the albite in the glaucophane schist was contemporaneous with that of the sodic actinolite and albite in the joint. In view of the identity of the sodic actinolite and albite in the host rock and in the joint filling and the probability of their simultaneous crystallization, it is logical to assume that the material of the joint filling has been supplied by the host rock rather than by some distant outside source. It is interesting to note the absence of epidote in the joint filling, though this mineral is a major constituent in the glaucophane schist. In the present example of metamorphic differentiation, joint formation has produced a chemical gradient leading to migration parallel to rather than normal to the schistosity and in the banding produced by metamorphic differentiation described above.

An aegirine- and riebeckite-bearing quartzite provides another example of chemical migration. This specimen was collected on the west side of

Whitechuck Mtn. at an elevation of 5500 feet from a folded four-foot-thick quartzite bed intercalated between phyllite below and metamorphosed basic volcanics above. The quartzite is completely recrystallized and its texture gives no indication of the kind of original rock. However, the original rock may have been a chert, since bedded cherts are very common and quartzose sandstones rare in those nonmetamorphic volcanic sequences in the Northern Cascades which may be equivalent to the Shuksan greenschist. The rock consists of about 65% quartz, 15% aegirine, and 15% riebeckite.

The aegirine has a moderately strong pleochroism X bright green, Y green (slightly yellowish), and Z brownish-yellow, X>Y>Z. The optic plane is 010. The extinction angle X:c on 010 is 2° to 3°. There seems to be dispersion of extinction, although its character could not be determined. The birefringence is near 0.045. The optic sign is negative and the estimated 2V about 65° to 70°. At least one of the optic axes shows distinct dispersion r>v. The riebeckite is very strongly pleochroic with X bluish-black, Y violet black, Z brownish-yellow, X=Y>Z. The deep colors make estimation of the birefringence difficult, but it seems to be very low. The optic plane is 010. The extinction angle X:c on 010 is 2° and the mineral shows a very strong dispersion of extinction r<v. 2V is large and the optic sign is positive. Both optic axes show a strong dispersion r<v.

In the quartzite the aegirine and riebeckite are concentrated in narrow layers parallel to the schistosity which are separated from each other by wider quartz layers. The aegirine occurs as euhedral prisms flattened parallel to 010; regular terminations of the prisms are lacking. The flattened prisms tend to lie in the plane of foliation and their c-axes are also roughly parallel, imparting a linear element to the rock. The riebeckite forms long thin needles which generally lie in the foliation plane but, unlike

the pyroxene, show no distinct linear parallelism. The riebeckite needles mantle the flattened pyroxene crystals and have grown somewhat later than these; however, the riebeckite shows no tendency to replace the aegirine.

The unusual composition of the aegirine-riebeckite quartzite seems to indicate considerable introduction of both iron and soda. The source of the added substances is believed to have been the overlying greenschist-blue amphibole schist complex, for it seems unreasonable to postulate a distant source in an area in which considerable local transfer of material is known to have taken place. Although the distance of transfer has been greater, the present metasomatism does not really differ in kind from the metamorphic differentiation which produced the banding described above. In addition to showing local chemical migration, this quartzite is of interest in that both aegirine and riebeckite have formed in a low grade rock (chlorite zone). Similar cherts containing aegirine and sodic amphibole (though generally crossite or glaucophane, not riebeckite) have been described in a number of areas (Suzuki, 1934), (de Roever, 1947). Siliceous sediments metamorphosed in the greenschist facies seem particularly susceptible to this kind of metasomatism.

Metasediments in the Shuksan Greenschist

In the present area intercalated metasedimentary rocks are relatively subordinate in the Shuksan greenschist unit. The main development of these rocks seems to be in the structurally, and possibly in the stratigraphically, lower parts of the Shuksan unit not far above the Gold Hill phyllite. They are exposed on the logging road along the Suiattle River just west of the mouth of Straight Creek and also on the NE side of the NW ridge of Whitechuck Mtn., about one mile north of the summit. The metasedimentary rocks are

chiefly black, quartz-rich phyllites which seem to be identical to the Gold Hill phyllites (see below) both mineralogically and in their deformational history. Two rocks diverging from this type were observed. One is the aegirine-riebeckite quartzite already described. The other is a quartz-rich phyllite (80% quartz) which contains tiny idiomorphic grains of garnet, presumably spessartine. The garnet is largely concentrated in thin sericite-rich layers which alternate with thicker quartz-rich layers. There is also some minor albite in the quartz-rich layers.

The Origin of the Shuksan Greenschist

The Shuksan greenschist has nowhere been traced into its nonmetamorphic equivalents, nor in consequence of intense deformation and complete recrystallization have any relict textures survived from the original rocks in the present area, although Misch has found drawn out relict phenocrysts of plagioclase in several tremolite-rich greenschists on Mt. Shuksan. However, the field relations and mineral composition of these rocks strongly suggest that the original rocks were basic volcanics. In the present area the Shuksan unit consists of a thick sequence of greenschists and blue amphibole schists with subordinate interlayered phyllites. This strongly suggests an original sequence of bedded volcanics with local sedimentary interbeds. The volcanics were probably in large part flows, as there are many large greenschist-blue amphibole schist members, some measuring several hundred feet in thickness, which seem to be completely free of admixed sedimentary material even at their contacts with interbedded sediments. Some of the thinner greenschist beds in the Gold Hill phyllite are believed to have been derived from tuffs, although the thicker Clear Creek crossite schist was probably a flow. The greenschists, containing epidote, albite, actinolite or tremolite, and chlorite, do

not differ from greenschists in other areas where derivation from basic igneous rocks has been demonstrated. The mineral composition of the blue amphibole schists likewise points to original rocks of basic composition, for the derivation of both glaucophane and crossite schists from basic igneous rocks by isochemical metamorphism has been clearly shown in a number of areas (Tschopp, 1924), (Quitzow, 1935), (Brouwer and Egeler, 1952), etc.

Misch's study of chemical analyses of blue amphibole schists and greenschists from the Shuksan unit north of the present area indicates that these rocks are very close in composition to ordinary olivine-free calc-alkaline basalts. As the present rocks do not differ in mineral composition from the analyzed rocks, their chemical composition must also be the same. The similarity in chemical composition of the greenschists and blue amphibole schists may seem somewhat surprising in view of their rather striking contrast in mineral composition. However, a close examination of the mineral compositions of the greenschists and blue amphibole schists, taking into account the composition of the minerals, shows that the difference is largely a result of a differing distribution of the same constituents.

Greenschist		Glaucophane Schist		Crossite Schist	
Epidote	37%	Epidote	45%	Epidote	41%
Albite	29%	Quartz-Albite	8%	Quartz-Albite	6%
Tremolite or Actinolite	23%	Glaucophane	37%	Crossite	40%
Chlorite	5%	Chlorite	4%	Chlorite	4%
Quartz	4%	Sericite	4%	Sericite	5%
Sphene	2%	Sphene	2%	Sphene	2%

Thus Na is bound in albite in the greenschists and mainly in glaucophane or crossite in the albite-poor blue amphibole schists. The average amphibole content of the blue amphibole schists is markedly higher than that of the greenschists. This is understandable when it is considered that most of the Na and much of the Al which would form albite in the greenschists, together

with most of the Mg which would form tremolite in the greenschists, and considerable iron all enter the blue amphibole. Misch's chemical analyses show that the only systematic chemical difference between the blue amphibole schists and the greenschists is their iron content and the state of oxidation of their iron and the higher Ca-content of the tremolite-rich greenschists. The blue amphibole schists are very rich in iron and the tremolite greenschists are poorer in iron. The sodic actinolite greenschists and the actinolite greenschists are between the blue amphibole schists and tremolite greenschists but closer to the blue amphibole schists in iron content. Misch also finds that the crossite schists and sodic actinolite greenschists have a high $Fe^{III}:Fe^{II}$ ratio and the glaucophane schists, actinolite greenschists, and tremolite greenschists have a low $Fe^{III}:Fe^{II}$ ratio. The differences in iron content also find expression in the mineralogy of the rocks, especially in the contrasts between the blue amphibole schists and the tremolite greenschists. The blue amphibole schists contain strongly pleochroic, iron-rich epidote, strongly colored chlorite, and iron-rich crossite and glaucophane. The tremolite greenschists contain weakly pleochroic, iron-poor epidote, rather pale chlorite, and iron-poor or iron-free tremolite.

The various greenschists and blue amphibole schists of the Shuksan unit are intimately interlayered and repeated apparently many hundreds of times in the section. These rocks and subordinate interlayered phyllites are believed to comprise an isochemical (physical) series, that is, to have formed under uniform physical conditions. The greenschists and blue amphibole schists are all uniformly strongly foliated and all have had the same deformational history, so shearing stress can hardly have varied within the sequence. Similarly, confining pressure can scarcely have varied through distances of a few feet or a few inches. Although a record of falling temperature seems to be

preserved by the zoned amphiboles in some rocks, temperature at a given time can scarcely have varied between thin interlayered greenschist and blue amphibole schist bands. In view of the isophysical nature of the metamorphism, it is concluded that the differences in the mineral composition of the rocks must be an expression of the chemical composition of the rocks.

As Misch has shown, the major chemical difference between various greenschists and blue amphibole schists is their iron-content and the state of oxidation of the iron. These differences, it appears, may control the kind of amphibole formed and determine whether Na is bound in amphibole or albite. Misch finds it difficult to accept these very pronounced differences in iron content as representing the composition of parent rocks which in all other respects are very similar in composition. He suggests that rather uniform parent rocks may have undergone an early metamorphic differentiation in which iron was relatively enriched in some layers and impoverished in others. Although there is no direct evidence of this iron differentiation, it deserves consideration as a possibility. However, it should also be pointed out that such a process is by no means essential for the making of blue amphibole schists, for the Clear Creek crossite schist, consisting chiefly of crossite schist with minor sodic actinolite greenschist contains none of the iron-poor tremolite greenschists so typical of the Shuksan unit. If there has been any iron-differentiation in the Clear Creek member, it has been very slight.

Chemical analyses of rocks from Misch's area do not support the view often encountered in the literature that the glaucophane schists arise by Na-metasomatism. Misch has shown that the Na content of the present blue amphibole schists does not exceed that of common olivine-free calc-alkaline basalts. Further, although the average soda content of the blue amphibole schists is slightly greater than that of the average greenschist this

difference is not systematic, for a number of individual analyzed greenschists have a higher soda content than individual analyzed blue amphibole schists. Iron content not soda content is the principal compositional difference. There is certainly no evidence of regional Na-metasomatism in the present area or for that matter anywhere in the outcrop area of the Shuksan greenschist.

The Gold Hill Unit

The Phyllites

The Gold Hill unit consists predominantly of black phyllites but includes in addition to these the Clear Creek crossite schist as well as a number of thin greenschist beds. The Gold Hill unit is best exposed along logging roads on Gold Hill and along the Sauk River between Darrington and the mouth of the Whitechuck River. In the southernmost part of the area the phyllite crops out in a narrow belt which extends farther south into the area recently studied by Zwart. The phyllites are often entirely recrystallized and typically show a tight crumpling of the foliation (s_1) and often a development of a later crosscutting foliation (s_2). Most of these rocks contain many small concordant quartz segregation veinlets and lenticles.

Essential minerals in the phyllites are sericite and quartz. Albite, chlorite and graphite are often present and may be major constituents. Apatite, tourmaline, and stilpnomelane (?), and less often iron ores are common as accessory minerals. The combined quartz-albite content ranges from as little as 45% to 50% in the mica-rich phyllites to as high as 80% to 85% in the quartz-rich phyllites and averages about 65%. The mica content ranges from less than 10% to nearly 50%, averaging about 30%. The albite content ranges from 0% to as much as 45%, averaging about 10%. Chlorite is a common

constituent though it generally does not exceed 5% in amount. The graphite content occasionally reaches as much as 5% or even 10%.

The mica is generally sericite. However, in a few rocks a faintly colored mica of unknown composition with a pale greenish- or brownish-gray pleochroism was observed. Another mica-like mineral is sometimes present; it shows an orange-brown pleochroism and may be stilpnomelane, though it is too fine-grained to permit positive identification. The chlorite of the phyllites is typically a pale green variety with positive elongation and deep reddish to purplish anomalous interference colors.

Although most of the phyllites are completely recrystallized rocks, relict clastic silt grains were observed in a few thin sections. Generally even in these rocks the greater part of the quartz has recrystallized and these relict grains comprise only a small portion of the total quartz. Two of the rocks contain a somewhat higher proportion of relict clastic grains. These rocks are more coarse-grained than the typical phyllites and could be termed microarkoses, for the clastic silt grains comprise considerable (25% in one rock, 40% in the other) plagioclase. The relict clastic plagioclase of these phyllitic rocks has presumably been completely decalcified and is now an almost pure albite. The anorthite component of the original plagioclase seems to have been entirely removed, for neither epidote nor any of the other anorthite substitute minerals has been found in any of the phyllites. As in these rocks, the albite content of the completely recrystallized phyllites was probably also derived from clastic plagioclase of the parent sediments. At any rate there is no indication of Na-introduction in the rocks. Albite and quartz with a porphyroblastic habit were seen in a single thin section of phyllite. Apart from the clastic silt grains, one other feature was observed which might be interpreted as a structure inherited from the original

sediments. This is a compositional banding consisting of alternating layers which differ in their quartz-sericite ratio. Some of the layers are very thin, less than a mm to several mm, while others are much thicker and are conspicuous even in the field. Unfortunately, it is impossible in many cases to establish whether these bands are bedding or are simply a compositional layering produced by metamorphic differentiation. Usually the banding parallels the schistosity. Of all the thin sections of well-banded phyllites observed, only one showed bedding at an angle to the foliation; in this rock the banding probably represents bedding. Relatively coarse-grained phyllite layers, such as the metamorphosed arkoses mentioned above, are occasionally observed in the field and seem to be original sedimentary layers.

Various lenticles, pods, veins, and stringers of quartz are very widespread in the phyllites. These quartz bodies range from microscopic dimensions to several inches in thickness and are typically concordant, although crosscutting bodies also occur. The quartz is believed to have been segregated from the phyllites, at the time of their crystallization. This is indicated by the occurrence of the minerals of the phyllites as minor constituents in the quartz segregations and by the fact that the segregations are commonly folded with the phyllites. Field and petrographic evidence indicate that some of the quartz segregations have been formed by replacement. This is shown by the lack of dilation around the quartz bodies, by the occurrence of undisturbed relic inclusions of phyllite in the segregations, and by the gradual fading-out of the phyllite into the segregations. Other quartz segregations have apparently formed as fillings and are localized in what were probably areas of lesser stress such as fractures and the crests and troughs of folds. Tiny crosscutting quartz-filled joints are also quite common and frequently have themselves been folded by further differential movement on the

foliation planes; these again show the contemporaneity of rock deformation and metamorphism with vein formation. The quartz of the segregations seems to have been derived from the phyllites, its migration controlled by local chemical gradients.

Folding of the schistosity in the phyllites is universal and is seen to be present at least to some degree in most larger outcrops. In its incipient stages this folding appears in the field as an extremely fine striation on the plane of foliation; in thin section tiny folds are observed whose axial planes are steeply inclined to the schistosity. As folding becomes tighter, movement begins on shear planes paralleling the axial planes of the folds (s_2). As movement on these planes continues, folding assumes an increasingly smaller role in the deformation and finally a second foliation (s_2) becomes fully developed. Continued movement on (s_2) ultimately eliminates (s_1) entirely. Immediately prior to its disappearance, s_1 is preserved only as tiny fold arcs between the closely-spaced movement planes (s_2). Those phyllites with pronounced compositional banding often show striking disharmonic folding, the relatively more competent quartz-rich bands forming broad folds, while the mica-rich bands are tightly crumpled and are often transected by a newly developing s_2 parallel to the axial planes of the folds. Whereas the quartz-rich layers tend to maintain a constant thickness, the mica-rich layers commonly show thinning on the limbs of folds and thickening by tectonic accumulation at the crests and troughs. It is certain that s_1 and s_2 were both developed within the same broad episode of deformation and metamorphism, for the same mineral assemblage has formed during the making of each.

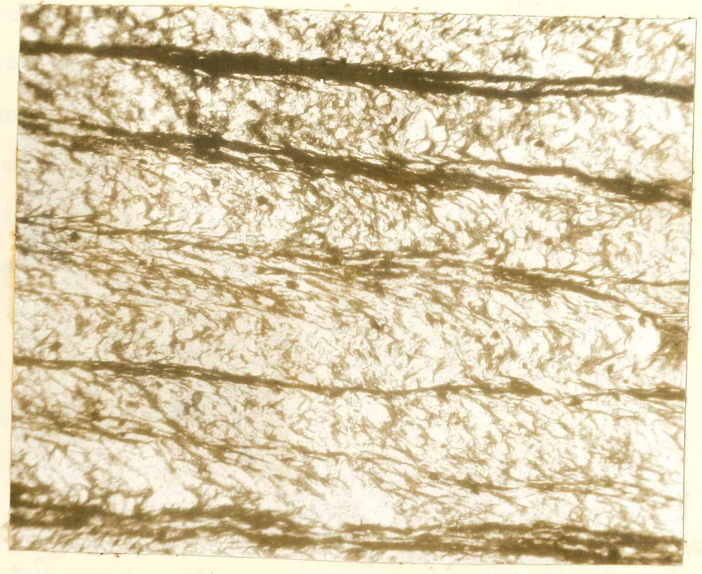
The tectonic strike of the phyllites as marked by the fold axes is about N 15-20°W, though individual strikes measured on the foliation planes occasionally deviate widely from this trend. The dip of the foliation of the

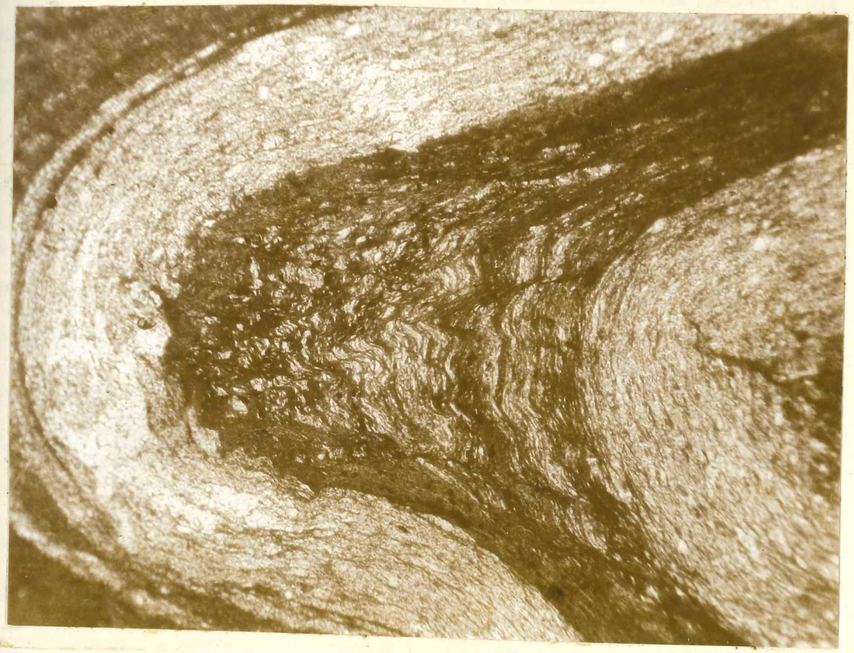
Fig. 2

Plane light. 40X. Quartz-rich phyllite (Gold Hill phyllite). A coarse s_2 is marked by graphitic films. S_1 is faintly preserved as small fold arcs of sericite.

Fig. 3

Plane light. 40X. Bedding well preserved in Gold Hill phyllite. The lighter bands are rich in quartz, a few clastic grains of which are still recognizable. The darker bands are rich in sericite and show disharmonic folding with thinning on the limbs and tectonic accumulation at the fold axes.





phyllites is generally steep and eastern dips seem to predominate somewhat over western dips which seems to suggest a tendency toward overturning to the west. The overturned minor folds actually observed in individual outcrops do not, however, seem to show any preference in their direction of overturning. Similarly, minor folds show no tendency toward a constant direction of plunge. The over-all structural picture is one of complex tight folds and minor folds which are generally upright or slightly overturned either to the east or west.

The Clear Creek Crossite Schist

Crossite schists are the dominant rock type in the Clear Creek member of the Gold Hill phyllite. In addition to these a number of amphibole-free, chlorite-rich greenschists were found in one outcrop. Apart from these two rock types, only one specimen of glaucophane schist and two specimens of sodic-actinolite greenschist were found. The Clear Creek member thus seems to lack the great diversity of rock types which characterizes the Shuksan greenschist. Since the crossite schists of the Clear Creek member are mineralogically and texturally very similar to the crossite schists of the Shuksan unit, only a brief description is given here.

Apart from occasional coarsely crystallized epidote-rich layers, the rocks are uniformly fine-grained; no coarser crossite-rich layers, like those sometimes seen in the Shuksan greenschist, were observed. The rocks are usually sharply schistose and often show a fine layering of alternating crossite-rich bands and epidote-rich bands, the latter often rich in chlorite. Again the banding seems to reflect metamorphic differentiation and local chemical migration. Epidote and crossite are the major constituents of the crossite schists and chlorite, sericite, quartz, and albite are generally also present. Late carbonate is common. Compared to the crossite schists of the Shuksan

unit the present rocks are richer in chlorite and slightly poorer in epidote and crossite. The average estimated mode of 5 crossite schists from the Clear Creek member is:

Epidote	37%
Crossite	36%
Chlorite	11%
Quartz-Albite	9%
Sericite	5%
Sphene	2%
Iron Ores	1%

As in similar rocks in the Shuksan greenschist unit, the crossite is always zoned and shows a uniform trend in zoning from darker riebeckite-richer cores to lighter riebeckite-poorer rims. Often the zoning passes through the uniaxial blue amphibole member and extends to sodic actinolite at the tips of the crystals. In one rock the zoning is in the sequence crossite - uniaxial blue amphibole - glaucophane - sodic actinolite. Some of the sodic actinolite crystals in one of the sodic actinolite greenschists have cores of crossite. The one specimen of glaucophane schist shows tips of sodic actinolite on some of the glaucophane crystals. "Crossactinolite" was not determined in any of the rocks. The absorption of the crossite varies from moderately strong in the darkest cores to slightly weaker near the rims of zoned crystals. The highest 2V for crossite is about 45° in the darkest cores, but smaller values are more common. A gradual decrease in 2V to near 0° in the uniaxial blue amphibole was followed in a number of zoned crystals. Relatively large extinction angles seem to characterize the crossites; the general range is from about 13° to 16° in the darker cores to 8° to 10° near the uniaxial blue amphibole.

The epidote is always a strongly pleochroic iron-rich variety. The chlorite is also strongly pleochroic, it has negative elongation, and in most cases has a brownish, brownish-red, or even purplish anomalous interference

color. Quartz and albite together average about 10% in the crossite schists, with the quartz usually predominating.

At one outcrop of the Clear Creek crossite schist on the Sauk River road 2.5 miles south of the Darrington bridge several interesting rock types are exposed in addition to typical crossite schists. These are amphibole-free greenschists comprising chlorite-epidote-albite schists and chlorite-albite-carbonate schists. The chlorite content of these rocks amounts to 30% to 40% in contrast to the general low chlorite content of the blue amphibole schists and amphibole-rich greenschists, both of which are more abundant in the present area. The typical chlorite of these rocks is strongly pleochroic, has negative elongation and anomalous brownish, reddish, or purple interference colors. The anorthite content of the albite does not exceed 2% to 3%. Epidote, when present, is a strongly pleochroic iron-rich type. Invariably 2% to 3% of iron ore is present. Like the crossite schists with which they are associated, these amphibole-free greenschists are sharply schistose and are believed to have formed during active differential movement in the rock. In addition they usually show a sharp compositional banding produced by metamorphic differentiation. These rocks and the associated crossite schists commonly contain late carbonate in crosscutting veinlets or as scattered porphyroblasts.

Petrographic evidence indicates that some, and possibly all of these amphibole-free greenschists have formed from the crossite schists, apparently in response to a change in chemical conditions at a late stage in the metamorphism. A number of these rocks show relict crossite and epidote which have not been completely replaced by the new assemblage. The mineralogical changes involved in this replacement are clearly seen in several of the crossite schists which show only incipient replacement by the new assemblage. Typical

is the development of chlorite-rich patches in which the crossite has generally been completely eliminated and in which the epidote has been penetrated by chlorite along cracks and cleavages or may only be recognizable as dusty pseudomorphs. Locally bands rich in chlorite but lacking in albite have formed, implying at least local removal of the Na present in the original crossite and minor albite. In thin section replacement of epidote by carbonate is often clearly seen, especially where the latter has crystallized statically. In a few rocks late carbonate was observed to have replaced crossite. Segregation of iron ores is always present where replacement of crossite has occurred. The abundance of iron ores in all the amphibole-free greenschists suggests, in fact, that these rocks have been derived from the crossite schists.

Recrystallization of the crossite schists to amphibole-free greenschists may proceed with the development of carbonate in which case chlorite-albite-carbonate schists form, or without the development of carbonate with the formation of chlorite-epidote-albite schists. In both cases there is a tendency toward complete elimination of crossite with the development of chlorite, albite, and iron ores. In the chlorite-albite-carbonate schists there is often a complete elimination of epidote, while the epidote in the chlorite-epidote-albite schists is reduced in amount but is not entirely eliminated. The partial elimination of epidote seems to indicate Ca-loss, for while the Al of the epidote finds accommodation in chlorite there is no Ca-bearing mineral present to bind up the Ca. As far as these rocks are concerned, the writer follows Vogt (1927, Sugi (1931), Turner (1933), and Hutton (1940) who have shown Ca-removal to be the controlling factor in the development of the assemblage chlorite-epidote-albite in the metamorphism of basic igneous rocks in the greenschist facies. Some writers, however, seem to have

overemphasized the importance of loss of Ca in low grade metamorphism. Barth (1951), for instance, has stated that "all basic igneous rocks will always lose CaO if they recrystallize in the greenschist facies." Certainly in the present area, and in the Northern Cascades in general (cf., Misch) chlorite-epidote-albite schists for which Ca-removal can be shown are quantitatively very insignificant compared to the extensive regional development of amphibole-rich greenschists and blue amphibole schists which are generally very poor in chlorite. As Hutton (1940) and Turner (1951) have pointed out, the association albite-epidote-chlorite-actinolite seems to be stable even at the lowest temperatures of the greenschist facies, provided that Ca is not removed. Hutton (1940) has rightly stated that the chlorite-epidote-albite schists are not necessarily derivatives of the amphibole-bearing greenschists but may form simultaneously with the latter provided Ca is removed. In the present rocks, however, the occurrence of incompletely replaced relics of crossite schist and considerable amounts of iron ores would seem to suggest their derivation from the crossite schists. Elimination of crossite and reduction in the amount of epidote are the principal mineralogical changes accompanying Ca-removal in the present rocks. These changes may be summarized as follows: crossite + epidote → chlorite + epidote (reduced in amount) + albite + iron ores + Ca. The derivation of the chlorite-epidote-albite schists from crossite schists again shows the chemical identity of the latter with ordinary calc-alkaline basalts from which the first named association very commonly forms.

While removal of Ca does seem to have played an important part in the formation of the Chlorite-epidote-albite schists, it is probable that Ca set free by elimination of epidote in the chlorite-albite-carbonate schists is still present in the rocks in the form of carbonate and that the amount of

Ca has not changed appreciably during the metamorphism. The presence of CO_2 under high partial vapor pressure would seem to account for the development of the chlorite-albite-carbonate schists. The mineralogical changes involved seem to be as follows: Crossite + epidote → chlorite + albite + carbonate + iron ores. The exact relations of the formation of the chlorite-epidote-albite schists (with removal of Ca) and the chlorite-albite-carbonate schists (without significant change in Ca content) are not definitely known, though the rocks are believed to be contemporaneous. Possibly the Ca removed in the making of the chlorite-epidote-albite schists has combined with introduced CO_2 and has been precipitated in the carbonate-rich segregation bands which are locally abundant in the amphibole-free greenschists.

In summary, special chemical conditions are believed to be responsible for the formation of the amphibole-free greenschists in the Clear Creek unit. These conditions seem to be the availability of CO_2 in the case of the chlorite-albite-carbonate schists and the removal of Ca in the case of the chlorite-epidote-albite schists. Although the amphibole-free greenschists are later than the crossite schists in that they replace the latter, their development is clearly still synkinematic and can be correlated with the main period of rock deformation and metamorphism. The various rock types, thus, all seem to be essentially isograde. The control definitely does not seem to have been physical, for it is difficult to visualize how physical conditions could have varied so locally in rocks which have experienced the same deformational history.

On the basis of its mineral composition and general similarity to crossite schists from the Shuksan greenschist, including Misch's analyzed specimens, the Clear Creek crossite schist is considered to be a metamorphosed basic igneous rock. Its thickness (about 300 feet), its structural

parallelism with the bedding of the underlying and overlying phyllites, together with its homogeneity and the lack of any admixed sedimentary material suggests that the original rock was probably a lava flow.

At the mouth of Clear Creek near the main body of crossite schist a number of thin, light-colored bands of chlorite-albite schist are intercalated in the black phyllites. These bands vary from less than an inch to about a foot in thickness and are probably metamorphosed tuff or ash layers. One of these beds consists of about 45% albite (near An_2) and 40% chlorite (pale green, length-fast, normal interference colors), with about 8% carbonate together with minor sericite, quartz, and iron ores. The rock is made up of narrow bands varying from less than a mm to 2 mm in thickness which are alternately rich in albite and chlorite; the carbonate is mostly restricted to the albite-rich layers. The most striking chemical feature of the rock is its very high Na- and very low Ca-content. If the composition of the original rock is considered to be basaltic like most of the metamorphosed basic igneous rocks in the area, the present composition indicates a very pronounced loss of Ca, either contemporaneous with or prior to metamorphism. Presumably the Al contained in the anorthite component of the original plagioclase has not been lost but is bound in the chlorite. The present chlorite-albite schists can probably be regarded as the ultimate product of Ca-removal of the kind which has produced the chlorite-epidote-albite schists discussed above (Vogt, 1927). The possibility that the parent materials of the chlorite-albite schists were of "spilitic" composition cannot be excluded with certainty, but seems unlikely in view of the general absence of spillites either as unaltered or metamorphosed basic volcanic rocks in the Northern Cascade area as far as is known at present.

Other Rock Types in the Gold Hill Unit

Apart from the Clear Creek crossite schist, a number of other beds of metamorphosed basic volcanics were observed in the Gold Hill unit. Two greenschist specimens, both of which show static recrystallization, were collected on the northwestern slope of Gold Hill. One specimen was collected from a greenschist outcrop on the Sauk River road 0.3 miles south of the Darrington bridge. It consists of very fine-grained, moderately pleochroic actinolitic hornblende which shows rough parallel alignment mimetic after the original schistosity, together with very fine-grained albite, and minor chlorite and epidote. Stubby anhedral prisms of coarser actinolitic hornblende have grown in crosscutting and concordant veins and patches. The other greenschist specimen was collected from a 20-foot-thick greenschist bed occurring about one and a half miles up the logging road on the north side of Gold Hill. The original greenschist has been completely recrystallized, although its compositional segregation banding is still preserved. In addition to albite, quartz, carbonate, and chlorite the rock contains almost 40% pumpellyite. The pumpellyite occurs as tiny nonoriented crystals in very fine-grained dark bands poor in quartz and albite, as elongate columns which show a tendency toward radial or transverse arrangement in coarser layers rich in quartz, albite, and carbonate. The pumpellyite columns are elongate parallel to the crystallographic b-axis, and since b=Y, some columnar sections have negative and others positive elongation. The mineral is faintly pleochroic with Y pale green and X and Z colorless. The relief is high and the birefringence is about 0.015. The interference colors are slightly anomalous blues and yellows. The estimated 2V is about 15°, the optic sign is positive, and there is distinct dispersion of the optic axes r<v. On the Sauk River road 0.6 miles north of

the bridge across the North Fork of the Sauk River is an outcrop of rocks which in hand specimen seem very similar to typical greenschists of the Shuksan unit. The one thin section examined, however, is a tremolite schist consisting of more than 80% tremolite and about 15% quartz-albite, together with much finely divided opaque material. If this rock is typical of the whole outcrop, and if the metamorphism was isochemical, the original material cannot have been a basic igneous rock but must have been close to a pigeonitic pyroxenite in composition.

Some of the phyllites occurring on the northwest side of Gold Hill show the same static recrystallization as the two greenschists collected there. At the Darrington bridge is an outcrop of banded, tightly-crumpled quartz-rich phyllite which has been statically metamorphosed to hornfels. The quartz-rich layers have recrystallized as a relatively coarse-grained mosaic and small nonoriented grains of static reddish-brown biotite have grown in the mica-rich layers. Another specimen of hornfelsed phyllite was collected on the Sauk River road 1.1 miles south of the Darrington bridge. The rock is a typical low grade spotted hornfels in which the spots are ovoid patches and lenticular bands rich in graphite; some extremely fine-grained brown biotite has crystallized. The static metamorphism of the phyllites and greenschists on the northwestern part of Gold Hill may have been caused either by a late static phase of the regional metamorphism or by a subjacent igneous body. The latter possibility seems to be more probable, in view of the restricted size of the area of hornfelsed rocks, and the localized occurrence in the area of hornfelsing of a number of dacitic dikes and of mineralization later than the regional metamorphism. Just south of the present area Zwart (personal communication) has found similar hornfelsing of phyllites and greenschists which is definitely related to an exposed intrusion of igneous quartz diorite. One

specimen of tightly folded banded phyllite collected by the writer on Bedal Creek near this area shows statically crystallized sericite in the originally more micaceous layers and scattered large porphyroblasts of reddish-brown biotite.

Two rocks of an unusual type which may or may not belong to the Gold Hill unit were collected on the northern part of Helena Ridge 2 miles south of the mouth of Clear Creek at an elevation of about 2500 feet. One specimen is a quartz-tremolite schist containing chlorite, sericite, and opaque matter in addition to the two major constituents. Some of the quartz grains appear to be original clastic silt grains, suggesting that the rock may be a metamorphosed dolomitic quartz-rich sediment. The other rock contains about 30% tremolite occurring as tiny needles roughly aligned in the schistosity and set in a turbid, almost isotropic groundmass of undetermined composition. Possibly this rock with which the quartz-tremolite schist is closely associated is also of sedimentary origin.

The Metamorphic Grade of the Shuksan and Gold Hill Rocks

The Shuksan and Gold Hill units together comprise a single broad unit, uniform both in structural position and metamorphic grade. The phyllites of both units show the same mineral assemblage (quartz-sericite-albite-chlorite) and clearly belong to the chlorite zone. None of the phyllites contains syn-kinematic biotite. Static biotite was observed in a few specimens but is clearly later than and unrelated to the regional metamorphism. Since the metamorphosed basic volcanics of the Shuksan and Gold Hill units which include both greenschists and blue amphibole schists are intimately interbedded with the phyllites and have shared the same deformational and metamorphic history, their metamorphism must also be placed in the chlorite zone. This is further

confirmed by the mineral assemblage of the greenschists (actinolite or tremolite-epidote-albite-chlorite); this is the characteristic assemblage of the greenschist facies (considered here to be synonomous with the chlorite zone). Synkinematic biotite was observed in one specimen of glaucophane schist and in one specimen of crossite schist both of which were collected on Mt. Pugh. This, however, is not the characteristic reddish-brown biotite which forms in metamorphosed argillaceous sediments, but is a brownish-green variety which as several writers have pointed out (Hutton, 1940) commonly forms in the higher grade portion of the chlorite zone. Both Misch and Bryant have described similar green biotite in greenschists and blue amphibole schists in the Shuksan greenschist farther north. The biotite seems to suggest that the Shuksan and Gold Hill units belong to the higher grade portion of the chlorite zone.

THE HIGHER GRADE METAMORPHIC ROCKS

General Statement

The easternmost part of the area is occupied by a complex of medium and locally high grade metamorphic rocks. Metasomatic gneisses of trondhjemitic and quartz dioritic composition form the greater part of the complex, but isochemical rocks including biotite schists, amphibolites, and marbles are also widespread. On the west these rocks are abruptly terminated against low grade metamorphic rocks and nonmetamorphic sedimentary rocks by the Straight Creek fault, a high angle fault of great displacement. One small area of higher grade rocks, probably a klippe, was mapped on Helena Ridge west of the fault. On the basis of lithology the main body of higher grade metamorphic rocks is separated into two broad units. One unit consists predominantly of homogeneous hornblende gneisses of quartz dioritic composition. This unit occupies the southwestern part of the migmatite area. Field and petrographic evidence discussed below indicate that these rocks have been derived metasomatically from amphibolites. In order to avoid the introduction of a new name this unit will be referred to simply as the hornblende gneiss unit. Northeast of the hornblende gneiss unit and in apparent stratigraphic concordance with this is a unit consisting of heterogeneous migmatitic gneisses of quartz dioritic and trondhjemitic composition associated with isochemical biotite schists, amphibolites, and more locally hornblendites and marbles. This unit, in contrast to the more uniform hornblende gneiss unit, will be referred to as the heterogeneous gneiss unit. In the northern part of the outcrop area of the heterogeneous gneiss unit is a prominent marble band, about 300 feet thick, which has been traced a distance of more than seven miles from the

Suiattle River on the north into the drainage basin of the Whitechuck River in the south. Where this marker bed is present the heterogeneous gneiss unit may be separated into three subunits, the western heterogeneous gneiss unit, the Circle Pk. marble, and the eastern heterogeneous gneiss unit. The eastern heterogeneous gneiss unit contains a much larger proportion of isochemical rocks relative to metasomatic rocks than the western heterogeneous gneisses.

Directly north of the heterogeneous gneiss unit of the present area, Bryant (1955) has mapped a series of predominantly isochemical metamorphic rocks similar to the present rocks in metamorphic grade. This series, the Green Mtn. unit, consists chiefly of isochemical biotite schists, hornblende-biotite schists, and amphibolites, and includes minor intercalations of lime-silicate rocks. The eastern heterogeneous gneiss unit resembles the Green Mtn. unit in that Isochemical schists are relatively abundant and seems to be stratigraphically equivalent to the southwestern part of the Green Mtn. unit mapped by Bryant. The southeastward continuation of the Green Mtn. unit has been mapped by Ford (personal communication) directly east of the present area. Here, as in the type area, the Green Mtn. unit consists chiefly of isochemical schists. The general close similarity in metamorphic grade and lithology of the rocks of the Green Mtn. unit and the isochemical rocks of the heterogeneous gneiss unit together with their structural concordance suggests that the two units belong to a single stratigraphic sequence. The southward extension of both the hornblende gneiss unit and the heterogeneous gneiss unit of the present area has been mapped by H. J. Zwart (personal communication). There, just as in the present area, the two units seem to be conformable. Northnortheast of the present area Misch (personal communication) has mapped a unit of rather uniform amphibolite-derived hornblende gneisses, the Eldorado gneisses, which is very similar to and may be

equivalent to the present "hornblende gneisses." A unit of heterogeneous migmatitic gneisses of migmatitic origin which occurs east of the Eldorado gneisses may be equivalent to the present "heterogeneous gneisses."

Taken together the "hornblende gneisses," the "migmatitic gneisses," and the rocks of the Green Mtn. unit seem to comprise a single stratigraphic sequence of metamorphosed geosynclinal sedimentary and basic volcanic rocks. However, here, as elsewhere in the Northern Cascades, no definite age assignment can be given to these rocks or to the time of their metamorphism. Both, however, are older than arkoses and other continental sediments, believed to be of uppermost Cretaceous or lower Tertiary age, which unconformably overlie similar crystalline metamorphic rocks in the Chiwaukum area (Willis, 1953). Presumably the metamorphics of the present are the equivalents of nonmetamorphic upper Paleozoic or Mesozoic rocks occurring to the west and northwest. The upper Paleozoic Chilliwack series mapped by Misch just south of the Canadian border includes thick basic volcanics and argillaceous sediments and may possibly represent the parent rocks of the present metamorphics. According to Misch, slates of the Chilliwack series grade eastward into epizonal phyllites north of the Mt. Shuksan. North of the Cascade River, Misch has traced similar phyllites associated with greenschists northeastward into medium grade schists and amphibolites. There is no conclusive evidence to indicate the relative age of the several metamorphic units within the present area. Zwart (personal communication) believes the hornblende gneiss unit to be structurally higher than the heterogeneous gneiss unit; however, his data do not seem to be wholly conclusive.

The hornblende gneiss unit and the heterogeneous gneiss unit have shared a common metamorphic history. The first phase was isochemical synkinematic metamorphism under conditions of the kyanite zone and at least

locally of the high grade zone. While there is a general uniformity in metamorphic grade among the synkinematic rocks, detailed mineralogical evidence, especially as revealed by a study of the plagioclase, shows a number of disequilibria. Under continued synkinematic conditions much of the isochemical rock has been transformed in situ into migmatitic gneisses by metasomatic addition of sodium and silica, and by the removal of iron and magnesium. The metasomatic origin of these gneisses is clear from: (1) detailed field relations showing gradual transition from isochemical rocks to coarser-grained, more leucocratic gneisses, (2) a tendency toward simple systematic mineralogical relationships between a given type of isochemical rock and the associated gneisses, and (3) the fact that although granitic rocks are by far the dominant rock type in the area, constituting perhaps 80% of the whole, the original stratigraphy may be followed without interruption across the entire area, a situation hardly compatible with the bodily introduction of large masses of granitic material. Locally late-kinematic and static recrystallization are prominent; where these were combined with metasomatism, they have produced numerous small dike-like and irregular replacement bodies of pegmatite and aplite. Some of the late pegmatite and aplitic dikes show true intrusive relationships.

In the following, first the isochemical schists and then the metasomatic rocks will be described. The term isochemical in the following discussion is applied to those rocks which have undergone no conspicuous or significant chemical change during their metamorphism. In the discussion of each of the various metasomatic rocks, a comparison with the related isochemical rocks will be included in order to evaluate the textural, mineralogical and chemical changes effected during granitization. Considerable attention was given to the determination of the composition of the plagioclase and the kind and range

of zoning of the plagioclase in the rocks studied. The zoning characteristic of the various rock types is described separately for each group of rocks, but the general discussion of the origin and significance of the zoning is not considered until the end of the chapter. A general summary of the structural and metamorphic history, together with a summary of the evidence for granitization is also deferred to the end of the chapter.

The Heterogeneous Gneiss Unit

The heterogeneous gneiss unit comprises an extremely variable group of metamorphics including biotite schists, biotite paragneisses, hornblende-biotite paragneisses, marbles, lime-silicate rocks, ortho-amphibolites, and hornblendites among the isochemical rocks, and an even more variable group of metasomatic migmatitic gneisses, pegmatites, and aplites of quartz dioritic and trondhjemitic composition derived from the isochemical rocks. Metasomatic gneisses predominate over isochemical rocks except in the eastern heterogeneous gneiss unit and locally in the western heterogeneous gneiss unit, as along the west side of the upper Whitechuck River. The best exposures of the heterogeneous gneiss unit are found on the high ridges, especially on "Lost Creek Ridge" between the Whitechuck River on the north and Lost Creek on the south, and on the ridge between Black Mtn. and Red Mtn. Good exposures which are somewhat more accessible are found along the road on the south side of the Suiattle River between Straight Creek and Lime Creek and also along parts of the Whitechuck River road east of Pugh Creek.

The Isochemical Metamorphic Rocks

The Biotite Schists and Paragneisses

Biotite schists and paragneisses are the most widespread isochemical rocks in the heterogeneous gneiss unit. The biotite schists occur widely as small outcrops associated with metasomatic gneisses as on the summits of Red Mtn. and Black Mtn., on "Lost Creek Ridge," and on the Suiattle River road just east of the mouth of Straight Creek, and locally, as in the eastern heterogeneous gneiss unit and west of the upper Whitechuck River, even dominate over the metasomatic rocks. Since there is no petrographic difference between the biotite schists of the western and eastern heterogeneous gneiss units, these rocks are all described together.

The biotite schists are rather coarsely cleaving rocks weathering to a somewhat brownish color, but showing shiny black plates of biotite and sometimes silvery flakes of muscovite on a fresh surface. Small garnets are usually conspicuous and a few rocks reveal small bluish blades of kyanite. Many of the rocks classified as biotite schists in the field proved upon microscopic examination to be fairly rich in plagioclase and may, hence, be termed paragneisses. The biotite schists and paragneisses do not differ in appearance and are transitional with a change in the quartz-plagioclase ratio. The quartz content of these rocks is in general slightly higher than that of plagioclase. The average estimated mode of 24 of these rocks, giving also the extreme variation in the amounts of the different minerals, is:

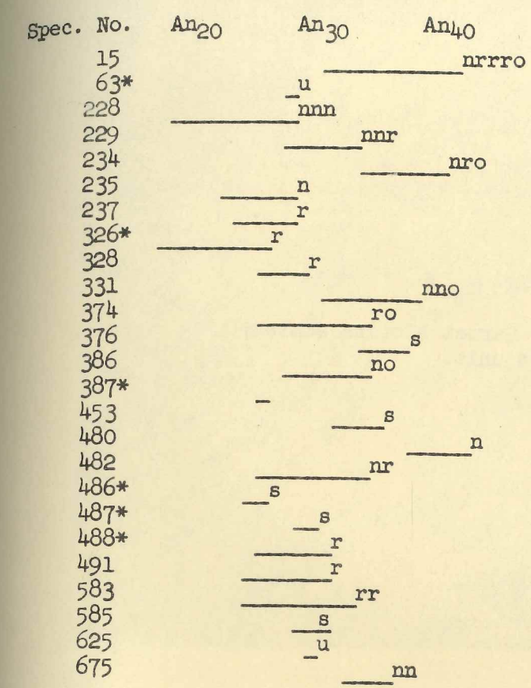
Quartz	38%	(13-51%)
Plagioclase	32%	(6-56%)
Biotite	17%	(11-27%)
Garnet	5%	(0-18%)
Muscovite and Sericite	4%	(0-17%)
Chlorite	3%	(0-14%)
Al-excess minerals	1%	(0-14%)

The biotite schists are fine- to medium-grained rocks showing a relatively sharp crystallization foliation marked by the parallel alignment of the biotite. The foliation is especially sharp in the finer-grained rocks containing abundant biotite. The biotite of these rocks has a moderately strong pleochroism with X pale brownish-yellow and with Y and Z variable from orange-brown to reddish-brown. The biotite shows pleochroic haloes around small included zircon grains. Quartz and plagioclase characteristically occur as anhedral grains forming an irregular mosaic. Less often the quartz and plagioclase show a tendency toward polygonal crystal outlines and form a pavement. Contemporaneous growth of quartz and plagioclase is suggested by the abundant occurrence in some rocks of quartz included in plagioclase and plagioclase included in quartz. The composition of the plagioclase in the present rocks was determined with the universal stage by measuring the extinction angles on 010 in sections perpendicular to the crystallographic a-axis. Inasmuch as the determinations of plagioclase composition given above are based on the standard statistically derived curves, the accuracy of which is not known for metamorphic plagioclase, the compositions cannot be considered exact, nor is the margin of error known. However, since the determinations were made with care, and since the plagioclase of all these rocks is believed to have formed in an approximately uniform metamorphic environment at least the relative differences in composition would appear to be reliable.

All but 4 of the 25 biotite schists and paragneisses contain zoned plagioclase. The zoning is typically anhedral and the passage between adjacent zones is usually not sharply marked. The range in composition of the zoned plagioclase is not great, averaging about 4% variation in An-content, but reaching 8% in several rocks. Of the 21 rocks containing zoned plagioclase, 4 show only normal zoning, 6 show only reverse zoning, 2 show simple

zoning (either normal or reverse) with an undetermined trend, 2 show some crystals with normal zoning and others with reverse zoning indicating indirectly oscillatory zoning with one recurrence, 2 show oscillatory zoning with one recurrence and a trend calcic core--sodic zone--calcic rim, and 3 show oscillatory zoning with one recurrence and an undetermined trend. In classifying a rock according to its type of zoning the highest degree of zoning observed among the various individual grains determined is taken. Thus a rock containing both unzoned crystals and crystals with normal zoning is considered to have normal zoning, and a rock containing crystals with normal, reverse, and oscillatory zoning is considered to have oscillatory zoning. Since, in some of these rocks, the determination of the range in composition is based on only one or two crystals, the actual zonal range is probably somewhat greater than is shown. The highest degree of zoning observed in the present rocks is oscillatory zoning with one recurrence. The maximum range in composition of the zoned plagioclase in each of the biotite schists and paragneisses is summarized below. In each rock the zoning of the various individual crystals determined is given (see page 69). From the chart it is seen that the average composition of the plagioclase is about An_{29} and that the extremes in composition are An_{17} and An_{41}.

Garnet is present in almost all the biotite schists and paragneisses. The garnets are characteristically small and usually show sieve texture, though in a few rocks they occur in well-formed crystals free of inclusions. Muscovite was observed in all but 6 of the rocks studied. In most of these rocks the muscovite seems to be later than the biotite as is shown by its frequent habit of transverse growth and by its common occurrence in obvious replacement relationships with biotite.



u unzoned
n normal zoning
r reverse zoning
o oscillatory zoning
s simple zoning (i.e., normal or reverse) trend undetermined
- no letter indicates plagioclase strongly altered and not known whether zoned or unzoned
* contains Al-excess minerals

A number of the biotite schists and paragneisses contain Al-excess minerals, including kyanite, sillimanite, and staurolite. Kyanite is the commonest of these in the present rocks. One specimen of garnet biotite paragneiss collected on the Whitechuck River trail 3 miles northwest of Kennedy Hot Springs contains 8% kyanite occurring as small scattered grains and as large porphyroblasts showing sieve texture and oriented roughly parallel to the schistosity. The kyanite in this rock is conspicuous on a weathered surface as small bluish bladed crystals. A specimen of biotite schist collected from float on a logging road on the north side of the Whitechuck River just opposite the mouth of Pugh Creek contains in addition to 11% kyanite, about 4% of staurolite in small anhedral crystals. Several of the kyanite-bearing rocks have undergone strong static recrystallization in which most or all of the kyanite and much of the biotite have been converted into muscovite.

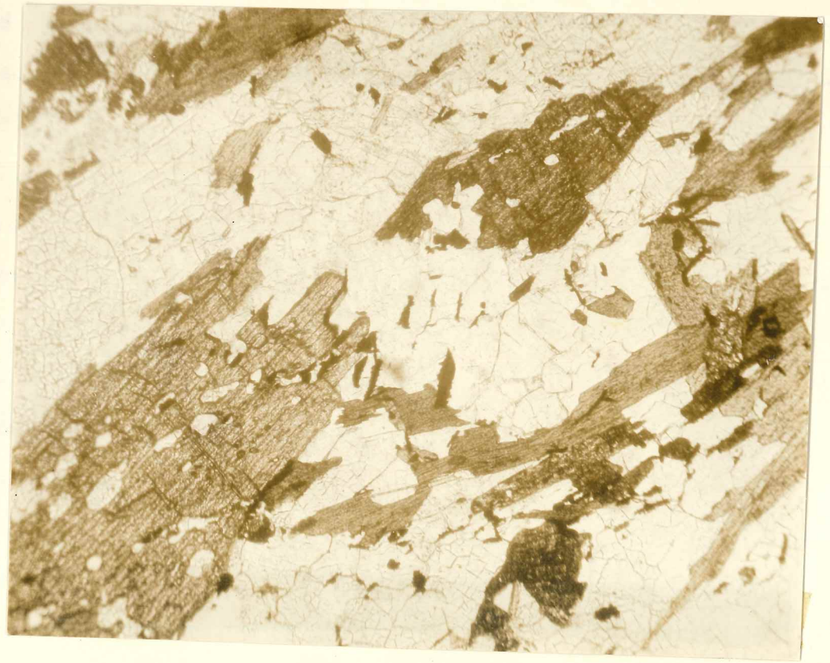
Fig. 4

Plane light. 40X. Garnet biotite schist. Heterogeneous gneiss unit.

Fig. 5

Plane light. 40X. Kyanite porphyroblasts in garnet-biotite schist. Heterogeneous gneiss unit.





Kyanite, if at all preserved in these rocks, is present only as tiny relict grains in large nonoriented muscovite porphyroblasts or protected in large including quartz grains. Small amounts of sillimanite, more properly fibrolite, are common in most of the rocks showing the development of late muscovite. The fibrolite generally occurs in large muscovite grains as groups of tiny needles or as dense bundles of needles in subparallel or weakly radiating arrangement. Less commonly the fibrolite occurs as subparallel needles in quartz grains. The fibrolite aggregates show a general rough alignment parallel to the schistosity. Muscovite-rich schists containing late fibrolite and relict kyanite were collected on the ridge about one-half mile west of the summit of Meadow Mt. (Pk. 6300), on the "Lost Creek Ridge" trail one-half mile west of Camp Lake, and on the summit of Black Mtn.

Many of the biotite schists and paragneisses show features arising from a later phase of retrogressive metamorphism. Biotite commonly is replaced by a pale green or almost colorless chlorite with normal interference colors and positive elongation. Sometimes biotite is replaced by aggregates of sericite, iron ores, and epidote. Garnet is often altered to chlorite, sericite, or sericite and chlorite with or without the formation of clinozoisite. Some of the plagioclase has broken down into zoisite or epidote and often sericite associated with a more sodic plagioclase. Muscovite often alters to sericite. Minor amounts of well-formed epidote associated with plagioclase were observed in a few rocks; but the composition of the plagioclase could not be determined.

Accessory apatite and zircon are present in all the rocks examined. Rutile is almost as common. Graphitic material and iron ores are present in many of the rocks. Tourmaline, interestingly, was found in all the schists containing Al-excess minerals but in none of the others.

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The occurrence of kyanite in the biotite schists and paragneisses indicates that these rocks have crystallized in the kyanite zone. The occurrence of plagioclase as calcic as An_{41} in these rocks without contemporaneous anorthite-substitute minerals suggests that a plagioclase at least this calcic was stable under conditions of the kyanite zone. The conditions under which sillimanite has crystallized are unclear. The fibrolite probably should not be taken as indicating temperatures of the high grade zone (Misch, unpublished MS).

One specimen of garnet-biotite schist collected at Kennedy Hot Springs is unusual in that much of the synkinematic biotite has statically recrystallized to aggregates of small unoriented biotite crystals. In the same rock static muscovite and zoisite have grown at the expense of plagioclase and some transverse muscovite has formed from the biotite. Since no other schists from this immediate area have been sectioned, the extent of this static recrystallization is unknown. There are no obvious features such as intrusive granite or statically granitized rocks exposed in the area to which the hornfelsing can be related.

The garnet biotite schists and paragneisses are metamorphosed argillaceous sediments, for the common occurrence of Al-excess minerals in these rocks clearly shows derivation from original materials rich in clay minerals. The rather high plagioclase content of these rocks, averaging about 32%, suggests that the original rock may have been rich in clastic plagioclase. In this connection the high content of clastic plagioclase in some of the incompletely reconstituted phyllites of the Gold Hill unit is recalled.

The Hornblende-Biotite Paragneisses

Five paragneisses from the heterogeneous gneiss unit were studied which contain hornblende in addition to biotite. Four of these rocks were

collected on the road on the south side of the Suiattle River, the other in the valley of Cougar Creek just east of the summit of Bedal Peak. In hand specimen they differ little in appearance from the biotite schists and paragneisses except in that garnet is generally absent and in that hornblende may be conspicuous. These rocks vary rather widely in mineral composition, though all are rich in plagioclase. They seem to be intermediate in composition between biotite paragneisses on the one hand and para-amphibolites on the other. The quartz content of the hornblende-biotite paragneisses is considerably lower than that of the biotite paragneisses. According to the ratio of biotite-hornblende the rocks are hornblende-bearing biotite paragneisses, hornblende-biotite paragneisses, and biotite-bearing hornblende paragneisses. As hornblende does not exceed 37% in any of these rocks, none are classed as true para-amphibolites. The estimated average mineral composition of these five rocks, and the maximum variation in the amount of the minerals is:

Plagioclase	48%	(40-55%)
Quartz	9%	(1-20%)
Hornblende	22%	(7-37%)
Biotite	10%	(3-19%)
Combined hornblende-biotite-chlorite	37%	(24-45%)
Epidote	2%	(0- 5%)
Garnet	3%	(0-14%)
Chlorite	5%	(1-15%)
Sericite	1%	(0- 7%)

The hornblende of these rocks varies greatly from rock to rock in its optical properties, especially in its pleochroism and absorption. These properties are summarized here.

Spec. No.	Z:c	X	Y	Z	absorption formula
236	15°	pale greenish-yellow	brownish-green	grayish-green	X<Y=Z
242	17°	faint greenish	grass green	grayish-green	X<Y=Z
243	18°	pale yellowish	brownish-green	grayish-green	X<Y=Z
269	14°	yellow green	dark grass green	dark bluish green	X<Y=Z
531	15°	colorless	pale green	pale green	X<Y=Z

The hornblende forms stubby anhedral prisms which roughly parallel the schistosity and which in a few rocks tend to be aligned in the schistosity. The biotite also shows marked preferred orientation parallel to the schistosity. The biotite has a moderately strong pleochroism with X pale yellowish-brown, and Y and Z variable in different shades of orange-brown.

The plagioclase of the hornblende-biotite paragneisses ranges from An_{19} to An_{34} in composition with an average composition of An_{28}. The plagioclase in all these rocks is zoned, with a 6% average range in composition for the five rocks. The zoning is anhedral and the passage between adjacent zones is not sharply marked. Two rocks show oscillatory zoning with one recurrence and a trend sodic core--calcic zone--sodic rim, two rocks show oscillatory zoning with one recurrence and an undetermined trend, and one rock shows simple zoning of an undetermined trend. The range in composition of the zoned plagioclase for the five rocks is as follows:

Spec. No.	An_{20}	An_{30}	An_{40}	
236		_s		u unzoned
242	_____	rroo		n normal zoning
243	_____	o		r reverse zoning
269		_____	rrro	o oscillatory zoning
531		_____	rro	s simple zoning (i.e., normal or reverse) trend undetermined
				- no letter indicates plagioclase strongly altered and not known whether zoned or unzoned

Garnet is generally absent in the hornblende-biotite paragneisses. One specimen, however, contains about 13% garnet as small poikiloblastic crystals some of which have been rotated subsequent to growth.

Well-formed epidote was observed in three of the rocks. Some of this epidote is closely associated with biotite suggesting biotization of hornblende. In one rock, however, well-formed epidote is in contact with the calcic rims (An_{34}) of zoned plagioclase, indicating this to be the most calcic

plagioclase possible under the particular P-T conditions under which the association plagioclase + epidote crystallized in this rock. Since plagioclase as calcic as An_{41} has crystallized in some of the closely associated biotite paragneisses, the present rock is interpreted as having crystallized at a somewhat different time under slightly different temperatures than the former.

Accessory iron ore is present in several of the hornblende-biotite paragneisses. Apatite was observed in one rock, apatite and rutile in another, and sphene in a third.

Most of the hornblende-biotite paragneisses show some degree of retrogressive recrystallization. The plagioclase commonly has broken down into a more sodic plagioclase and a fine-grained aggregate of zoisite or sericite. In one rock the plagioclase has altered to muscovite. Biotite in some of the rocks has altered to a pale green chlorite with negative elongation and normal gray or slightly anomalous brownish-green interference colors. The plagioclase in two of the rocks is surrounded by very narrow albitic rims giving thus a sort of secondary zoning (Misch, unpublished MS). This secondary zoning has apparently been caused by decalcification of the plagioclase along the intergranular.

In addition to the presence of hornblende and to the general absence of garnet, the hornblende-biotite paragneisses differ from the biotite paragneisses in their higher plagioclase and their much lower quartz content. Since, however, the two rock types are closely associated in the field, and since they do approach each other in mineral composition, the hornblende-biotite paragneisses are also considered to have been derived from sedimentary rocks containing a considerable argillaceous component. For those hornblende-biotite paragneisses associated with the Circle Pk. marble, at least,

derivation from calcareous-dolomitic argillaceous sediment seems definite. Some of the hornblende-biotite paragneisses may have formed from argillaceous sediments containing admixed basic tuffaceous material or clastic material of basic volcanic derivation.

The Circle Pk. Marble and Associated Lime-Silicate Rocks

The Circle Pk. marble is a prominent stratigraphic marker in the northern part of the outcrop area of the heterogeneous gneisses and as far as is known at present, is one of the most extensive units of its kind in the higher grade metamorphics of the Cascades. It has been traced almost continuously for a distance of over four miles from north of Circle Pk. on the northwest into the drainage basin of the Whitechuck River on the southeast. Throughout this interval it dips almost vertically and has not been involved in any minor folding. The area along the prolongation of the marble bed to the southeast has not been mapped; however, if the marble bed does extend farther southeast, its continuation will probably be found somewhere on the lower west flank of Glacier Pk. Careful mapping has shown that it does not occur on the ridge west of the upper Whitechuck River. The thickness of the marble bed including the associated lime-silicate rocks was estimated to be nearly 300 feet on Circle Pk. and almost as much at the southernmost outcrop observed. The probable northward extension of the marble bed is exposed on the road on the south side of the Suiattle River 0.7 miles east of the mouth of Circle Creek. This bed is not an along-the-strike continuation of the Circle Pk. marble farther south, but is offset nearly two miles to the northeast either by faulting or folding. At this outcrop the marble bed has an exposed thickness of 80 feet but is probably much thicker. Mapping has shown that the marble nowhere reappears in the present area and Ford has not found it in the area directly to the east. It, thus, seems unlikely that the

heterogeneous gneiss unit has been repeated by folding in the present area. At present no definite correlation of the Circle Pk. unit with other marbles in the northern Cascades can be made. Further work may possibly show marbles occurring on the Little Wenatchee River and on Lake Wenatchee along the approximate continuation of the strike of the Circle Pk. thirty miles to the southeast to be equivalent.

The marble is a coarse-grained rock weathering grayish with a rough granular surface. The fresh rock is a massive pure white marble often containing scattered specks or fine bands of lime-silicate minerals and occasionally small flakes of muscovite. The lime-silicate bands weather out in relief against the adjacent marble bands. Among the lime-silicate minerals visible in hand specimen are greenish diopside, pale brownish zoisite and iron-poor epidote, and small needles of amphibole including colorless tremolite, greenish actinolite, and dark green hornblende. White bands rich in plagioclase or plagioclase and quartz are common, both in association with the lime-silicate bands and in the marble itself. Since petrographic examination shows a uniform mineral development, metamorphic history, and metamorphic grade along the entire extent of the unit, no distinction need be made between rocks collected at different outcrops along the strike. For the purpose of description the rocks are divided into three major groups: (1) lime-silicate-bearing marbles, (2) lime-silicate rocks, mostly rich in epidote, and (3) diopside-quartz-plagioclase bands of quartz dioritic composition.

Rather pure marbles containing only minor amounts of lime silicate minerals make up the greater portion of the Circle Pk. unit. Since these, however, are of little petrographic interest, more attention was given to those marbles containing conspicuous amounts of lime-silicate minerals.

Lime-silicate-bearing marbles. The carbonate of the marbles is believed to be chiefly calcite as is suggested by its vigorous effervescence with dilute hydrochloric acid and by the occurrence of the association carbonate-quartz-diopside in the rocks. The calcite is coarse-grained forming an interlocking mosaic of irregularly rounded or less often of rudely polygonal grains. Post-crystalline deformation of calcite is shown in several of these rocks by bent and ruptured cleavages and twin lamellae. The occurrence of tiny granules of calcite along the boundary of large calcite crystals in some of these rocks indicates differential movement between individual crystals. Quartz is present in small amounts in most of the marbles.

Diopsidic pyroxene was found in all the lime-silicate-bearing marbles examined. It occurs as small rounded grains scattered unevenly through the marble and less often in small glomeroblastic clusters. Occasionally it forms large anhedral porphyroblasts which often show sieve texture. A few of the diopside crystals show some development of the front and side pinacoids and of prismatic faces. A very sharp 100 parting is conspicuous on the diopside in some of the marbles. Some of the diopside showing this parting exhibits a very fine parallel intergrowth on 100 of a mineral with low birefringence and parallel extinction.

Zoisite, like diopside, is present in most of the lime-silicate-bearing marbles. The zoisite is generally the iron-bearing variety with normal interference colors but sometimes contains patchy intergrowths of iron-free zoisite with deep blue anomalous interference colors. Zoisite occurs as isolated crystals among calcite crystals where it often attains good crystal form and in parallel intergrowth with plagioclase.

Minor plagioclase associated with zoisite is very common in the marbles. The plagioclase is unzoned and has a uniform composition near An_{32}

in all the marbles studied. Without exception the plagioclase and zoisite are diablastically intergrown and unquestionably are contemporaneous. Not a single grain of plagioclase was found in any of the marbles which is not intergrown with zoisite. The association of the zoisite with plagioclase of this uniform composition is so constant that it implies a dependent genetic relation between the two minerals. The association zoisite-plagioclase (An_{32}) can be explained only if each individual intergrowth is interpreted as a kind of composite pseudomorph. This association cannot have been chemically controlled in view of the uniform composition of the plagioclase. The association must, then, have been physically controlled and must be interpreted as having formed from the breakdown of an originally more calcic plagioclase in response to a uniform lower temperature. The ratio of zoisite to plagioclase where the two are intergrown is nowhere less than 1:4 and often exceeds 10:1. Assuming that all the zoisite associated with plagioclase was originally anorthite component in plagioclase we can roughly determine the composition of the original calcic plagioclase. This plagioclase must have varied from about An_{45} to almost pure anorthite depending on the amount of Na locally available in the marble. From the composition of the original plagioclase now represented by the zoisite-plagioclase pseudomorphs, temperatures of the high grade zone may be inferred. In addition to the well-formed zoisite, fine-grained dusty zoisite is associated with the plagioclase in a few of the marbles. In these rocks, however, the composition of the plagioclase could not be determined, and it is not possible to establish the relationship between the crystallization of the fine-grained zoisite and that of the well-formed zoisite.

Most of the marbles contain minor amphibole, usually tremolite or an actinolitic amphibole. The amphibole is generally pale green or colorless in hand specimen and colorless in thin section. The amphibole forms acicular

prisms with ragged terminations. It occurs both as isolated crystals and in little clusters and often is associated with diopside. The diopside and the amphibole, however, both occur independently of each other and are apparently in stable association.

A colorless mica is often observed in thin section as a minor constituent. In hand specimen both colorless and pale brown mica are identified, thus in different specimens both muscovite and phlogopite may be represented. Sphene and apatite are almost constant accessories in the marbles and ore minerals are also common.

The lime-silicate rocks. The lime-silicate rocks invariably contain epidote and diopside and commonly quartz, hornblende, plagioclase, and calcite in addition to these. The rocks vary widely in mineral composition depending on the relative amounts of the above minerals. With increase in the amount of calcite these rocks pass into lime-silicate-bearing marbles, and with increase in plagioclase and decrease in epidote into rocks of diopside-quartz-dioritic composition. The lime-silicate rocks occur as layers ranging from a few mm to many feet in thickness within the marble and near its contacts with the adjacent schists and gneisses.

Epidote is a dominant constituent in most of the lime-silicate rocks and in some layers exceeds 70% in amount. Just as zoisite is confined to the marbles, epidote seems to be confined to the lime-silicate rocks. The epidote is generally coarse-grained, forming large anhedral porphyroblasts some of which show excellent sieve texture. The mineral generally has a rough columnar habit and often exhibits preferred orientation parallel to the bedding and foliation. Occasionally well-developed crystal faces are observed. Simple and polysynthetic twinning are sometimes observed. The epidote is a nonpleochroic iron-poor variety with anomalous interference colors of the first

order. The interference colors commonly vary in different parts of a single crystal, having an irregular patchy distribution.

Diopsidic pyroxene occurs in all the lime-silicate rocks, both as small anhedral grains and as larger porphyroblasts. Most of the lime-silicate rocks are rich in quartz, though it is entirely absent in one specimen. Some of these rocks are, in fact, actually epidote-quartz granulites containing diopside and minor amounts of other minerals such as amphibole, calcite, and plagioclase. The lime-silicate rocks often contain minor plagioclase and are occasionally rich in this mineral. In two rocks a uniform unzoned plagioclase near An_{32} in composition was observed in diablastic intergrowth with epidote. The relations here are identical to those of zoisite and plagioclase in the marbles. Calcite is generally abundant only in rocks adjacent to marble bands. Actinolitic hornblende or more often true hornblende is generally present as acicular prisms. The pleochroism of the amphibole varies in intensity in different rocks, the absorption being Y pale yellowish, Y grass green, Z bluish green. Diopside and hornblende seem to be contemporaneous. Sphene and apatite are almost constant accessories.

One lime-silicate rock examined differs rather sharply from the rocks just described. It is a strongly schistose rock containing approximately 30% hornblende, 24% chlorite, 19% diopside, 14% clinozoisite, 9% muscovite, 2% sphene, and 1% plagioclase. Clinozoisite, hornblende, muscovite, chlorite, and to a lesser extent diopside are all aligned parallel to the schistosity. The pleochroism of the hornblende is X pale greenish, Y brownish-green, Z grayish green. Z:c 20°. The chlorite is a very pale green, almost colorless variety with normal interference colors and negative elongation. The chlorite has apparently formed from the hornblende and the latter, where in contact with chlorite, has generally been altered to a colorless tremolitic

amphibole with higher interference colors than the hornblende. The minor plagioclase present is near An_{32} in composition and is in equilibrium with associated clinozoisite.

Diopside-rich quartz dioritic bands. These rocks are very common as thin layers both in the marble and associated with the lime-silicate rocks. In the marbles these layers often show a boudinage-like pinch and swell structure resulting from stretching during penetrative deformation. All these rocks are rich in plagioclase which reaches as much as 80% in a few rocks. Quartz is generally present though its amount is often small. Most of these rocks contain a diopsidic pyroxene which may reach 30% in amount. Quartz and plagioclase join in a mosaic of zenoblastic grains among which roughly columnar crystals of anhedral diopside are scattered. The diopside sometimes shows a weak preferred orientation parallel to the schistosity and occasionally forms porphyroblasts which contain large inclusions of quartz and plagioclase and seem to have grown along the intergranular at a late stage in the crystallization. The plagioclase in the diopside quartz dioritic bands has an average composition of about An_{29}, somewhat less calcic than the plagioclase in the associated marbles and lime-silicate rocks, and unlike the latter, it is commonly zoned. The zoning is anhedral and the transition between zones is in part quite gradual and in part sharply marked. The zoning and range in composition of the plagioclase in three of the diopside quartz diorites are given below.

Spec. No.	An_{20}	An_{30}	An_{40}	
239	———	nooo		n normal zoning
381		n		r reverse zoning
383		nrro		o oscillatory zoning
				- no letter indicates plagioclase strongly altered and not known whether zoned or unzoned

The highest degree of zoning observed in these rocks is oscillatory zoning with two recurrences; oscillatory zoning with one recurrence is much commoner, however. The reason why zoned plagioclase occurs in these rocks and not in the associated marbles and lime-silicate rocks is not clear. Any plagioclase less calcic than An_{32} would of course be stable at temperatures at which An_{32} forms. This, however, does not explain the occurrence of plagioclase as calcic as An_{37} in one specimen. In this connection it may be noted that many biotite schists and gneisses closely associated with the Circle Pk. marble also contain plagioclase more calcic than An_{32}. Late epidote occurs in two of the quartz dioritic rocks examined. Some of the plagioclase in a few of the diopside quartz diorites shows incipient alteration to zoisite and sericite or to zoisite alone. The plagioclase in two of the rocks has very narrow albitic rims which are believed to be a secondary zoning (Misch, unpublished MS) resulting from decalcification along the intergranular. Hornblende was found in one of the rocks and small amounts of microcline in another. All these rocks contain accessory sphene and apatite.

The origin of these diopside quartz diorites is not entirely clear, but whatever their origin, they are clearly metamorphic. The textures are wholly crystalloblastic and the rocks have clearly participated in the same deformational history as the closely associated marbles and lime-silicate rocks. If the rocks were igneous, it would be extremely fortuitous to find them associated only with diopside-bearing marbles and lime-silicate rocks and not with other rocks such as the biotite schists and gneisses which occur nearby. Clearly the diopside quartz diorites are somehow related to the marbles and lime-silicate rocks. However, they cannot be isochemical members of this group of diopside-bearing lime-silicate rocks, for some of the quartz diorites are very rich in plagioclase (up to 80%) and poor in quartz; no known

sediment has such a composition and could give rise to such a rock by isochemical metamorphism. It is conceivable that the diopside quartz diorite layers have formed from small intrusive trondhjemitic aplitic bodies such as the small crosscutting intrusive dikes which are commonly observed in the marble. These, if forced into the direction of the foliation by shear folding and "plastic flowage" and if metamorphically recrystallized with the introduction of diopside, might give rise to the quartz diorites. Another interpretation is that the diopside quartz diorites are granitized lime-silicate bands and that the sodic plagioclase has largely formed from a more calcic plagioclase, or from zoisite, or epidote with the introduction of Na.

The original rocks and metamorphic grade of the Circle Pk. unit. On the basis of their mineral assemblage the lime-silicate-bearing marbles are judged to be derived from limestone containing appreciable dolomitic, quartzose and argillaceous components. The parent sediments of the lime-silicate rocks were very rich in argillaceous material and generally also in silica, while lesser amounts of dolomite and calcite have also participated. In neither of the rock types is it known how much of the Na was originally present and how much has been introduced. The origin of the quartz-plagioclase-diopside layers has already been discussed.

The lime-silicate-bearing marbles are of interest in that they contain the assemblage calcite-quartz-diopside-zoisite. Temperatures then were not yet high enough to develop typical high grade minerals such as wollastonite, grossularite, anorthite, vesuvianite, and forsterite. Further, the diopside appears to be in stable association with a relatively sodic plagioclase (around An_{32}) not only in the marbles and lime-silicate rocks, but also in the diopside quartz diorites. Temperatures then were not yet of the high grade zone. This seems to be confirmed by the close association of the Circle Pk.

marble with biotite schists of the kyanite zone. It is probable that the Circle Pk. marble and presumably also the heterogeneous gneiss unit, or at least those parts of this unit associated with the Circle Pk. marble, were at an earlier time crystallized in the high grade zone. The evidence for this view has already been discussed. Further evidence is the occurrence of labradorite, and even more calcic plagioclase, in some of the ortho-amphibolites and the occurrence in many of the biotite schists, of plagioclase more calcic than An_{32} (this latter being the plagioclase associated with contemporaneous zoisite in the marbles). The ortho-amphibolites and biotite schists in question, like the Circle Pk. marble, are part of the heterogeneous gneiss unit.

The Ortho-Amphibolites

Intercalations of ortho-amphibolite are widely distributed in the heterogeneous gneiss unit, especially in the western division of this unit. These ortho-amphibolites are very commonly associated with migmatitic hornblende gneisses and often also with isochemical rocks, especially with the biotite schists and paragneisses. In general the ortho-amphibolites have been very strongly granitized and the proportion of unaltered isochemical rocks to metasomatic hornblende gneiss is small. Under the present heading only those rocks are described which are considered to be isochemical on the basis of their textures, mineralogy and field relations.

The amphibolites are sharply schistose rocks and are mostly very dark in color. Some of them show a fine banding, light-colored plagioclase-rich layers generally not exceeding a few mm in thickness alternating with thicker dark layers rich in hornblende. This banding is very common and is only rarely absent in any larger outcrop. The banding is interpreted as segregation banding formed by metamorphic differentiation, during penetrative deformation, involving transfer of hornblende and plagioclase perpendicular to

the schistosity and the relative concentration of these minerals in certain layers. More coarse-grained bands of quartz-dioritic hornblende gneiss are also extremely common in the ortho-amphibolites; these, however, are interpreted as "lit par lit replacement" bands and are described with the metasomatic rocks. In addition to the thin plagioclase-rich bands, some of the amphibolites contain light-green layers varying from less than a mm to several cm in thickness. Some of these layers are rich in diopsidic pyroxene, and others are rich in clinozoisite or epidote. Garnet is present in many of the ortho-amphibolites, generally as small scattered porphyroblasts. In a few of these rock garnets up to half an inch in diameter were found.

The ortho-amphibolites are quite simple mineralogically, containing hornblende and plagioclase as essential minerals and commonly garnet and quartz in addition. The average estimated mode of 12 amphibolites is:

Hornblende	48%	(28-61%)	(Ignoring one atypical rock
Plagioclase	36%	(16-60%)	with an abnormally high
Quartz	10%	(0-44%)	quartz content, the average
Garnet	2%	(0-13%)	quartz is only 6%.)
Clinozoisite	2%	(0-18%)	
Sphene	1%	(0- 3%)	

The rocks range from fine-grained to medium-grained, and hornblende and plagioclase generally show about the same grain size. The hornblende occurs as stout zenoblastic crystals elongate after c which show a marked preferred orientation parallel to the foliation and sometimes a marked linear parallelism as well. The textures of the amphibolites vary somewhat with the relative amounts of hornblende and plagioclase. Where the hornblende predominates, the plagioclase occurs as scattered anhedral grains among the more numerous grains of stubby anhedral hornblende. Where plagioclase predominates, the arrangement is just the reverse: the hornblende grains are unevenly distributed in a matrix consisting of a mosaic of more or less round or roughly polygonal

plagioclase anhedra. The hornblende and plagioclase generally form discrete crystals free of inclusions; however, in a few rocks these minerals form larger porphyroblasts with sieve texture and include each other poikiloblastically. Hornblende and plagioclase are generally rather even-grained.

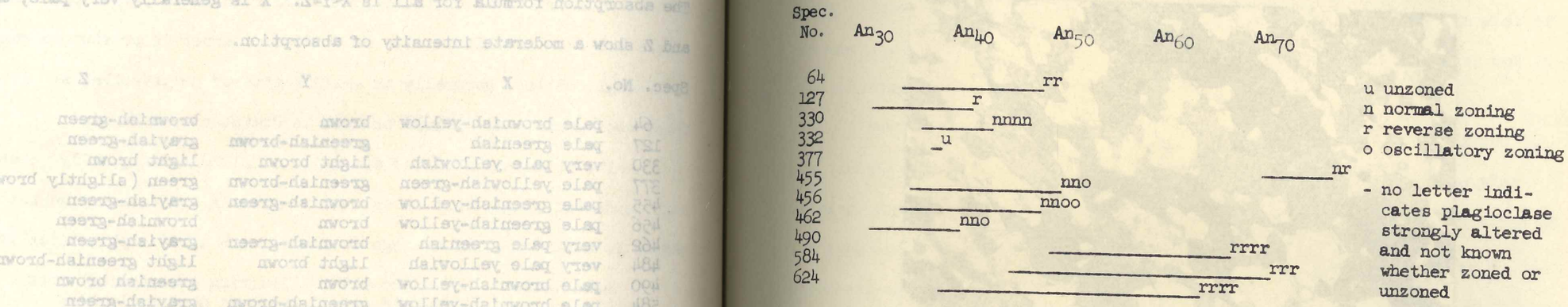
The hornblende varies rather widely in its optical properties, especially in its pleochroism. Some of these properties are summarized here. The absorption formula for all is X<Y=Z. X is generally very pale, and Y and Z show a moderate intensity of absorption.

Spec. No.	X	Y	Z	Z:c
64	pale brownish-yellow	brown	brownish-green	13°
127	pale greenish	greenish-brown	grayish-green	14°
330	very pale yellowish	light brown	light brown	16°
377	pale yellowish-green	greenish-brown	green (slightly brown)	15°
455	pale greenish-yellow	brownish-green	grayish-green	15°
456	pale greenish-yellow	brown	brownish-green	15°
462	very pale greenish	brownish-green	grayish-green	13°
484	very pale yellowish	light brown	light greenish-brown	15°
490	pale brownish-yellow	brown	greenish brown	13°
584	pale brownish-yellow	greenish-brown	grayish-green	15°
624	pale yellowish-brown	light brown	light brown	14°

The average extinction angle Z:c on 010 is about 14° or 15°. The typical pleochroism is X pale brownish-yellow, Y light brown, and Z brownish-green. This characteristic brown hornblende shows a weak zoning in four of the rocks with narrow irregular rims of a greener hornblende with the pleochroism X pale greenish-yellow, Y brownish-green, and Z grayish-green. All extinction angles were measured on crystals giving a centered optic normal figure and are thus the true extinction angles on 010. The maximum extinction angle in the prismatic zone is much larger, often reaching 23° to 24°.

In all but one of the twelve amphibolites studied the plagioclase is zoned. The zoning is anhedral and the transition between adjacent zones is generally gradual rather than sharply marked. Five of the rocks have only reverse zoning; one has only normal zoning; two contain some crystals with

reverse and other crystals with normal zoning, indicating oscillatory zoning with one recurrence; and three have oscillatory zoning with one recurrence (of these, two have a trend sodic core--calcic zone--sodic rim, and one has a trend calcic core--sodic zone--calcic rim). The range in composition of the zoned plagioclase and the kind of zoning of the individual zoned crystals determined in each amphibolite are summarized in the following chart.



The observed extremes in plagioclase composition are An_{30} and An_{74}, and the average composition is about An_{45}. The average range in composition of the zoned plagioclase for the 12 rocks is about 13% An.

Garnet is quite common in the amphibolites and usually forms porphyroblasts with a pronounced sieve texture. Apart from the presence of garnet, there is no obvious mineralogical difference between the garnet-bearing and the garnet-free amphibolites. Quartz is present in some of the amphibolites, though usually in small amount. The quartz occurs both as small grains evenly distributed through the rock and in almost monomineralic bands. One amphibolite with an exceptionally high quartz content (about 45%) and a rather low hornblende content (about 28%) was collected about two miles up the Circle Pk. trail. This rock is of further interest in that it contains a small amount (about 1%) of diopsidic pyroxene and several narrow bands, up to a few mm in

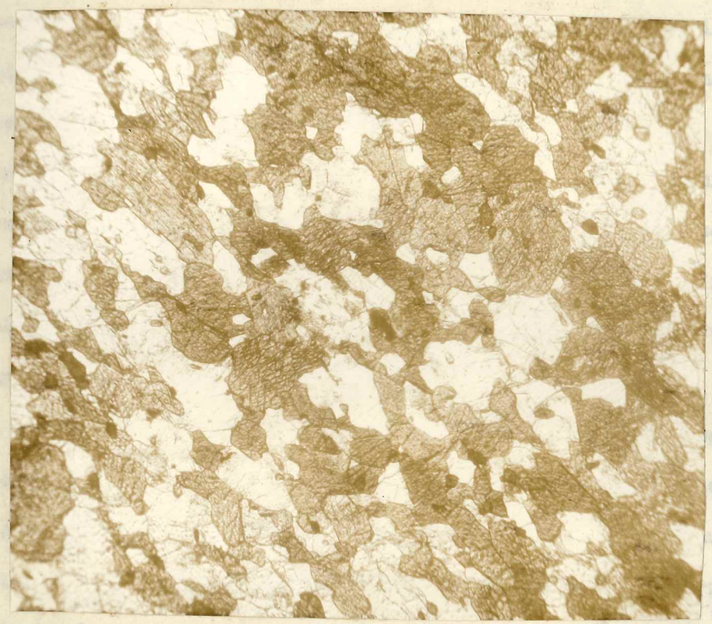


Fig. 6

Plane light. 40X. High grade ortho-amphibolite, greenish-brown hornblende and sodic labradorite. Heterogeneous gneiss unit.

thickness, rich in clinozoisite which appears to be in stable association with intermediate andesine. Similar thin bands rich in clinozoisite were observed in two other amphibolites. In both rocks the clinozoisite is well-formed and is clearly in equilibrium with the plagioclase which is intermediate labradorite in one rock and sodic bytownite in the other. Minor biotite has formed through biotization of hornblende in three of the amphibolites.

Sphene, apatite and ores are present as minor accessories in most of the amphibolites. In two rocks rutile is present rather than sphene, and in one rock the two minerals occur together.

Retrogressive alteration in the amphibolites is largely confined to the incipient breakdown of plagioclase into a more sodic plagioclase plus zoisite (and less often epidote) and sometimes sericite as well. In three of the amphibolites some of the hornblende has been partially altered to a colorless amphibole.

One of the amphibolites deserves special mention in that the amphibole is cummingtonite rather than hornblende. This specimen was collected from abundant float on the logging road on the north side of the Whitechuck River about one mile east of the mouth of Pugh Creek. The rock has a striking appearance in hand specimen, consisting of silvery-brown bladed prisms of cummingtonite up to 2 inches in length which show a rough preferred orientation parallel to the schistosity. The amphibole blades are set in a matrix consisting of medium-grained plagioclase and minor garnet. Small shiny flakes of biotite are conspicuous, especially as inclusions in the cummingtonite. The rock contains approximately 45% cummingtonite, 49% plagioclase, 2% garnet, and 2% biotite, together with minor apatite and ore. The cummingtonite shows good amphibole cleavage and a sharp basal parting. The birefringence is near 0.029, the estimated 2V is 85°, and the optic sign is positive. One optic

axis shows dispersion r<v. This amphibole is weakly pleochroic with X colorless, Y and Z pale pinkish-brown. Some crystals show simple or polysynthetic twinning on 100. The optical properties of the cummingtonite indicate the presence of about 40 molecular % of grunerite (Winchell, 1951, p. 428). The plagioclase is unzoned and has a composition of near An_{36}. Minor reddish-brown biotite has formed at the expense of cummingtonite. Some of the plagioclase shows incipient alteration to a more sodic plagioclase plus zoisite, epidote, and sericite.

In addition to the very thin clinozoisite-rich layers already described, greenish layers rich in calcium silicate minerals are occasionally observed in some of the amphibolites. They range up to several inches in thickness. Thin sections of two such rocks were studied. One specimen collected on the ridge between Red Mtn. and Black Mtn. consists of about equal amounts of diopsidic pyroxene as large anhedral grains, and an unknown mineral forming a matrix of tiny anhedral grains in which the pyroxene is set. Considerable accessory sphene is present. Superficially the unknown mineral somewhat resembles plagioclase. It is biaxial and its birefringence is about 0.011. It has polysynthetic twinning like albite twinning in plagioclase and has a maximum extinction angle of about 36° measured perpendicular to the twin plane. It has two directions of good cleavage at approximately right angles to each other, one of which is parallel to the twinning plane. It does not seem to be plagioclase, however, for its relief is too high and it has a limpid appearance very similar to that of apatite. Another specimen of such a greenish intercalation in amphibolite was collected on the north ridge of Black Mtn. just below the summit. This rock contains approximately 30% clinozoisite, 30% of strongly pleochroic brownish-green hornblende, 15% plagioclase, 10% quartz, 10% garnet, and 5% diopsidic pyroxene, together with

minor sphene. None of the minerals shows good crystal form. These minerals are intergrown in a matted fibrous aggregate and their time relations are uncertain. The textural relations in this rock are further obscured by saussuritization of the plagioclase and by incipient alteration of the hornblende to fibrous actinolite.

On the basis of their field relations and mineral composition, the amphibolites are considered to be metamorphosed volcanic rocks chiefly of basic though possibly also in part of intermediate composition. In particular the relatively calcic composition of the average plagioclase (about An_{45}) seems to point to basic parent rocks. Uncertainty as to the composition of the hornblende precludes a closer evaluation of the composition of the original rocks. None of these amphibolites appear to be derived from dolomitic-argillaceous sedimentary material. This is clear from the mineral composition of the amphibolites, from their general uniformity even in larger outcrops, and from absence of intergradation of these rocks with rocks of obvious sedimentary origin, such as hornblende-biotite schists, biotite schists, lime-silicate rocks and marbles. Very locally a few narrow bands rich in lime-silicate minerals, ranging up to a few inches in thickness, were observed; however, these are not common and their sedimentary origin can perhaps be questioned. The original basic volcanics were probably for the most part flows, but certain very thin amphibolite layers occurring as intercalations in biotite schist are interpreted as metamorphosed tuff or ash layers. One specimen of amphibolite varies from the normal type in that it contains almost 45% quartz, suggesting that it was derived from a basic tuff containing an abundant sedimentary silica component in the form of either chert or quartzose silt. The cummingtonite amphibolite differs from the other amphibolites in its rather low Ca-Al content. This rock, if it is to be

considered as isochemical, has probably been derived from a hypersthene andesite exceptionally rich in hypersthene.

From the composition of the plagioclase it is clear that at least some of the ortho-amphibolites have formed under temperatures of the high grade zone. Two amphibolites were studied in which the average composition of the plagioclase is An_{52}, one in which the plagioclase averages An_{57}, and one in which the plagioclase averages An_{71}. These rocks were collected at widely separated localities, one near the summit of Black Mtn., two on the eastern part of "Lost Creek Ridge" west of Kennedy Hot Springs, and one on the ridge north of the Whitechuck River three miles west of Meadow Mtn. Some of the other amphibolites in which the plagioclase is less calcic than labradorite may have formed at temperatures of the kyanite zone. This, however, cannot be definitely established--except for one amphibolite which contains clinozoisite in equilibrium with intermediate andesine--since sodic plagioclase is stable in the high grade zone in the absence of potential anorthite. The amphibolites give further indications of disequilibria such as we have already found in some of the other isochemical rocks. Some of the high grade amphibolites, for instance occur in the same general area where the kyanite-bearing biotite schists were collected. Further, two of the high grade amphibolites contain main-assemblage clinozoisite; in each of these the clinozoisite is in equilibrium with a different plagioclase. It is interesting to note that the high grade amphibolites generally contain plagioclase with reverse zoning and thus do not preserve a record of falling temperature.

The Hornblendites*

Massive black hornblendites, consisting almost wholly of hornblende, are locally very abundant as small bodies and are not uncommon as large masses in the heterogeneous gneiss unit. The hornblendites are widely developed in a broad zone about a mile and a half wide and over three miles long, extending from the ridge between Red Mtn. and Black Mtn. on the south, to the area of upper Camp Creek on "Lost Creek Ridge" on the north. The largest of the hornblendite masses in this zone lies on the ridge between Red Mtn. and Black Mtn. and occupies an area of at least one-third square mile, and probably more, since its extent to the south is not known. A hornblendite body occurring at Camp Lake on "Lost Creek Ridge" is about 300 feet wide and has been traced almost half a mile. Throughout the "hornblendite belt" hundreds of smaller hornblendite bodies occur as pods and lenses ranging from a few feet to many hundreds of feet in length. Associated with the hornblendites and making up the greater part of the "hornblendite belt" is a group of extremely heterogeneous hornblende-bearing rocks of migmatitic aspect. The typical rocks are of dioritic to quartz dioritic composition, include both massive and schistose varieties, and show a wide compositional range from very basic to very leucocratic types. These rocks are believed to have formed by feldspathization and granitization of the hornblendites. This relation is clear where the hornblendites can be observed to pass gradually into schistose or directionless dioritic or quartz dioritic rocks; however, in many places the rocks have been so strongly transformed that little or none of the original material is preserved, and while the metasomatic origin of the rocks is clear, it may be

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* The term hornblendite is used purely descriptively and not genetically in the present description.

impossible to show that the original rocks were hornblendites rather than amphibolites. In addition to the hornblendites and the metasomatic rocks derived from these, sediment-derived schists and related metasomatic rocks are locally found in the belt of hornblendites. A narrow zone of kyanite-bearing garnet biotite schists and related migmatitic gneisses was encountered on "Lost Creek Ridge" about one-third mile west of Camp Lake, and similar schists and gneisses occur at the 5900 foot pass just northeast of Red Mtn. also in the "hornblendite belt." At its eastern and western borders the northsouth-trending "hornblendite belt" is in contact with and is slightly discordant with biotite schists and related migmatitic gneisses of the heterogeneous gneiss unit. I would interpret the hornblendites and the related migmatitic dioritic and quartz dioritic rocks as isochemically and metasomatically metamorphosed ultrabasic igneous rocks, probably pyroxenites. It is not clear whether there was originally one large intrusion or a number of smaller ones, and the position of the sediment-derived metamorphic rocks which occur locally in the "belt of hornblendites" is also uncertain. The sediment-derived metamorphics could be variously interpreted as septa of country rock between separate ultrabasic intrusions, as roof pendants or large inclusions in a single intrusion, or as slivers tectonically infolded or infaulted after the emplacement of the ultrabasics. Only a single occurrence of hornblendites was encountered outside the "hornblendite belt." This body occurs at Crystal Lake, a small lake at the head of Crystal Creek. Its full extent has not been traced, but it measures more than 200 feet in one of its dimensions. This body, like the other hornblendites, has in part been granitized.

The hornblendites are medium- to coarse-grained black rocks composed almost exclusively of hornblende which commonly reaches 98-99% in amount. Most of the hornblendites are massive, though a few show a rude schistosity.

Shiny black plates of biotite are conspicuous in some of the hornblendites, as are scattered white grains of plagioclase. The hornblende generally occurs as stout anhedral columns making up an irregular mosaic. In a few of the hornblendites the hornblende grains are extremely irregular in form and are intimately intergrown. In basal sections the hornblende occasionally shows euhedral outlines. In several of the hornblendites the hornblende shows marked preferred orientation parallel to the schistosity, and in one rock the hornblende has a pronounced linear parallelism.

Most of the hornblendites contain a brown hornblende. The character of the pleochroism does not vary much in the different hornblendites, but the intensity of the absorption does differ, ranging from moderate in most varieties to rather weak in a few. The typical pleochroism is X colorless to very pale brownish, Y light brown, Z light brown, with X<Y=Z. The extinction angle Z:c on 010 is 13-14°, the 2V is large and the optic sign is negative. Both simple and polysynthetic twinning are common. The hornblende is zoned in all the biotite-bearing hornblendites studied, but in none of the biotite-free hornblendites. The zoning is generally confined to the very narrow outermost margin of the hornblende crystals. The hornblende of this outer zone is usually greenish and has a weaker absorption than that of the brown hornblende. The pleochroism is somewhat variable but averages X colorless, Y pale brown to pale greenish-brown, Z pale grayish green. The zoning is interpreted as secondary zoning related to the metasomatic crystallization of late biotite (and in some instances biotite and plagioclase) in the hornblendite.

Biotite was observed in some of the hornblendites up to a maximum amount of about 12%. The biotite is generally nonoriented but shows rough alignment parallel to the foliation in some of the hornblendites. The biotite generally has a pleochroism X very faintly yellowish or brownish, Y and

Z orangish-brown to reddish-orange brown. Almost without exception the biotite is confined to the intergranular between the hornblende grains. Late crystallization of the biotite is suggested by its position in the intergranular and by several secondary features which are found in the biotite-bearing hornblendites but not in the biotite-free hornblendites. These features include secondary zoning of the hornblende, and the universal presence in the intergranular of abundant late ores and sometimes also of small clusters of secondary sphene. Biotization of the hornblende is believed to have been caused by potash introduction.

Many of the hornblendites contain minor plagioclase. The plagioclase-bearing hornblendites without exception also contain biotite although the converse is not true. The plagioclase occurs as scattered isolated anhedral grains or in clusters of several grains, and appears to have replaced the hornblende. Determination of the plagioclase is difficult in most of the hornblendites as a result of the incipient alteration of this mineral to a fine-grained aggregate of sericite and zoisite. As far as can be determined, the plagioclase is usually andesine. In one hornblendite medium andesine with normal zoning was determined. Like biotite, plagioclase is generally late and metasomatic in the hornblendites. Its late development is especially clear from the field relations of the hornblendites. All gradations may be traced from plagioclase-free hornblendites, through hornblendites containing only minor scattered grains of plagioclase, to plagioclase-rich hornblendites and diorites and finally to very leucocratic, hornblende-poor diorites. Late crystallization of the plagioclase in the plagioclase-bearing hornblendites is further confirmed by the frequent occurrence of the same secondary features which accompany the formation of late biotite. The metasomatic formation of plagioclase in the hornblendites implies introduction of sodium and removal of

magnesium and probably some removal of iron as well. Some of the iron released in the conversion of hornblende to plagioclase remains fixed in the rock as iron ores.

Apatite and ore minerals are almost constant accessories in the hornblendites. Ores, as already mentioned, are most abundant in the hornblendites showing biotization and feldspathization. Accessory rutile is also very common. Sphene is present in some of the hornblendites and generally appears to be secondary. Minor amounts of a pale brownish or greenish chlorite with negative elongation and normal interference colors are sometimes present replacing biotite and/or hornblende.

Some of the hornblendites contain a weakly pleochroic amphibole instead of the usual brown hornblende. These rocks are green to dark green in color and are somewhat finer-grained than the typical hornblendites. The pleochroism and the extinction angles Z:c on 010 of the amphibole in two of these rocks are given.

Spec. No.	Z:c			
604	15°	colorless	faintly brownish	faintly grayish
630	16°	colorless	pale brownish-gray	Pale greenish-gray

A third specimen, a greenish rock, contains a completely colorless amphibole, with Z:c 17°. The optic sign of these amphiboles is negative and the estimated 2V is 80-85°. The two rocks containing weakly pleochroic amphibole also both contain about 5% biotite. Whether these rocks are metasomatically altered hornblendites of the usual type containing brown hornblende or are an indpendent rock type is not known.

The textures of the hornblendites and in particular the crystallization foliation which is sometimes observed show these rocks to be metamorphic. The hornblendites have also participated in the same isochemical and

metasomatic metamorphism through which the adjacent biotite schists and related rocks have formed. Unfortunately nothing conclusive can be said as to the kind of original rock. The somewhat discordant structural position of the "hornblendite belt" in the heterogeneous gneiss unit suggests that the rocks of the former are part of a transgressive intrusive body. And since the hornblendites are very close in chemical composition to an augitic pyroxenite, it is not unlikely that they have been derived from the latter. Since, however, no relict igneous minerals have been discovered in the hornblendites, this conclusion can be tentative only. An alternative interpretation would be that these rocks are metasomatically altered peridotites or serpentinites. This possibility seems unlikely, however, considering the profound chemical transformation which would be required. Instead of the very homogeneous rocks which we find there should somewhere occur incompletely converted relics of the original materials. Still another interpretation of the hornblendites would be that they comprise a great basic segregation or "basic front" in which iron and magnesium expelled during granitization at depth have been precipitated. However, the size, localization, and discordant character of the "hornblendite belt" do not fit well with this view and the hornblendization which would be expected to have affected the biotite schists and related rocks within and at the margins of the "hornblendite belt" is nowhere observed.

Two interesting amphibole rocks were collected west of the "hornblendite belt" on "Lost Creek Ridge." One of these rocks was collected on the "Lost Creek Ridge" trail about a mile and a half west of Camp Lake and about 100 feet west of the contact of the "hornblendite belt." It is a fine-grained, pale green, schistose rock containing greenish columns of amphibole and silvery flakes of a micaceous mineral and occurs in a narrow concordant

8 by 2-foot lens in biotite schists. The amphibole is tremolite (65%) and occurs as narrow prisms showing a sharp parallel alignment. A micaceous mineral (about 35%) occurs as highly birefringent plates between the tremolite prisms. The optic sign of this mineral is negative, and the estimated 2V is 5°. Because of its extremely high birefringence and its association with tremolite, this mineral is probably talc rather than muscovite. If the metamorphism of this rock is considered to be isochemical, the parent rocks must have been highly magnesian, corresponding perhaps to a magnesium-rich and very Al-poor pyroxenite. Its origin from a peridotite by silica-addition is perhaps more likely. The other amphibole rock is an almost pure tremolitite. It was collected from the hornblende gneiss unit on the northeast side of the 6400 foot peak east of Round Lake directly below the summit. It occurs in a concordant 4 by 10-foot lens which is in contact with amphibolite on one side and hornblende gneiss on the other. The tremolitite is a pale green, medium-grained, slightly schistose rock consisting of stout anhedral columns of tremolite and minor scattered grains of ore minerals. This rock is probably a metamorphosed ultrabasic igneous rock.

Metasomatic and Granitized Rocks

Metasomatic gneisses of quartz dioritic to trondhjemitic and locally of dioritic composition together with related directionless pegmatitic and aplitic rocks are developed much more widely than isochemical metamorphics in the heterogeneous gneiss unit and constitute perhaps 70% of this unit. Careful study has revealed that each of the several varieties of gneisses is generally associated with a particular type of isochemical rock. This constant association strongly suggests that at least most of the granitic rocks have formed metasomatically from the isochemical rocks. This conclusion is

further confirmed by the complete mineralogical and textural gradation between specific isochemical rocks and the associated gneisses and directionless rocks and by incontestable field evidence for replacement. According to their mineral compositions the metasomatic rocks fall into several broad groups each of which is associated with and is genetically related to a particular isochemical rock. The major groups are: (1) biotite gneisses of trondhjemitic composition derived from the biotite schists and paragneisses; (2) quartz dioritic and trondhjemitic hornblende-biotite gneisses derived from hornblende-biotite paragneisses; (3) hornblende quartz dioritic gneisses derived from amphibolites; and (4) hornblende diorites derived from hornblendites. Each of these groups is here described separately and compared mineralogically and texturally with its parent rocks.

Feldspathized and Granitized Biotite Schists and Paragneisses

Trondhjemitic gneisses. Trondhjemitic biotite gneisses are the most abundant single rock type in the heterogeneous gneiss unit. They comprise a heterogeneous group of medium to coarse-grained, roughly schistose leucocratic rocks. These rocks commonly show a banded structure, but they also occur in relatively homogeneous bodies. The contrasted layers in the banded gneisses are marked chiefly by differences in biotite content and in grain size. The leucocratic layers in the banded gneisses differ from the darker layers only in the amount, not the kind, of minerals present. In general the more leucocratic layers are somewhat coarser-grained than the biotite-rich layers and occasionally approach pegmatitic size. Some of the darker layers in the banded gneisses consist of isochemical biotite schists, while other of the darker layers, less rich in biotite, appear to be metasomatic. The thickness of the bands varies greatly, ranging from only a few mm to many feet. Isochemical biotite schists and paragneisses are often migmatitically associated

with the trondhjemitic gneisses, and their field relations are often such as to show that the trondhjemites have formed metasomatically from the biotite schists. In many outcrops all transitions can be traced both along and across the strike from isochemical biotite schists, to feldspathized biotite schists containing isolated plagioclase porphyroblasts aligned in the foliation, to banded gneisses marked by alternating thin layers of biotite schist and leucocratic layers consisting of discontinuous stringers of individual plagioclase porphyroblasts or continuous trondhjemitic bands, and finally to banded or relatively uniform trondhjemitic gneisses containing no trace of the parent biotite schists. The transition from isochemical schist to metasomatic gneiss is commonly very abrupt. An intrusive mode of emplacement of the leucocratic bands can be excluded, since there is no evidence of wedging or splitting open of the adjacent darker bands. Some of the thin quartz-rich and quartzo-feldspathic bands in the biotite schists and paragneisses have probably formed by metamorphic differentiation, that is by a simple process of isochemical redistribution of minerals already present in the rocks. The bands formed by metamorphic differentiation, however, are uniformly thin and the proportion of light to dark colored bands tends to be constant. The formation of the thicker leucocratic layers cannot be attributed to this process, for here there is no fixed ratio of light to dark colored bands, the thickness of the light colored bands often greatly exceeds that of the darker bands, and biotite-rich bands are not present in amounts truly complementary to the leucocratic bands. Here a definite change in over-all composition must be assumed. These same considerations have been discussed by Misch (1949, pp. 288-289). The banded trondhjemitic gneisses also differ texturally from the biotite schists showing differentiation banding. This would seem to indicate that the two rock types have formed under different chemical conditions (that

metasomatizing solutions were possibly present during the crystallization of the trondhjemitic gneisses).

Larger bodies of relatively homogeneous trondhjemitic biotite gneisses are not uncommon in the heterogeneous gneiss unit. These homogeneous gneisses locally occur in bodies measuring up to 200 feet in thickness across the foliation. Most of these rocks are very leucocratic. Texturally they range from fine-grained aplitic types to coarse-grained almost pegmatitic types. Even in these relatively uniform gneisses careful examination usually reveals some heterogeneity marked by slight variations in grain size or biotite content or by the presence of shadowy concordant relics of less completely transformed materials. Those banded gneisses and homogeneous gneisses which are not migmatitically associated with isochemical biotite schists, are probably also of metasomatic origin and seem to represent an advanced stage of transformation. This is demonstrated by the textural and mineralogical identity of these rocks with the proven metasomatic bands in the banded gneisses in which remnants of isochemical rocks are still present and by the local gradation of biotite schists into these more advanced metasomatic rocks. Relics of isochemical biotite schists, insofar as these are still preserved in the more advanced metasomatic gneisses, are oriented with their foliation parallel to the foliation of the enclosing gneisses. The chief mineralogical changes brought about by metasomatism are decrease in biotite and increase in plagioclase. The metasomatism has been synkinematic in that these rocks are typically foliated and in that feldspathization and granitization have been localized along certain paths of easiest access ("Wegsamkeit") represented by planes of differential movement.

The mineral composition of the trondhjemitic gneisses is remarkably uniform, considering the wide textural and structural variation of these

Fig. 7

Folded migmatitic garnet-biotite paragneiss with quartz-rich differentiation bands and metasomatic biotite gneiss. Lost Creek Ridge.

Fig. 8

Replacement patch of biotite trondhjemite in folded biotite schist. Note the sharp contact (probable fracture control) in the center of the photo. Black Mtn.





Fig. 9

Quartz-dioritic hornblende gneiss formed by metasomatic replacement of ortho-amphibolite. Undisturbed inclusions of amphibolite in hornblende gneiss. Note particularly the gradational contact on the right and the delicate, undisturbed septa. Black Mtn.

Fig. 10

Circle Peak marble with discontinuous bands of diopside-bearing quartz diorite some of which are folded and show boudinage. One mile west of Meadow Mtn.



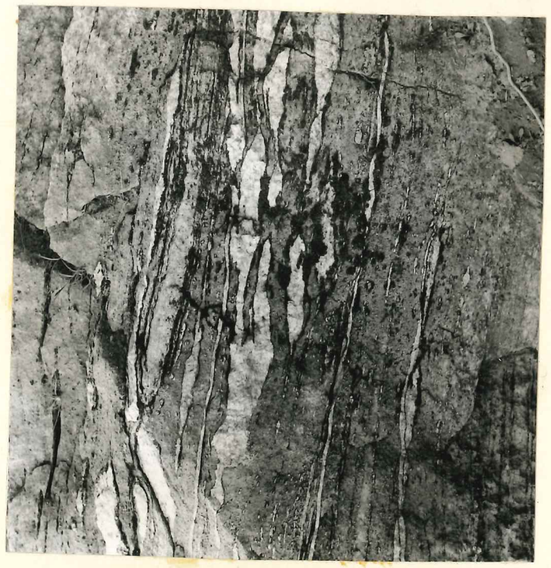




Fig. 11

Syncline and anticline in metasomatic biotite gneiss. Axial planes overturned slightly to east. Height of folds 8 feet. Folds cut by gently dipping pegmatite dike. Suiattle River road between Circle Creek and Lime Creek.

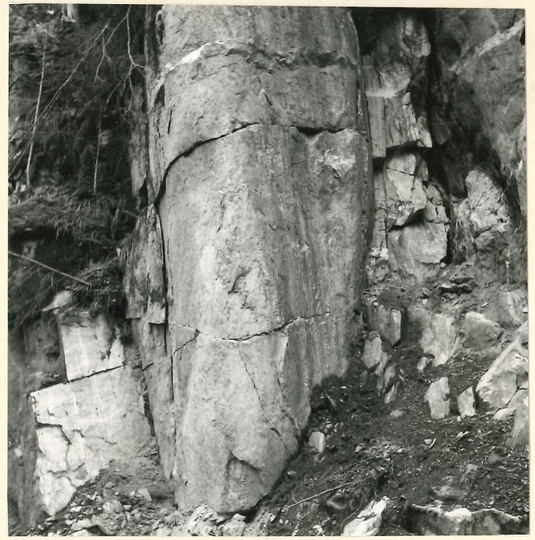


Fig. 12

Vertically plunging fold in metasomatic biotite gneiss. Height of picture 30 feet. A small pegmatite dike fills the uppermost of the gently dipping cross joints.

Geology 323 Optical Mineralogy
10 minute quiz October 12, 1956 Name_____

1. Define index of refraction by means of equation. Indicate what the terms
mean.

2. Outline the steps in the derivation of Snell's Law and give the general
and
3. statement of Snell's Law.

4. Sketch the relations which illustrate the conditions for the critical angl
and
5. and define the critical angle (Snell's Law).

Fig. 13

Strongly folded migmatitic banded garnet-biotite gneiss. Northeast ridge of Red Mtn.

Fig. 14

Dike of mobilized migmatitic material cutting biotite paragneiss with quartz-rich differentiation bands. Note flow structures parallel to the dike walls in the upper part of the dike.





rocks. The essential constituents are plagioclase, quartz, and biotite; garnet is also a common constituent. Below is the average estimated mode of 21 of the trondhjemitic gneisses.

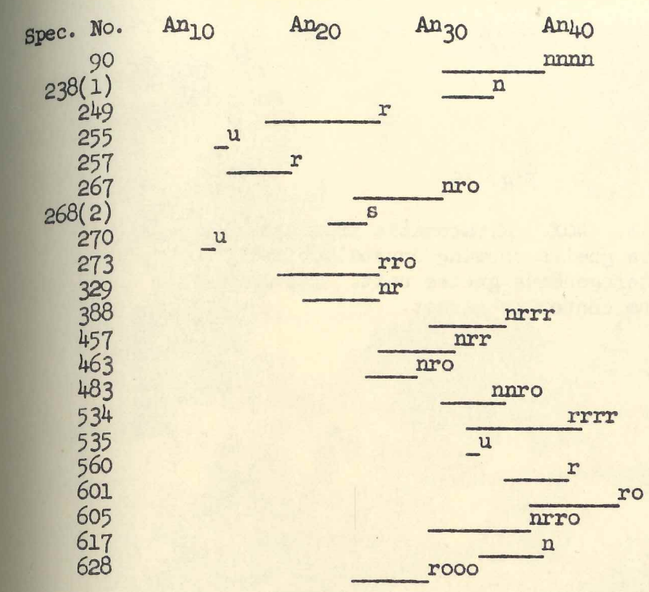
Plagioclase	51%	(41-62%)
Quartz	39%	(26-50%)
Biotite	6%	(1-14%)
Garnet	1%	(0- 5%)
Muscovite	1%	(0- 3%)
Chlorite	1%	(0- 6%)

The trondhjemitic gneisses have a characteristic texture which differs markedly from the texture of the isochemical biotite schists and paragneisses. Quartz and plagioclase in the trondhjemitic gneisses generally show a considerable range in grain size in the same rock; this variation, however, is usually gradational, and large porphyroblasts of either mineral are rare. In the biotite schists, quartz and plagioclase tend to be equigranular. Quartz and plagioclase in the trondhjemitic gneisses are generally much more irregular in outline than in the biotite schists. In contrast to the typically inclusion-free quartz and plagioclase of the biotite schists, both quartz and plagioclase in the trondhjemitic gneisses commonly contain abundant small included grains of quartz, plagioclase, biotite, garnet, etc. This mutually inclusive relationship of quartz and plagioclase suggests contemporaneous growth of these minerals and reflects their progressively coarsening grain size in time.

The biotite of the trondhjemitic gneisses shows a variable pleochroism. In some of the gneisses the biotite is almost identical to that of the biotite schists with X pale brownish-yellow, Y and Z orange-brown to reddish-brown, and a moderately intense absorption. The most common biotite, however, is more strongly pleochroic with X yellow, Y and Z dark reddish-brown to chocolate brown. In one gneiss a strongly pleochroic biotite with X yellow,

Y and Z dark greenish-brown has formed by biotization of garnet. The biotite is generally more fine-grained than the quartz and plagioclase and usually occupies an intergranular position, though it is often in part included by quartz and plagioclase. In some of the trondhjemitic gneisses the biotite is sharply oriented parallel to the schistosity, but in most it is poorly oriented suggesting late static recrystallization of the gneiss.

Zoned plagioclase was found in all but 3 of the 21 thin sections of trondhjemitic gneiss studied. The zoning is anhedral and the transition between zones is transitional not sharp. In three of the gneisses the plagioclase shows only normal zoning. Four other gneisses show plagioclase with only reverse zoning and one shows simple zoning with an undetermined trend. Three of the gneisses contain some crystals with normal zoning and others with reverse zoning, indirectly indicating oscillatory zoning with one recurrence. In six gneisses oscillatory zoning with one recurrence was directly determined. In four of these six rocks the trend in zoning is calcic core--sodic zone--calcic rim, in one the trend is sodic core--calcic zone--sodic rim, and in one the trend could not be determined. One gneiss contains oscillatory zoned plagioclase with two recurrences and a trend sodic core--calcic zone--sodic zone--calcic rim. The range in composition of the plagioclase for each of 21 trondhjemitic gneisses and the kind of zoning determined for individual crystals in each rock is given in the chart on page 115. The average composition of the plagioclase in the trondhjemitic gneisses is about An_{27} and the extremes in composition are An_{11} and An_{43}. The range in composition of the zoned plagioclase averages about 5% An reaching 8% An in a few rocks. Both the average composition of the plagioclase and the zonal range in composition of the plagioclase in these rocks are almost identical to those of the isochemical biotite schists and paragneisses. Further, the different types of



u unzoned
n normal
r reverse zoning
o oscillatory zoning
s simple zoning (i.e., normal or reverse) trend undetermined
- no letter indicates plagioclase strongly altered and not known whether zoned or unzoned

zoning are represented in almost exactly the same proportion in the biotite schists and in the trondhjemitic gneisses.

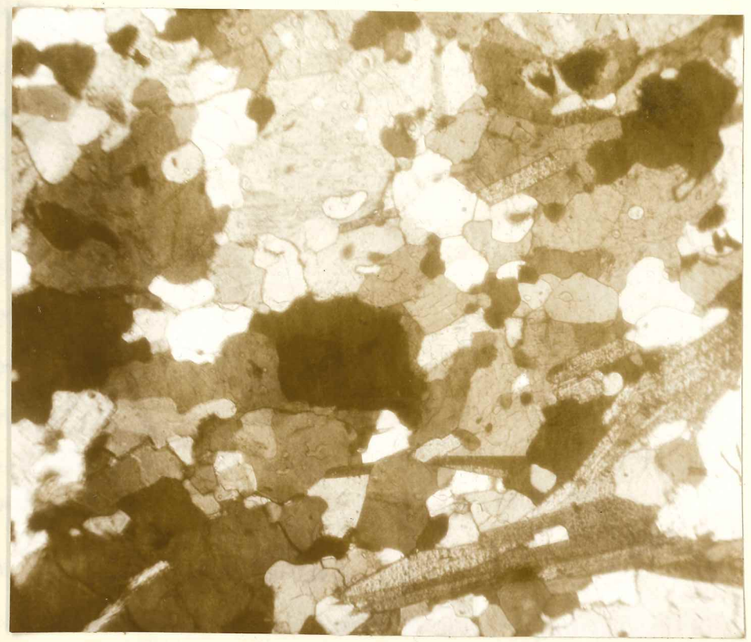
Garnet is common in the trondhjemitic gneisses and is present in almost half the thin sections studied. The garnet usually forms small anhedral porphyroblasts which often show sieve texture. Less often the garnet occurs as well-formed discrete crystals. Minor muscovite is present in about half of the thin sections examined. In all these rocks the muscovite is late, having formed after biotite, often along with epidote and sometimes with sphene or iron ores. Minor epidote is present in many of the trondhjemites. Some of this epidote has formed from biotite and some from the saussuritization of plagioclase. The plagioclase is usually only in part saussuritized, the alteration being confined to the area of the intergranular boundary in some rocks and spreading irregularly through the plagioclase in others. Around the epidote the plagioclase shows a secondary zoning marked by an albitic plagioclase. In six of the trondhjemitic gneisses well-formed epidote

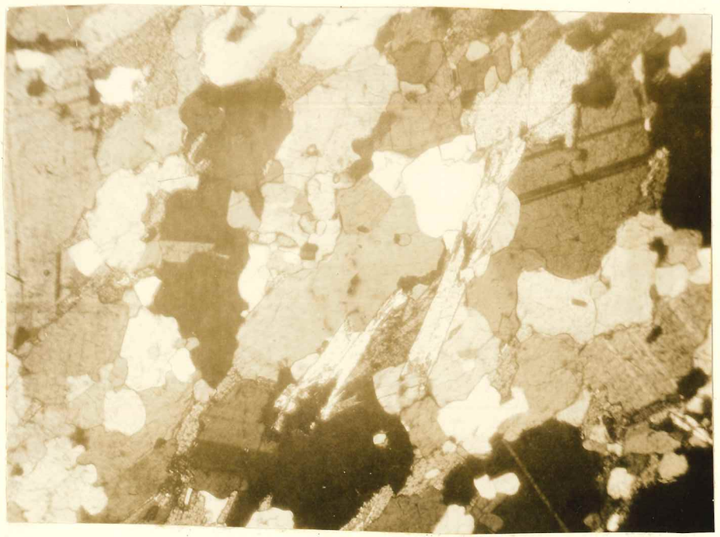
Fig. 15

Crossed nicols. 40X. Metasomatic trondhjemitic garnet-biotite gneiss showing crystalloblastic texture. Heterogeneous gneiss unit. The dark grain near the center is garnet.

Fig. 16

Crossed nicols. 40X. Trondhjemitic two-mica gneiss of metasomatic origin. Heterogeneous gneiss unit.





is associated with fresh, clear plagioclase showing no trace of secondary zoning. Here the epidote and plagioclase appear to be in equilibrium with plagioclase of the composition An_{12}, An_{15}, An_{25}, An_{25}, An_{32}, and An_{34}. Three specimens of trondhjemitic gneiss contain relict kyanite and one specimen contains relict staurolite. These Al-excess minerals occur as tiny inclusions surrounded by large protecting grains of plagioclase or quartz. Since kyanite and staurolite are typical minerals of the biotite schists and paragneisses in the heterogeneous gneiss unit, their presence supports the interpretation of the trondhjemitic gneisses as granitized biotite schists. The common occurrence of garnet in the trondhjemitic gneisses further supports this origin. One of the trondhjemitic gneisses is unusual in that it contains almost 5% kyanite. The kyanite in this rock has been marginally altered to muscovite.

Some of the trondhjemitic gneisses have been affected by incipient retrogressive alteration. This alteration includes saussuritization or sericitization of the plagioclase, chloritization and sericitization of garnet, and chloritization of biotite. The chlorite is generally a pale green, length-fast variety with normal interference colors, but a dark green, length-slow chlorite with abnormal interference colors was observed in a few rocks.

Apatite, zircon, and ore minerals are almost ubiquitous accessories in the trondhjemitic gneisses, just as they are in the biotite schists and paragneisses. Rutile is also present in some of the trondhjemitic gneisses, but is not as common as it is in the biotite schists. Unlike the biotite schists, many of the trondhjemitic gneisses contain sphene. Most of the sphene, however, is secondary, having formed from biotite and apparently also from rutile.

The occurrence of kyanite in three of the trondhjemitic gneisses and staurolite in another indicates that these rocks have formed at temperatures of the kyanite zone. Further indication of the metamorphic grade is given by those six gneisses in which well-formed epidote is associated with contemporaneous plagioclase. The average composition of the plagioclase in these six rocks is An_{12}, An_{15}, An_{25}, An_{25}, An_{32}, and An_{34}. The occurrence of calcic oligoclase or sodic andesine and associated contemporaneous epidote in four of the trondhjemitic gneisses indicates crystallization in the kyanite zone. The two gneisses containing sodic oligoclase appear to have crystallized at temperatures corresponding to the cooler part of the medium grade zone, a much lower grade than the kyanite zone in which most of the biotite schists and trondhjemitic gneisses have formed.

The mineral assemblage of the trondhjemitic gneisses is the same as that of the biotite schists from which they have been derived. The modes of these rocks are different, however, indicating a considerable change in chemical composition. The main changes in the mineral composition from the parent biotite schists to the trondhjemitic gneisses are: increase in plagioclase, from 32% to 51%; decrease in biotite (plus chlorite and muscovite, both of which have formed from biotite) from 24% to 8%; and decrease in garnet from 5% to 1%. The amount of quartz is almost the same in both rocks averaging about 38%. Garnet tends to be eliminated in that it is present in most of the biotite schists but is much less common in the trondhjemitic gneisses. In most of the trondhjemitic gneisses Al-excess minerals have been eliminated except for a few relict grains. These contrasts in mineral composition permit some generalizations as to the relative chemical changes effected by the granitization. The silica content has apparently not changed much. Since the average composition of the plagioclase (around An_{28}) is the same in both the

isochemical and metasomatic rocks, the increase in plagioclase means a relative increase in and a probable introduction of sodium and calcium. If sodium and calcium actually have been introduced, the aluminum and some of the silica for the new plagioclase have presumably been supplied by the eliminated biotite, garnet, and Al-silicates. Decrease in the amount of biotite and garnet indicates a relative decrease in iron, magnesium, and potassium.

Metasomatic Gneisses Derived from Hornblende-Biotite Paragneisses

This group includes the granitized equivalents of the hornblende-bearing biotite paragneisses, hornblende-biotite paragneisses, and biotite-bearing hornblende paragneisses, all of which have already been described. Some of the present gneisses have been assigned to this group on the basis of their intimate migmatitic association and replacement relations with the isochemical hornblende-biotite paragneisses. Other gneisses of the present group, although not directly associated with the hornblende-biotite paragneisses, nevertheless show certain definite mineralogical relationships with both these and with metasomatic gneisses whose derivation from the hornblende-biotite paragneisses can be demonstrated. Possibly some of the metasomatic hornblende-biotite gneisses included here are actually products of an advanced stage of metasomatism of ortho-amphibolites, for there does appear to be a tendency toward mineralogical and textural convergence in the granitization of the hornblende-biotite paragneisses and the ortho-amphibolites.

The present group of metasomatic hornblende-biotite gneisses comprise a very heterogeneous assemblage of migmatitic rocks generally of trondhjemitic composition. Various specimens show all the transitions from the original fine- to medium-grained isochemical paragneisses relatively rich in mafics to coarse-grained leucocratic gneisses. The field relations of these rocks do not differ from those of the trondhjemitic gneisses derived from the biotite

schists and paragneisses, and inasmuch as the field evidence for granitization is also the same, it is not repeated here. The metasomatic hornblende-biotite trondhjemitic gneisses were observed in a number of widely scattered outcrops within the area of the heterogeneous gneiss unit. The area of upper Cougar Creek, due north of Sloan Pk., is especially mentioned, as these rocks seem to be particularly prominent there. The average estimated mode of 9 of these gneisses is:

Plagioclase	43%	(26-52%)
Quartz	41%	(29-55%)
Hornblende	6%	(1-13%)
Biotite	7%	(1-11%)
Garnet	1%	(0- 7%)
Chlorite	1%	(0- 6%)

These rocks are texturally almost identical to the biotite trondhjemitic gneisses metasomatically derived from biotite schists and paragneisses. Very uneven-grained quartz and plagioclase occurring as highly irregular interlocking grains are characteristic. The larger quartz and plagioclase grains may include quartz and plagioclase and to a lesser extent mafics. This texture is strongly contrasted with the generally inclusion-free, equidimensional quartz and plagioclase of the isochemical hornblende-biotite paragneisses. Anhedral grains of hornblende and biotite are scattered somewhat unevenly through the rock, or less often they are concentrated in certain layers. In general hornblende and biotite are confined to the quartz-plagioclase intergranular. These minerals usually show a rough parallel orientation imparting a pronounced planar foliation to the rocks; in other gneisses, however, they are without good parallel alignment and the foliation is marked by alternating darker and lighter bands. Three of the hornblende-biotite gneisses contain small well-formed porphyroblasts of garnet.

The plagioclase of the metasomatic hornblende-biotite gneisses ranges from An_{16} to An_{41} in composition, averaging about An_{31}. Six of the nine gneisses studied contain zoned plagioclase, in two rocks the plagioclase is unzoned, and in a third the plagioclase is too strongly altered to permit determination. Oscillatory zoning is the predominant type. The zoning is anhedral and the transitions between adjacent zones are generally not sharply marked. Two rocks show oscillatory zoning (sodic core--calcic zone--sodic rim) with one recurrence, three show oscillatory zoning with one recurrence and an undetermined trend, and one shows oscillatory zoning with two recurrences (calcic core--sodic zone--calcic zone--sodic rim). The average zonal range in composition of the plagioclase for the nine rocks is 4% An. The composition and zoning of the plagioclase in these nine gneisses is summarized as follows:

Spec. No.	An_{20}	An_{30}	An_{40}
244		nno	
254	nro		
264	o		
327		ro	
375		rro	
530		u	
532		u	
536			
623			ro

- no letter indicates plagioclase strongly altered and not known whether zoned or unzoned
- n normal
- r reverse zoning
- o oscillatory zoning
- u unzoned

The typical biotite of these gneisses is moderately strongly pleochroic with X pale brownish-yellow, and Y and Z orange-brown and less often reddish-brown. In one rock a strongly pleochroic biotite with X yellow and Y and Z dark brown was determined. Biotization of hornblende was observed in most of these gneisses. This process is especially clear in several of the rocks in which epidote occurs concentrated in little clusters with biotite and hornblende, or with biotite alone. In other gneisses biotite appears to have formed from hornblende without the development of epidote. Most of the early,

well-formed epidote in these gneisses appears to have been released from hornblende through biotization. The hornblendes of the metasomatic hornblende-biotite gneisses are all characterized by rather small extinction angles (Z:c on 010) but show considerable variation in pleochroism in the different gneisses. The absorption formula of all the hornblendes is X<Y=Z. The pleochroism and extinction angles of the various hornblendes are summarized here.

Spec. No.	X	Y	Z	Z:c
244	greenish-yellow	brownish-green	grayish-green	-
254	brownish-yellow	dark olive green	dark bluish-green	15°
264	greenish-yellow	dark green	deep bluish-green	15°
327	pale yellowish	brownish-green	grayish-green	13°
375	pale yellowish-green	light brownish-green	light grayish-green	14°
530	pale greenish	light brownish-green	light grayish-green	14°
532	pale yellow	brownish-green	grayish-green	13°
536	colorless	pale green	pale green	13°
623	pale yellowish	brownish-green	grayish-green	13°

Accessory apatite and iron ores are invariably present in these gneisses. In addition to apatite, zircon was found in three rocks and sphene in three others. Orthite was found in one rock and shows pleochroic haloes where in contact with biotite.

One of the hornblende-biotite gneisses collected on Cougar Creek is of interest in that it contains porphyroblastic andesine. This rock is also unusual in that much of the biotite has recrystallized to muscovite and in that its hornblende has been bleached with the release of iron ores. A later (?) retrogressive recrystallization has converted most of the plagioclase to zoisite and sericite, and the remaining biotite to chlorite. Several other gneisses show incipient retrogressive recrystallization of biotite to chlorite, and plagioclase to zoisite or zoisite plus sericite.

A very general comparison of the mineral compositions of the metasomatic hornblende-biotite gneisses and their isochemical parent rocks is given here in order to make at least a qualitative evaluation of the metasomatic changes brought about by the granitization. Both the parent paragneisses and their derivative metasomatic gneisses show the same mineral assemblage, plagioclase, quartz, biotite, hornblende, and occasionally garnet. The ratio of combined quartz and plagioclase to mafics is much higher in the metasomatic gneisses than in the parent rocks, the amount of quartz is much greater, the amount of plagioclase is almost the same, and the ratio of biotite to hornblende is higher. The chief metasomatic changes effected by the granitization are a relative increase in silica, and a relative decrease in iron and magnesium. The average composition of the plagioclase of the parent rocks (An_{28}) and of the metasomatic gneisses (An_{31}) differ little and the average zonal range in composition of the plagioclase in the isochemical rocks (6% An) and the metasomatic gneisses (4% An) are closely comparable. The typical zoning in both is oscillatory zoning with one recurrence. The optical properties and presumably also the chemical composition of the biotite and hornblende of the original rocks and the metasomatic gneisses are very similar and the accessory minerals in both are the same.

Metasomatically Altered and Granitized Ortho-Amphibolites

These rocks comprise a wide variety of types, ranging from dark amphibolites which show only slight metasomatic recrystallization, marked by the appearance of metasomatic biotite, plagioclase, and quartz, to relatively leucocratic hornblende-biotite-quartz dioritic gneisses. These rocks tend to be very heterogeneous even in small outcrops and commonly show very pronounced changes in mineral composition and texture within short distances. The metasomatic alteration of the less strongly transformed amphibolites can scarcely

be doubted, for every gradation can be traced from isochemical ortho-amphibolites to amphibolites containing newly formed metasomatic minerals. The more strongly transformed and granitized amphibolites occur most commonly as banded gneisses consisting of alternating darker, hornblende-rich, and lighter, hornblende-poor bands. The bands vary greatly in thickness, ranging from only a few mm to many feet. The lighter-colored bands tend to be coarser-grained than the darker bands, reflecting a general progressive increase in grain size with metasomatic recrystallization. Some of the darker bands are still isochemical amphibolites, while others are metasomatic bands which have simply been less strongly transformed than the adjacent more leucocratic bands. None of the darker bands are more basic than the original amphibolites. The metasomatic origin of the lighter bands associated with isochemical ortho-amphibolites is clear, for these rocks often show a complete mineralogical and textural intergradation both along and across the strike. The structural relations of the darker and lighter bands preclude the possibility that the lighter bands are intrusive. While some of the isochemical amphibolites show metamorphic differentiation banding, the banded gneisses here considered are clearly not of this origin, for these two kinds of banding differ markedly in character. The metamorphic differentiation banding of the amphibolites is characterized by: (1) uniform thinness of the bands (the light-colored bands rarely exceed a few mm in thickness); (2) a tendency toward a constant ratio of dark to light-colored bands; (3) the same minerals in different proportions in adjacent bands; and (4) uniform texture and grain size in both dark and light-colored bands. The banding of the banded gneisses, on the other band, is characterized by: (1) a wide range in the thickness of the bands which may measure several feet across; (2) lack of any tendency toward a constant ratio of light to dark-colored bands; (3) differing mineralogy in the adjacent dark

and light-colored bands (quartz and often biotite are present in the light and absent in the dark-colored bands); and (4) textural contrasts between adjacent dark and light-colored bands (the lighter bands are commonly coarser-grained than the dark bands, and the light and dark bands commonly show certain microscopic textural differences). The first two of these four differences have been discussed by Misch (1949, pp. 288-289). At the more advanced stages of transformation many of the original amphibolites have been metasomatically recrystallized to relatively leucocratic gneisses. Even here, though, some heterogeneity marked by darker and lighter bands is generally present. These more leucocratic hornblende gneisses are also believed to be of metasomatic origin, even where they are not directly associated with isochemical amphibolites, since they are mineralogically and texturally identical to proven metasomatic gneisses associated with isochemical amphibolites elsewhere in the area. In the following petrographic description the metasomatically transformed amphibolites are treated in two groups: (1) the less strongly transformed amphibolites which do not differ greatly from the isochemical amphibolites in texture and mineral composition; and (2) more strongly transformed amphibolites, now chiefly hornblende-rich quartz dioritic gneisses. Although this separation is somewhat arbitrary in that there are all gradations between these two groups of rocks, this treatment does serve to give a clear idea of the sequence of metasomatic and textural changes involved in the granitization.

The less strongly altered amphibolites. These rocks are mineralogically and texturally intermediate between the isochemical amphibolites and the metasomatic hornblende quartz dioritic gneisses. Some of these rocks are relatively fine-grained like their parent amphibolites, while others are more coarsely crystallized. Like the original amphibolites they are dark in color,

but they tend to be less uniform and show frequent transitions to more coarse-grained and more leucocratic rocks which have undergone a more thorough recrystallization and metasomatic transformation. Most of these rocks show a distinct schistosity. A few, however, have been statically recrystallized and appear almost massive in hand specimen, although some weak alignment of the mafics is usually discernible under the microscope.

The present rocks differ from the isochemical amphibolites chiefly in their higher plagioclase and lower hornblende content, and in that biotite and sometimes quartz are present as additional mineral phases. The average estimated mineral composition of seven of these metasomatically altered amphibolites is:

Plagioclase	61%	(50-73%)
Hornblende	29%	(21-43%)
Quartz	4%	(0-10%)
Biotite	3%	(1-10%)
Epidote	1%	(0- 3%)
Ore	1%	(0- 2%)
Garnet	1%	(0- 2%)

These rocks show considerable textural variation. In general, however, the texture is very similar to that of the isochemical amphibolites, and rather even-grained plagioclase and hornblende are typical. The plagioclase is anhedral but not highly irregular in form. Plagioclase and hornblende occur as inclusion-free crystals or contain only minor small inclusions (of hornblende, plagioclase, garnet, etc.). In some of these rocks, especially those in which metasomatic quartz is more abundant, the textures approach those of the metasomatic hornblende-quartz dioritic gneisses. The plagioclase and quartz are more irregular in form and tend to be uneven-grained and richer in inclusions.

The plagioclase is zoned in all seven of the present rocks. The zoning is anhedral, and the transition between adjacent zones is generally

gradual rather than sharp. Three of the amphibolites contain crystals with both normal and reverse zoning indicating oscillatory zoning with one recurrence. One amphibolite shows oscillatory zoning with one recurrence and a trend calcic core--sodic zone--calcic rim, and one shows oscillatory zoning with one recurrence and a trend sodic core--calcic zone--sodic zone. Two amphibolites show oscillatory zoning with two recurrences; one of these has an undetermined trend and the other a trend calcic core--sodic zone--calcic zone --sodic rim. The characteristic zoning is thus oscillatory with one recurrence. The zoning is slightly more complex than that of the isochemical amphibolites in which only 5 of 12 specimens show oscillatory zoning with one recurrence, one shows normal zoning, 5 show reverse zoning, and one no zoning. The average zonal range in composition of the plagioclase in the present rocks is 10% and is closely comparable to that of the isochemical amphibolites (13%). The range in composition of the zoned plagioclase and the kind of zoning determined in individual zoned crystals in each of the present rocks is summarized here.

Spec. No.	An_{20}	An_{30}	An_{40}	
252			rroo	- no letter indicates
253			roooo	plagioclase strongly
272		nrr		altered and not known
454			nnnooo	whether zoned or
561		nnnr		unzoned
620			oo	r reverse zoning
633		nnnnr		o oscillatory zoning

The observed extremes in plagioclase composition are An_{21} and An_{46}, and the average composition is An_{36}. This compares with an average composition of An_{45} for the isochemical amphibolites.

The hornblende of these rocks varies rather widely in its optical properties, especially in its pleochroism. These properties are summarized here. The absorption is X<Y=Z. All the extinction angles Z:c were measured

on 010.

Spec. No.	X	Y	Z	Z:c
252	greenish-yellow	dark green	dark bluish-green	16°
253	greenish-yellow	dark green	dark bluish-green	18°
272	yellowish-green	dark green	dark bluish-green	18°
454	pale yellowish	light brown	light greenish-brown	16°
561	pale yellowish-brown	greenish-brown	grayish-green	16°
620	brownish-yellow	brown	brownish-green	13°
633	pale greenish	greenish-brown	grayish-green	13°

The strongly pleochroic hornblende of the first three rocks is of a somewhat unusual type not present in any of the isochemical amphibolites. These three specimens were all collected on the road on the south side of the Suiattle River west of Lime Creek. Whether the occurrence of this strongly pleochroic hornblende is due to the composition of the original rock or to a special kind of metasomatism is not known. The hornblendes of the other four rocks all correspond to common types among the isochemical amphibolites. The hornblende occurs as stout anhedral crystals which commonly are elongate after c and which usually show a weak preferred orientation parallel to the foliation. The brown hornblende of specimen number 620 shows weak zoning similar to that of some of the isochemical amphibolites and the biotite-bearing hornblendites. The zoning is confined to a very narrow and irregular outer rim of the hornblende grains. This outer zone shows a pleochroism X almost colorless, Y brownish-green, and Z grayish-green.

Unlike the isochemical amphibolites, all these rocks contain at least minor biotite. The biotite is often closely associated with hornblende and appears to have formed from it by biotization. In two of the metasomatically altered amphibolites epidote appears to have been released in the biotization of hornblende. In these two rocks hornblende, biotite, and epidote partly form little clusters of crystals and partly occur as individual grains in plagioclase intergranular. In most cases biotization of hornblende has

proceeded without the formation of epidote. One excellent example of biotization of hornblende is described below under the aplites. The most common biotite in the present rocks shows a pleochroism X yellowish, Y and Z dark brown. In two rocks a biotite with X pale yellowish, Y and Z orange-brown was observed, and in one rock a biotite with X pale brownish-yellow, Y and Z reddish-brown was observed.

Main assemblage epidote is present in two of the rocks in which it has apparently formed by biotization of hornblende. The epidote occurs partly as well-formed crystals and partly as anhedral grains. The epidote is in equilibrium with plagioclase with an average composition of about An_{33} in both rocks. Two of the rocks contain anhedral porphyroblasts of garnet. In two others garnet is present as tiny relict inclusions in the plagioclase. Apatite and iron ores are ubiquitous accessory minerals in the present rocks, just as in the isochemical amphibolites. Sphene is present in some of these rocks, occurring partly as well-formed crystals and partly as clusters of late poorly-formed grains. In two rocks rutile is a prominent accessory.

A few of these rocks show minor retrogressive alteration including chloritization of biotite and saussuritization and sericitization of plagioclase.

The occurrence of andesine and calcic oligoclase in these rocks indicates crystallization at temperatures at least as high as the kyanite zone. Crystallization under temperatures of the kyanite zone is indicated for the two rocks in which plagioclase (An_{33}) is associated with main assemblage epidote.

The present rocks differ mineralogically from their parent amphibolites in their higher plagioclase content (61% vs. 36%), in their more sodic plagioclase (An_{36} vs. An_{45}), in their lower hornblende content (29% vs. 48%)

and in the presence of biotite. The increase in plagioclase and decrease in mafics indicates a relative increase in and a probable introduction of sodium and a relative decrease in and a probable removal of iron and magnesium. Biotization of hornblende indicates introduction of potassium, and the presence of abundant quartz in some of these rocks suggests introduction of silica.

The quartz dioritic hornblende gneisses. These rocks vary widely in their texture and mineral composition. Some are rather dark fine-grained rocks which do not differ much megascopically from amphibolites, while others are very leucocratic granitic rocks. All these rocks are much poorer in hornblende and richer in quartz than either the isochemical amphibolites or the metasomatically altered amphibolites just described. Most are classed as quartz diorites and a few as trondhjemites. The average estimated mineral composition of thirteen of these hornblende quartz dioritic gneisses is:

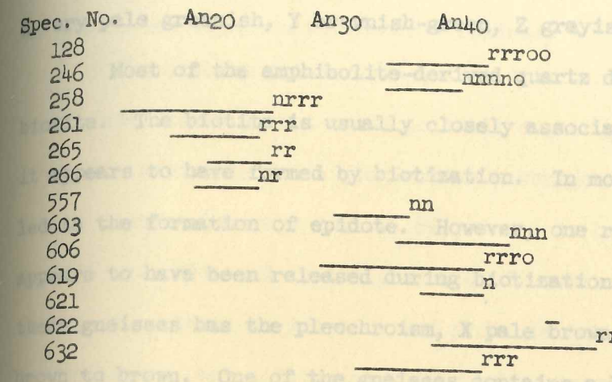
Plagioclase	57%	(47-75%)
Quartz	18%	(8-39%)
Hornblende	17%	(2-38%)
Biotite	4%	(0-11%)
Garnet	1%	(0- 5%)
Iron ores	1%	(0- 2%)

In general the hornblende quartz dioritic gneisses are somewhat more coarse-grained than their parent amphibolites. The quartz and plagioclase of these rocks tend to be uneven-grained and are frequently very irregular in form. Quartz and plagioclase generally contain abundant small inclusions of quartz, plagioclase, hornblende, garnet, etc. These features contrast with the fine- and even-grained textures of the parent amphibolites in which hornblende and plagioclase generally occur as inclusion-free, anhedral, but not highly irregular grains. In a few of the migmatitic hornblende gneisses a complete textural and mineralogical transition could be traced in an

individual thin section from isochemical amphibolite or slightly altered amphibolite to hornblende gneiss.

Hornblende forms irregular anhedral grains often showing a weak tendency toward preferred orientation parallel to the schistosity. Biotite, where abundant, generally shows a distinct preferred orientation.

Twelve of the thirteen gneisses studied contain zoned plagioclase; the plagioclase of the thirteenth gneiss is too strongly altered to permit determination of the composition and zoning of the plagioclase. The zoning is anhedral and the transition between adjacent zones is usually rather gradual. In three rocks all the zoning is normal; in four, all the zoning is reverse; two specimens contain some plagioclase crystals with normal and others with reverse zoning, indicating oscillatory zoning with one recurrence; one specimen shows oscillatory zoning with one recurrence and an undetermined trend; one shows oscillatory zoning with a more sodic core, a more calcic intermediate zone, and a more sodic rim; and one shows oscillatory zoning with a more calcic core, a more sodic intermediate zone, and a more calcic rim. The character of the zoning is similar to that in the isochemical amphibolites and is not quite as complex as that in some of the metasomatically less strongly altered amphibolites. The average zonal range in composition is 7% An which compares with 13% An for the isochemical amphibolites and 10% for the amphibolites showing less strong metasomatic alteration. The range of composition of the zoned plagioclase in each of the present hornblende gneisses is as shown on page 133. The observed extremes in plagioclase composition are An_{13} and An_{50}, and the average composition is An_{33}. This compares with an average composition of An_{45} for the isochemical amphibolites and An_{36} for the amphibolites showing weaker metasomatic alteration.



The following tabulation shows the pleochroism and extinction angles of the hornblende of the thirteen quartz dioritic gneisses. The absorption of all the hornblende is generally of medium intensity for Y and Z but is occasionally darker. All extinction angles were measured on 010.

Spec. No.	X	Y	Z	Z:c
128	pale greenish-gray	brownish-green	grayish-green	15°
246	pale greenish-gray	brownish-green	grayish-green	15°
258	pale greenish-yellow	green	bluish-green	-
261	yellowish-green	dark green	dark bluish-green	16°
265	greenish-yellow	green	grayish-green	14°
266	yellowish-green	dark green	dark bluish-green	17°
557	pale greenish-yellow	brownish-green	grayish-green	15°
603	pale greenish	greenish-brown	grayish-green	14°
606	pale greenish	brownish-green	grayish-green	15°
619	pale yellowish	greenish-brown	green (slightly brownish)	13°
621	pale greenish	brown	brownish-green	13°
622	pale greenish-yellow	greenish-brown	grayish-green	13°
632	pale greenish	brown	brownish-green	14°

The hornblende of specimens 258, 261, and 266 is identical to that of some of the less strongly metasomatically altered amphibolites. These three specimens and those of the metasomatically altered amphibolites containing the same hornblende were all collected from a small area on the road on the south side of the Suiattle River west of Lime Creek. The hornblendes of all the other quartz dioritic gneisses correspond to the common types occurring in the isochemical amphibolites. Four specimens containing the typical greenish-brown hornblende show weak zoning with a greener thin outer rim with the pleochroism

X very pale greenish, Y brownish-green, Z grayish-green.

Most of the amphibolite-derived quartz dioritic gneisses contain biotite. The biotite is usually closely associated with hornblende from which it appears to have formed by biotization. In most cases biotization has not led to the formation of epidote. However, one rock contains epidote which appears to have been released during biotization. The most common biotite of these gneisses has the pleochroism, X pale brownish-yellow, Y and Z reddish-brown to brown. One of the gneisses contains a biotite with X pale yellowish, Y and Z orange-brown, and one contains biotite with X yellowish, Y and Z dark brown.

More than half of the hornblende gneisses studied contain garnet. In some of these gneisses the garnet forms anhedral sieve-textured porphyroblasts while in others it occurs as relict inclusions in the quartz and plagioclase or as tiny grains along the intergranular of these minerals. One of the gneisses contains well-formed main assemblage epidote which, as stated above, appears to have formed from the biotization of hornblende. This epidote is associated with plagioclase of the composition An_{21}. Apatite and iron ores are ubiquitous accessory minerals in all these hornblende gneisses, as in the parent amphibolites. Five of the gneisses contain conspicuous accessory rutile, and one contains sphene.

Some of these rocks show minor retrogressive alteration including chloritization of biotite, and saussuritization and sericitization of plagioclase.

The general occurrence of calcic oligoclase and andesine in the hornblende gneisses indicates crystallization at temperatures of the kyanite zone or higher. Crystallization at temperatures of the intermediate part of the medium grade zone is indicated for the one gneiss in which plagioclase (An_{21})

is associated with contemporaneous epidote.

The amphibolite-derived quartz dioritic gneisses contrast mineralogically with their parent rocks in their higher plagioclase content (57% vs. 36%), in their more sodic plagioclase (average An_{33} vs. An_{45}), in their higher quartz content (average 18% vs. 6%), in their lower hornblende content (average 17% vs. 48%), and in the presence of biotite. The major metasomatic changes are, thus, an increase and probable introduction of sodium, silica, and potassium, and a decrease and probable removal of iron and magnesium. The amount of aluminum probably has not changed much, although calcium may have decreased slightly. The quartz dioritic gneisses differ from the less strongly metasomatically altered amphibolites in their higher quartz content (18% vs. 4%) and in their lower hornblende content (17% vs. 29%). The amount and composition of the plagioclase differ little in these two rock types. The chief metasomatic changes effected in the conversion of the less strongly transformed metasomatic amphibolites to quartz dioritic gneiss are increase and probable introduction of silica and decrease and probable removal of iron and magnesium. Whether quartz dioritic gneiss or less strongly altered amphibolite forms from the isochemical amphibolite depends on the nature of the metasomatism. Where sodium-introduction and a moderate degree of iron- and magnesium-removal are the major metasomatic changes the less strongly metasomatic amphibolites are developed. On the other hand, greater introduction of silica and more thoroughgoing removal of iron and magnesium lead to the formation of quartz dioritic gneisses. Inasmuch as the quartz dioritic gneisses may form either from the less strongly metasomatically altered amphibolites or directly from the isochemical amphibolites, the character of the metasomatism appears to have varied in both space and time.

Diorites Formed from the Hornblendites by Metasomatism

Isochemical hornblendites comprise only a very minor part of the hornblendite-bearing belt. The predominant rocks in this belt are a group of heterogeneous migmatitic hornblende-bearing diorites and quartz diorites among which both schistose and directionless types are represented. These rocks range from hornblende-rich types to leucocratic aplitic and pegmatitic variations. Some of the hornblende-bearing rocks have been metasomatically derived from the hornblendites, others appear to have been derived from amphibolites. Where the metasomatic changes have been great and none of the unaltered parent material has been preserved, the original rock often cannot be determined. A schistose diorite derived from hornblendite, for instance, is often scarcely distinguishable from a slightly metasomatized amphibolite, and after further transformation the determination of the original material may be impossible. As only limited field work has been done on the metasomatic rocks of the hornblendite-bearing belt an evaluation of the proportion of hornblendite-derived rocks to metasomatic rocks of different origin cannot be attempted here. The present description is confined to that considerable volume of dioritic rocks which can definitely be shown to have been derived from the hornblendites. In addition to the hornblende-bearing rocks, sediment-derived schists and paragneisses, and metasomatic rocks derived from these are locally prominent in the hornblendite-bearing belt. These rocks and the amphibolite-derived metasomatic rocks in this belt do not differ from corresponding rock types elsewhere in the heterogeneous gneiss unit. The feldspathized and granitized hornblendites of the hornblendite-bearing belt are well exposed on the high ridge between Red Mtn. and Black Mtn. and are especially well displayed on "Lost Creek Ridge" west of Camp Lake.

Most of the dioritic rocks in the hornblendite-bearing belt have formed metasomatically from the hornblendites. A metasomatic origin is particularly evident for those hornblendites which show only incipient transformation. Biotization of hornblende is usually the first stage in metasomatism, and biotite in amounts up to about 10% has often formed at this time. Generally, however, small scattered porphyroblasts of plagioclase have already appeared before biotite has reached this amount. Sometimes a few scattered grains of garnet have appeared in the hornblendite at this stage of the metasomatism. The petrographic description of the hornblendites showing incipient biotization and feldspathization has been given under the isochemical hornblendites.

At the incipient stage of metasomatism just mentioned, the rocks are still hornblendites. With further feldspathization marked by the spreading of porphyroblastic plagioclase and the coalescence of groups of plagioclase grains into leucocratic bands and patches these rocks pass into diorites. The transition from slightly biotized and feldspathized hornblendites to plagioclase-rich diorites is sometimes very gradual but is often abrupt and may take place within a distance of a few inches or less. Among the diorites of metasomatic origin both schistose, synkinematic types and directionless, static types are found. These two types differ only in their structure, not in their mineralogy. The schistose diorites are in part "lit par lit" rocks, consisting of narrow alternating bands of dark hornblendite or hornblende-rich diorite and more leucocratic diorites, and in part more homogeneous gneissose diorites. The directionless diorites occur as irregular patches in the hornblendite or in a darker, more hornblendic diorite. In the final stages of diorite formation relatively homogeneous bodies of diorite are formed in which the original hornblendite has been entirely eliminated or is present only as

Fig. 17

Directionless patches of leucocratic hornblende-diorite formed by feldspathization of hornblendite. Ridge between Red Mtn. and Black Mtn.

Fig. 18

Leucocratic hornblende diorite formed metasomatically by static feldspathization of hornblendite. Dark patches are less completely transformed hornblendite. On left is an aplite dike. Lost Creek Ridge.





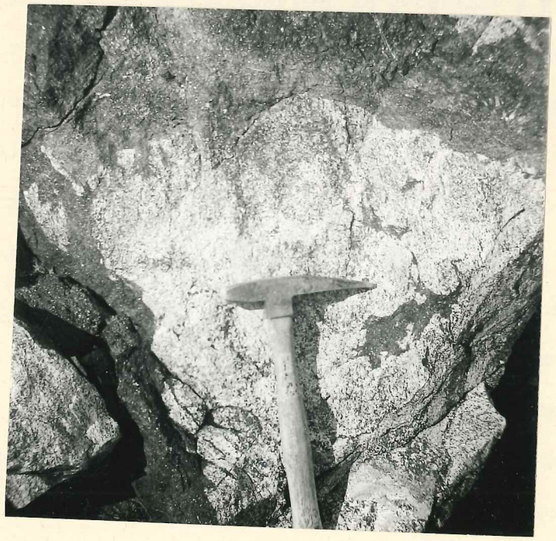
Fig. 19

Coarsely gneissose heterogeneous diorite formed by synkinematic replacement of schistose hornblendite. The darker bands are less strongly feldspathized hornblendite. Lost Creek Ridge.

Fig. 20

Leucocratic diorite formed by static feldspathization of partially biotized hornblendite. Lost Creek Ridge.





small biotized relics. Some of these relatively homogeneous bodies measure several hundred feet in diameter. That the diorites have formed by replacement of the hornblendites, rather than by intrusion, is clear not only from the complete intergradation of these two rock types but from their spatial relations. The diorite commonly occurs in the hornblendites or in more mafic diorites as isolated patches and ductless bodies which clearly cannot be intrusive. In the "lit par lit" diorites the dioritic bands have not wedged apart the adjacent hornblendite layers or more mafic diorite layers as would necessarily occur in bodily injection.

The diorites contain a hornblende identical to that in the hornblendites, except that the pleochroism may be slightly weaker than in the latter. This further emphasizes the close genetic relations of the diorite with the hornblendite which itself has been shown to be of metamorphic origin. The pleochroism of the hornblende in the diorites is generally X extremely pale brownish, Y light brown, and Z light brown to light grayish-brown. The extinction angle Z:c on 010 is 14-15°. The plagioclase in many of the diorites has been altered to a fine-grained aggregate of zoisite and sericite and determination of its composition and kind of zoning is often impossible. Where the plagioclase could still be determined, it was found to be andesine. Plagioclase forms a mosaic of rounded irregular grains surrounding anhedral grains of brown hornblende. The plagioclase has clearly replaced the hornblende and some of the iron released from the hornblende has been fixed as ore minerals in the intergranular between the plagioclase grains.

Feldspathization, in these rocks the replacement of hornblende by plagioclase, has been the one most significant process in the development of the diorites from the hornblendites. Biotization has commonly also been important, especially in the early stages of metasomatism when as much as 10

to 15% biotite has formed in some of the hornblendites. Generally, however, biotization plays a role subordinate to that of feldspathization in that it does not seem to be a necessary preliminary to the latter and in that hornblende, not biotite, is the dominant mafic mineral in the diorites. Since the exact chemical composition of the hornblende is not known, the chemical balance during metasomatism can only be evaluated in a very general way in spite of the very simple mineralogical changes involved in the formation of the diorites. Biotization of hornblende clearly entails the introduction of potassium but the behavior of the other constituent elements is less certain. Since biotization has proceeded without the formation of calcium-bearing minerals such as epidote or plagioclase, in many of the hornblendites some removal of calcium is probable, although some of the calcium released is fixed in sphene. Iron, as ore minerals, and titanium, as sphene, have commonly been precipitated in the hornblendites during biotization and it is possible that these elements have also been removed in some degree. The chemical changes during feldspathization have been very great, especially in the leucocratic diorites where almost all the hornblende has been replaced by plagioclase. Sodium in particular has been added in great amount, magnesium has been almost entirely removed. The amount of aluminum has apparently changed only slightly. Much iron has been lost though some remains in the diorites as iron ores. The silica content of the rocks must have increased during metasomatism, although not to such an extent that free quartz was produced. This is somewhat remarkable in view of the general ready availability of sufficient silica to produce free quartz during metasomatism elsewhere in the area, as in granitization of amphibolites in the hornblende gneiss unit and in the heterogeneous gneiss unit.

Pegmatitic and Aplitic Trondhjemites

Directionless trondhjemites are widely distributed throughout the heterogeneous gneiss unit. These rocks are commonly quite uniform in texture and are often very leucocratic. Pegmatitic types are most abundant, but aplitic types are also prominent. These directionless rocks are not confined to any particular part of the heterogeneous gneiss unit but are found in association with almost every rock type and are so abundant as to be scarcely ever absent in any larger outcrop. These trondhjemites occur only as smaller bodies, especially as dikes and irregular patches. Both aplite and pegmatite commonly form dikes. The irregular patches are typically pegmatitic, less often they are medium-grained. The dikes only rarely exceed five feet in thickness and commonly are much narrower. The irregular patches, like the dikes are mostly small and seldom exceed five feet in their maximum dimension.

The general crosscutting relationship of the trondhjemitic dikes and patches with the associated isochemical and metasomatic rocks shows these bodies to be late. Many of the bodies are not entirely postkinematic, however, for they have themselves been deformed by shear folding and plastic flow. The emplacement of the dikes appears to have extended over a considerable length of time, for often in a single outcrop dikes are observed which show different degrees of folding and hence have a different age. In different dikes all stages of folding are observed, ranging from only slight displacement of an originally planar dike to extremely complex ptygmatic folds. In the advanced stages of deformation the originally crosscutting dikes have been bodily rotated into the plane of schistosity ("Einschlichtung") by differential movement on closely spaced shear planes and have been further deformed by boudinage. As the crosscutting relationship disappears in the final stages of deformation, the identity of the dike is lost, and it cannot

be distinguished from a concordant lit par lit replacement or injection band. It is, in fact, probable that many of the leucocratic bands in the banded gneisses are of this origin.

Field relations indicate that some of the pegmatitic and aplitic bodies have formed by replacement and others by intrusion. Most of the irregular patches of late pegmatite have formed by replacement. The country rock structure is often undisturbed around these pegmatitic patches and is often preserved within the patches as shadowy remnants or in nonrotated inclusions of country rock. The contact between the country rock and the patches of replacement pegmatite is generally gradational, being marked by a progressive increase in porphyroblastic plagioclase and a decrease in mafics. Many of the patches appear to be ductless bodies, lacking any conduit along which the pegmatite could have been injected. In general replacement appears to have proceeded without change in volume, but increase in volume is indicated locally by dilation and swelling. It is interesting to note that static granitization, as evidenced by these replacement bodies reached isochemical schists unaffected by the earlier synkinematic granitization.

In contrast to the irregular patches most of which seem to have formed by replacement, many of the better defined dikes of pegmatitic and aplitic material are clearly intrusive, although others appear to have formed by replacement. The criteria for distinguishing replacement dikes and dikes formed by intrusion have been summarized by Goodspeed (1940). The intrusive relationship of the present injected dikes is demonstrated by dilation and offset of country rock structures transected by the dikes. Observations in the field show no pronounced textural or mineralogical differences between pegmatites and aplites of replacement origin and corresponding rocks occurring as intrusive bodies. Although dilation demonstrates an intrusive mode of

Fig. 21

Incipient development of a ptygmatic fold by shear folding of an originally planar dikelet cutting slightly feldspathized garnet-biotite schist. Note parallelism of schistosity and the axial planes of the shear folds. Kennedy Hot springs, upper Whitechuck River.

Fig. 22

More advanced ptygmatic folding of originally planar dikelets cutting garnet-biotite schist. Note pegmatitic patch on upper left. Kennedy Hot Springs, upper Whitechuck River.





Fig. 23

Ptygmatically folded leucocratic bands in garnet-biotite gneiss. Northeast ridge of Red Mtn.

Fig. 24

Complex ptygmatic fold of aplite in garnet amphibolite. The aplite is believed to have originally been a small crosscutting dike. Suiattle River road between Lime Creek and Circle Creek.





Fig. 25

Postkinematic replacement pegmatite patch in synkinematic metasomatic garnet biotite gneiss. Bending out of schistosity indicates indrease in volume during formation of the pegmatite. Northeast ridge of Red Mtn.

Fig. 26

Postkinematic replacement pegmatite in synkinematic metasomatic garnet-biotite gneiss. Note undisturbed relict inclusions of gneiss. Northeast ridge of Red Mtn.





Fig. 27

Metasomatic diorite and a dark relict band of feldspathized hornblendite cut by dilation dikes of pegmatite. Slight fault movement is indicated parallel to the walls of the dike in the center of the photo. Lost Creek Ridge.

Fig. 28

Aplitic dilation dike cutting metasomatic biotite gneiss. Lost Creek Ridge.





emplacement, the intrusive relationship in itself reveals nothing as to the origin of the intruded material, or as to its physical state at the time of emplacement. The intruded material may be either locally-derived mobilized metasomatic material or may have been derived from a magmatic source entirely outside of the area of the heterogeneous gneiss unit. The intruded material of either origin could have been emplaced as a wholly liquid magma, as a mixture of magma and crystals (of either magmatic or metamorphic origin), or as an essentially solid, but nevertheless mobile, mass. A few dilation dikes composed of heterogeneous migmatitic material showing good flow structure were observed. This demonstrates at least some mobilization and intrusion of essentially solid, locally-derived metasomatic material. Most of the rocks of the dilation dikes show no flow structure, however, and their physical state at the time of intrusion generally cannot be determined. The similarity of the pegmatites of replacement origin to those occurring as intrusive bodies would seem to suggest mobilization. A final answer to this problem must await a detailed field and petrographic study. The most fruitful approach would probably be a comparative mineralogical and textural study of the trondhjemites of the dilation dikes with similar trondhjemites of known replacement origin in the same area. Since only a limited number of specimens of pegmatites and aplites were collected, and since the replacement or intrusive mode of emplacement of many of these could not be established, a general genetic interpretation of these rocks cannot be attempted here. Only a brief discussion of a few typical pegmatites and aplites will be given.

A one cm thick dike cutting fine-grained garnet biotite paragneiss is a good example of a replacement pegmatite. In hand specimen the contact of the dike and paragneiss appears quite sharp, the replacement origin, however, is clear from the lack of dilation. In thin section the pegmatite is seen to

consist chiefly of large, highly irregular interlocking grains of plagioclase and quartz. Along the intergranular boundary of the quartz and plagioclase, and within these minerals as inclusions, occur muscovite, kyanite, and minor staurolite, none of which is present in the paragneiss. Incompletely replaced individual crystals and groups of crystals of the minerals of the fine-grained paragneiss are present in the intergranular and as inclusions in the porphyroblastic plagioclase and quartz. In thin section porphyroblasts of plagioclase and quartz are seen to penetrate into the paragneiss, and the contact of the dike is not as sharp as it appears in hand specimen. The plagioclase of the dike is unzoned oligoclase, while that of the paragneiss is sodic andesine showing weak simple zoning (normal or reverse zoning of an undetermined trend). In the dike only minor biotite and garnet have survived from the paragneiss. The relict biotite in the pegmatite is an orange-brown variety identical to that of the paragneiss.

Two thin sections of pegmatites from definite dilation dikes were studied. Both of these contain oscillatory zoned plagioclase which is calcic oligoclase, with a zonal range in composition of 4-5% An. The oscillatory zoning shows as many as 3 recurrences in one rock and as many as 5 in the other. The zoning in both rocks is euhedral, and the transition between adjacent zones is not sharply marked. The plagioclase grains themselves, however, are very irregular in outline and the zoning is sometimes abruptly truncated against adjacent quartz and plagioclase grains. Quartz and plagioclase form a highly irregular interlocking mosaic. One rock is almost free of mica, consisting almost wholly of quartz and plagioclase which are roughly equigranular and include each other poikiloblastically only to a small extent. The other pegmatite contains both biotite and muscovite, partly as coarse flakes in the intergranular and partly as small inclusions in quartz and

plagioclase. This rock is less even-grained than the first, and porphyroblastic quartz and plagioclase include all the minerals of the rock poikiloblastically. The biotite in this pegmatite is an orange-brown variety and shows incipient alteration to chlorite. Both rocks contain accessory apatite and zircon. Whether the euhedrally zoned plagioclase should be interpreted as of igneous origin is uncertain. If so, the inclusions of quartz and plagioclase within the euhedrally zoned plagioclase would still have to be interpreted as earlier solid crystals, possibly of metamorphic origin. In any case truncation of the zoned plagioclase indicates later replacement.

Some of the trondhjemitic gneisses are sufficiently coarse-grained to be termed pegmatitic gneiss. They are texturally and mineralogically identical to the other trondhjemitic gneisses and, like these, are considered to be of metasomatic origin. A typical example is a trondhjemite composed essentially of oligoclase and quartz with some biotite and very minor muscovite. Oligoclase and quartz are present as extremely irregular grains of uneven size, interlocking in an intricate mosaic. The larger quartz and oligoclase grains include grains of earlier quartz and plagioclase and partly also of biotite and muscovite. Biotite and muscovite are also present along the intergranular boundary of quartz and oligoclase. The plagioclase is a calcic oligoclase; it shows anhedral oscillatory zoning with one recurrence, with a more sodic core, a more calcic intermediate zone, and a more sodic rim, and a zonal range in composition of about 5% An.

One pegmatite is of particular interest in that it contains potash feldspar and is of granodioritic rather than trondhjemitic composition. This pegmatite is, in fact, one of the very few rocks collected in the entire migmatitic area which contains any potash feldspar at all. The pegmatite was collected on the road along the south side of the Suiattle River 3.5 miles

east of Straight Creek. It occurs as a replacement dike associated with statically recrystallized garnet biotite schist containing large metasomatic microcline porphyroblasts. The rock consists of approximately 35% oligoclase, 30% quartz, 25% microcline perthite, 6% muscovite, and 2% garnet. Oligoclase, quartz, and microcline form an interlocking mosaic of extremely irregular grains. Microcline appears to be late because it includes all the other minerals. Microcline has clearly replaced oligoclase, for where the two minerals are in contact, the oligoclase always shows a narrow irregular albitized zone and sometimes also the development of myrmekite adjacent to the albitic zone. Plagioclase and quartz include each other. Muscovite occurs as irregular plates in the quartz-feldspar intergranular and as inclusions in the other minerals. The occurrence of narrow albitic zones around the muscovite where this mineral is included by oligoclase indicates that muscovite has formed at the expense of oligoclase. The plagioclase is intermediate oligoclase showing weak anhedral normal zoning.

Description of the aplites will be confined to three specimens. One is a fine-grained muscovite-bearing trondhjemitic aplite containing minor biotite and garnet. The origin of this rock is not certain, but since it appears to be gradational with garnet-bearing leucocratic gneiss in which it occurs as a directionless aplitic patch, and since it contains minor garnet itself, a metasomatic origin is likely. The plagioclase of this aplite is sodic oligoclase showing euhedral oscillatory zoning with as many as three recurrences and a zonal range in composition of about 7% An. The outlines of the oligoclase grains are very irregular and do not conform to the zoning which is typically truncated by adjoining quartz grains. The quartz and plagioclase tend to be uneven grained and interlock in an irregular mosaic. The oligoclase is either free of inclusions or contains only a few tiny quartz

or plagioclase grains. Unlike the oligoclase, the quartz contains abundant inclusions of oligoclase and also some inclusions of quartz. The truncation of the plagioclase by quartz and the poikiloblastic character of the quartz indicate replacement of oligoclase by quartz. This relation clearly implies late introduction of silica. Muscovite occurs as highly irregular plates showing a considerable range in size. It often has a vermicular texture marked by wormlike intergrowth with plagioclase or quartz. The muscovite is not confined to the quartz-plagioclase intergranular, for large muscovite crystals commonly straddle several grains of quartz and plagioclase which the muscovite appears to replace. Muscovite also occurs with biotite (X brownish-yellow, Y and Z very dark brown) and epidote, and has clearly replaced the biotite. The epidote appears to be in equilibrium with sodic oligoclase.

A muscovite-bearing aplite collected from a dilation dike is mineralogically and texturally very similar to the previous specimen. The aplite is a fine-grained, sugary-textured trondhjemite consisting essentially of quartz and plagioclase which show a considerable variation in grain size. The plagioclase is medium oligoclase showing oscillatory zoning with as many as three recurrences and a zonal range in composition of about 11% An. The zoning is euhedral and the boundary of adjacent zones is in part sharply marked and in part gradually transitional. Some of the oligoclase grains preserve relatively straight crystal outlines, although, on close inspection, many of these are found to be slightly embayed. In other grains the oligoclase shows more irregular outlines and some truncation of zoning. A few small inclusions of quartz and plagioclase and sometimes biotite or muscovite may be present in the oligoclase. Anhedral quartz appears to fill in between the plagioclase grains. Quartz, like the oligoclase, tends to be free of inclusions, but may include minor oligoclase and quartz and sometimes

muscovite or biotite. Truncation of zoned oligoclase by quartz indicates replacement and suggests some late introduction of silica. The muscovite and the minor biotite (X yellow, Y and Z dark chocolate brown) tend to be confined to the quartz-oligoclase intergranular, though they partly protrude into neighboring quartz and oligoclase grains and occasionally are present in these minerals as inclusions. Muscovite appears to be late and has formed at the expense of biotite.

Some very interesting metasomatic features are associated with a 2 cm thick aplite dike cutting directionless hornblende-plagioclase granulite. The dike is a fine-grained, sugary-textured aplite of trondhjemitic composition which cuts dark fine-grained hornblende-plagioclase granulite with a very sharp contact. The aplite consists of approximately 52% plagioclase, 45% quartz, 2% biotite, and contains very minor epidote and iron ores. The plagioclase and quartz of the aplite are very uneven-grained and highly irregular in form, interlocking in a tight mosaic. The plagioclase characteristically contains many tiny quartz inclusions. To a lesser extent quartz includes plagioclase. Small plates of biotite (X brownish-yellow, Y and Z dark brown) are sparsely distributed along the quartz-plagioclase intergranular, and a few tiny grains of epidote and iron ores are also present. The plagioclase is calcic oligoclase showing anhedral reverse zoning with a zonal range in composition of about 9% An. In general the zoning conforms to the irregular outlines of the plagioclase, but it sometimes appears to be slightly truncated. The transition between adjacent zones is gradational. At a distance of 2 cm away from the contact of the aplite the mineral composition of the directionless hornblende-plagioclase granulite is approximately 72% plagioclase, 21% hornblende, 2% biotite, 2% epidote, 2% iron ore, with minor garnet and apatite. As the contact of the dike is approached, the hornblende decreases in

amount and is gradually supplanted by biotite and epidote. At the contact of the dike hornblende is almost completely absent, the mineral composition being 69% plagioclase, 21% biotite, 5% epidote, 3% iron ore, with minor garnet and apatite. The plagioclase-biotite-epidote zone of the hornblende-plagioclase granulite does not differ texturally from the plagioclase-hornblende zone. The plagioclase in both zones is oscillatory zoned plagioclase with as many as 3 recurrences and a composition ranging from about An_{27} to An_{40}. The zoning is anhedral and the transition between adjacent zones is not sharply marked. The plagioclase is quite even-grained and occurs as more or less equidimensional, anhedral crystals which are either free of inclusions or do not contain more than a few small inclusions of plagioclase, hornblende, biotite, epidote, iron ores, and garnet. In general hornblende, biotite, epidote, and iron ore are confined to the intergranular where they often tend to be grouped in small clusters. The hornblende forms stout anhedral columns. This hornblende is a strongly pleochroic variety with X yellow-green, Y very deep green, Z very deep bluish-green, and X<Y=Z. The extinction angle Z:c on 010 is 18°. The biotite is optically identical to the biotite of the aplite dike. The epidote occurs partly as irregular and partly as euhedral grains, and seems to be in equilibrium with the associated plagioclase (An_{33}). In thin section the contact of the granulite and the dike is marked by an abrupt disappearance of the mafics on the one hand and quartz on the other. Through a layer of the thickness of about one plagioclase grain the plagioclase of the hornblende-plagioclase granulite appears to be transitional to the plagioclase of the dike. The origin of the dike itself is not clear. Its textures appear to be crystalloblastic; however, the abrupt mineralogical contrast between the dike and the hornblende-plagioclase granulite make emplacement by replacement rather unlikely. It is probable, then, that the material of the dike has been

introduced in its entirety, either as mobilized metamorphic material or in solution accompanying gradual opening of the fissure now occupied by the dike. Whatever the origin of the aplite, it is clear that alteration of the hornblende-plagioclase granulite has been brought about by metasomatizing solutions acting outward from the dike. A continuous mineralogical sequence marked by decreasing hornblende and increasing biotite and epidote may be followed from the hornblende-plagioclase granulite which contains 21% hornblende, 2% biotite, 2% epidote, and 2% iron ore at a distance of 2 cm from the contact of the dike, and which contains 21% biotite, 5% epidote, and 3% iron ore at the contact of the dike. The plagioclase has remained unchanged in composition, amount, and zoning throughout the hornblende-plagioclase granulite. The principal mineralogical change is the conversion of hornblende to biotite plus epidote and minor iron ore. This transformation implies introduction of potassium.

The Hornblende Gneiss Unit

The hornblende gneiss unit is a rather homogeneous unit composed chiefly of coarse-grained hornblende gneisses of quartz dioritic composition. Like the heterogeneous gneiss unit, the hornblende gneiss unit is migmatitic, but it differs in that isochemical metamorphic rocks are extremely subordinate and are, with a few exceptions, confined to amphibolites. The hornblende gneiss unit occupies the southwestern part of the migmatite area and is well exposed on the summit and south ridge of Mt. Pugh, on Bedal Pk., and on "Lost Creek Ridge" just east of Round Lake and extends farther south to Sloan Pk. (Zwart, personal communication). On the northeast the hornblende gneiss unit is apparently concordant with the heterogeneous gneiss unit. On the west it is abruptly terminated against low grade metamorphic rocks and unmetamorphosed

sediments by the Straight Creek fault.

Amphibolites and Other Isochemical Rocks

Remnants of isochemical amphibolites are very subordinate in the hornblende gneiss unit compared to the greatly predominant metasomatic hornblende gneisses. Wherever isochemical amphibolites do occur, they are intimately associated with migmatites which are transitional into the hornblende gneiss. The best exposures of the amphibolites are found on "Lost Creek Ridge" just northeast of the summit of Pk. 6400 which is directly east of Round Lake. The amphibolites described below were all collected on this ridge.

The amphibolites of the hornblende gneiss unit differ very little from the ortho-amphibolites of the heterogeneous gneiss unit described above. They are dark, fine-grained, sharply schistose rocks which sometimes show a thin metamorphic differentiation banding. The average estimated mode of three of the amphibolites is:

Hornblende	49%	(47-52%)
Plagioclase	48%	(46-50%)
Sphene	1%	(0- 2%)
Iron Ores	1%	(0- 3%)

Some of the amphibolites contain garnet though none was found in the specimens studied in thin section. None of these specimens contain quartz. The hornblende and plagioclase form a mosaic of rounded to irregular, even-sized, xenoblastic grains. The hornblende crystals are generally slightly elongate after c. The hornblende grains show preferred orientation parallel to the schistosity and sometimes also a linear parallelism.

The characteristic hornblende is brown with X pale brownish-yellow, Y brown, Z brownish-green to greenish-brown, X<Y=Z, and an extinction angle

(Z:c) of 13° on 010. The intensity of pleochroism ranges from intermediate to moderately strong. Normally zoned plagioclase was determined in one amphibolite and oscillatory zoned plagioclase with one recurrence and a trend sodic core--calcic zone--sodic rim in another. The range in composition of the plagioclase and the kind of zoning determined in individual crystals in these two rocks is as follows:

Spec. No.	An_{40}	An_{50}	
476	_____	nn	- no letter indicates plagioclase strongly altered and not known whether zoned or unzoned
478(1)	_____	nno	n normal
			o oscillatory zoning

The average composition of the plagioclase is about An_{45} and the range in composition of the zoned plagioclase averages about 14% An. These figures are almost identical with the averages for the plagioclase in the amphibolites of the heterogeneous gneiss unit. Sphene and iron ores are common accessory minerals in the present amphibolites. Some of the plagioclase in these rocks shows incipient saussuritization with the formation of zoisite or epidote. One amphibolite specimen studied shows some static recrystallization. This rock is very fine-grained and consists of weakly oriented grains of brown hornblende and plagioclase. It is cut by transverse intersecting veinlets of coarse-grained nonoriented brown hornblende and by one veinlet of roundish grains of diopsidic pyroxene.

On the basis of their mineral composition and uniformity, and the general absence of intergradations with sediment-derived metamorphic rocks, the amphibolites are considered to be metamorphosed basic igneous rocks. Since the hornblende gneisses have themselves been metasomatically derived from the amphibolites, it follows that almost the whole of the hornblende gneiss unit has been ultimately derived from basic igneous parent rocks. The

presence of occasional thin interbeds of metamorphosed sedimentary rocks in the hornblende gneiss unit and the regional concordance of the unit as a whole with other stratigraphic units in the migmatitic complex indicate an original sequence of layered basic volcanic rocks. Judging from the mineral composition of the amphibolites, the parent volcanic rocks were probably tholeitic basalts. The thickness of this original volcanic sequence must have been very great.

The mineralogy of the amphibolites in the hornblende gneiss unit gives no conclusive indication of their metamorphic grade. However, from the fairly basic composition of the plagioclase (average An_{45}) it is probable that temperatures were either of the hotter part of the kyanite zone or of the high grade zone. The occurrence of brown rather than green hornblende and the absence of main-assemblage epidote also suggest relatively high temperatures.

Two unusual rocks were studied which occur as narrow bands up to a few inches in thickness in the amphibolites. One of these consists of alternating green and red bands, rich respectively in iron-poor epidote and garnet. The epidote (50%) and garnet (20%) form large anhedral porphyroblasts in which abundant small grains of fibrous green hornblende, quartz, and saussuritized plagioclase are included. This rock may represent a metamorphosed dolomitic-argillaceous sediment. The other rock consists of 41% quartz, 38% plagioclase, 10% brown hornblende, and 9% diopsidic pyroxene. The rock is weakly banded, consisting of alternating light colored layers relatively rich in grayish-green diopside and darker layers containing abundant small black grains of hornblende. All the minerals have approximately the same grain size. The hornblende and diopside form small anhedral grains which are scattered somewhat unevenly through a matrix of roundish to irregular quartz and plagioclase grains. The plagioclase ranges from An_{34} to An_{54} in composition

and is normally zoned. This rock contrasts with its associated amphibolites by its high content of quartz and its low mafic content. This rock has probably formed from a calcareous-dolomitic argillaceous-sandy sediment, rather than from a basic tuff containing admixed sedimentary material rich in silica.

Other kinds of metamorphosed sedimentary interbeds are not common either in the hornblende gneiss unit, but were observed at a few places. Banded quartzites ranging up to several feet in thickness were found at several localities, both in the amphibolites and in the hornblende gneisses. These quartzites are considered to be metamorphosed ribbon cherts. Except for minor feldspathization the quartzite bands have not been affected by metasomatism. East of Round Lake a single outcrop of garnet-bearing biotite schist was observed intercalated in the hornblende gneiss.

The Metasomatic Hornblende Gneisses

The greater part of the hornblende gneiss unit consists of relatively homogeneous hornblende gneiss of quartz dioritic composition. The typical hornblende gneiss is a light-colored, uniform, fairly coarse-grained rock, showing a coarse but distinct foliation marked by stubby black hornblende crystals. The hornblende crystals are oriented parallel to the schistosity and in some of the gneisses parallel to b as well. These amphibolites are characteristically found in intimate migmatitic association with the hornblende gneisses, commonly as banded gneisses. Field relations clearly indicate formation of the hornblende gneisses by metasomatic replacement of the amphibolites where these two rock types are associated, for there is a continuous textural and mineralogical gradation between these rocks both along and across the strike. The transition is commonly very rapid, often occurring



Fig. 29

Hornblende gneiss near the summit of Mt. Pugh. Somewhat more sharply layered than most of the gneisses in the hornblende gneiss unit.

Fig. 30

Bands of hornblende gneiss in ortho-amphibolite. The very thin feldspathic layers in the amphibolite may have formed by metamorphic differentiation. The wider gneiss layers are believed to have formed by metasomatic replacement. Incipient boudinage on right. Lost Creek Ridge, one mile east of Round Lake.

Fig. 31

Thick replacement band of hornblende gneiss in ortho-amphibolite. Lost Creek Ridge, one mile east of Round Lake.





within a distance of a few cm or less. Inasmuch as the field evidence for the metasomatic origin of the migmatitic hornblende gneisses in the hornblende gneiss unit is the same as for similar gneisses in the heterogeneous gneiss unit, it is not repeated here. The metasomatic origin of those hornblende gneisses which are not migmatitically associated with amphibolites is demonstrated by the textural and mineralogical identity of these rocks with hornblende gneisses of proven metasomatic origin elsewhere in the hornblende gneiss unit. The isochemical amphibolites of the hornblende gneiss unit have already been described. Before discussing the typical hornblende gneisses themselves, a brief description of some of the metasomatically altered but less completely granitized amphibolites is given. These rocks, like the isochemical amphibolites, are found in close migmatitic association with the hornblende gneisses.

Amphibolites showing weak metasomatic alteration appear to be more abundant than strictly isochemical amphibolites in the hornblende gneiss unit. These rocks differ from the isochemical amphibolites in being slightly coarser-grained, somewhat more leucocratic, and not as sharply schistose. The average estimated mineral composition of three such rocks is: hornblende 38% (32-44%), plagioclase 56% (50-62%), biotite 3% (1-5%), quartz 1% (0-4%). Texturally these rocks closely resemble the isochemical amphibolites and are characterized by even-grained hornblende and plagioclase, occurring as anhedral but roughly equant crystals which are relatively free of inclusions. The one specimen containing quartz has a slightly different texture, for the quartz occurs as small inclusions in both the plagioclase and the hornblende. The plagioclase shows normal zoning in two of these rocks and reverse zoning in the third. The composition of the plagioclase of the three specimens is:

n - no letter indicates plagioclase strongly altered and not known whether zoned or unzoned
n normal
r reverse zoning

The average zonal range in composition of the plagioclase is 9% An. The average composition is An_{34} and the range is An_{27} to An_{43}. The hornblende is a brownish variety often showing simple twins, with a pleochroism of intermediate to moderately strong intensity, and X<Y=Z. The pleochroism and extinction angle (on 010) of the hornblende of these three rocks are:

Spec. No.	X	Y	Z	Z:c
325	pale yellowish-green	greenish-brown	grayish-green	12°
390	pale greenish	green (slightly brownish)	grayish-green	15°
391	pale greenish	greenish-brown	brownish-green	14°

All these rocks show biotization of hornblende. In one rock the biotite occurs as fine-grained nonoriented plates in the larger hornblende crystals. Accessory minerals are apatite, iron ores, and commonly also sphene.

Two banded gneisses are cited as examples of granitized amphibolites which are mineralogically and texturally intermediate between the isochemical amphibolites and the typical hornblende gneisses. One of these rocks consists of about two thirds dark layers and one third light-colored layers. The dark layers are up to 2 cm thick and consist of fine-grained amphibolite which contains scattered garnets, some as much as a cm in diameter. The light bands range from less than a mm to a cm in thickness; they are irregular and discontinuous, but concordant, and consist of medium-grained quartz and plagioclase with only minor hornblende and garnet. Their composition is leuco quartz dioritic. The rock consists of approximately 49% plagioclase, 34% hornblende, 18% quartz, 6% garnet, and 2% biotite, together with accessory iron ores and apatite. The amphibolite bands show the characteristic textures of the

isochemical amphibolites. The leucocratic bands are coarser-grained and consist of highly irregular interlocking quartz and plagioclase grains which show a wide range in size and may contain any of the minerals of the rock as inclusions. Garnet is largely restricted to the darker layers where it forms large sieve-textured porphyroblasts containing as much as 65% inclusions. The darker and lighter bands merge through a very narrow transition zone. The plagioclase shows oscillatory zoning with one recurrence and ranges from An_{29} to An_{37} in composition. The hornblende is identical in both the amphibolitic and quartz dioritic bands; it has a moderately strong pleochroism with X pale yellowish, Y greenish-brown, Z brownish-green, X<Y=Z, Z:c on 010 12°.

The other specimen of layered gneiss is very sharply banded and consists of about half dark fine-grained amphibolite bands and half light medium-grained quartz dioritic bands. The bands range from less than a mm to about a cm in thickness. The estimated mineral composition of the whole rock is 41% quartz, 40% plagioclase, 14% hornblende, and 3% biotite together with accessory iron ores, apatite, orthite, and sphene. The textures of the darker and lighter layers are the same as in the previous specimen. The plagioclase shows normal zoning and ranges from An_{31} to An_{44} in composition. The hornblende has a pleochroism of moderate intensity with X pale yellowish, Y brown, Z greenish-brown.

The hornblende gneisses of the present unit are characterized by a striking mineralogical and textural uniformity, and differ thus very markedly from otherwise comparable but heterogeneous amphibolite-derived quartz dioritic hornblende gneisses in the heterogeneous gneiss unit. The uniformity of the hornblende gneisses is attributed to their derivation from a uniform mass of basic volcanic rocks. The average estimated mineral composition of six of the present hornblende gneisses is:

Plagioclase	62%	(56-57%)
Quartz	22%	(13-28%)
Hornblende	8%	(0-17%)
Biotite	7%	(1-15%)
Chlorite	1%	(0- 6%)

The textural pattern of the medium- to coarse-grained hornblende gneisses is set by their main mineral constituent, plagioclase. The plagioclase is uneven-grained with the larger crystals generally predominating. Often, though not always, the plagioclase grains tend to approximate lathlike form. This form is very imperfect, however, for the crystal outlines are generally very irregular in detail and the euhedral zoning of the plagioclase is usually truncated, often very abruptly, against any other mineral grain at the crystal boundary. The quartz is also uneven-grained and irregular in form and never reaches the size of the larger plagioclase grains. The space between the larger plagioclase grains is occupied by the more fine-grained quartz, hornblende, biotite, and the smaller plagioclase crystals. The interstitial quartz sometimes occurs as a number of small interlocking grains, rather than as one larger grain. The hornblende is uneven-grained and generally anhedral, though it occasionally occurs as rather large rough prisms. It shows a distinct over-all parallelism with the planar schistosity and sometimes also a linear parallelism. The biotite is generally uneven-grained, forming irregular plates which roughly parallel the schistosity; in two rocks, however, it occurs in clusters of small nonoriented plates and has clearly formed by replacement of hornblende. One of the most conspicuous textural features of the hornblende gneisses, as contrasted to comparable quartz dioritic hornblende gneisses in the heterogeneous gneiss unit, is the general absence of inclusions in all the minerals. While any of the minerals occasionally may include any of the other minerals, the inclusions tend to be small and very subordinate. In this respect the hornblende gneisses resemble

the isochemical metamorphic rocks (amphibolites, biotite schists, etc.), though they differ in their uneven-grain size and in their irregular grain form. The hornblende gneisses resemble the isochemical metamorphic rocks also in their mineralogical uniformity.

Zoned plagioclase was observed in all of the hornblende gneisses except in those in which the plagioclase was too badly altered to be determined. Of four specimens studied, one shows only normal zoning, one shows oscillatory zoning with one recurrence, one shows oscillatory zoning with as many as two recurrences, and one shows oscillatory zoning with as many as three recurrences. The zoning is generally euhedral, although anhedral zoning is occasionally observed. The transition between adjacent zones is in part quite rapid and in part rather slowly gradational. The zonal range in composition of the plagioclase and the kind of zoning determined in individual crystals in each of these four rocks is:

Spec. No.	An_{30} — An_{40}	
16	nnoo	- no letter indicates plagioclase strongly altered and not known whether zoned or unzoned
324	nnoo	
478(2)	nnnroo	
479	n	n normal
		o oscillatory zoning
		r reverse zoning

The average zonal range in composition of the plagioclase is 11% An. This compares with 14% An for the isochemical amphibolites and 9% An for the less strongly metasomatically altered amphibolites. The observed extremes in plagioclase composition are An_{26} and An_{43}, and the average composition is An_{34} which compares with An_{45} for the isochemical amphibolites and An_{34} for the less strongly metasomatically altered amphibolites. The plagioclase of the hornblende gneisses differs from that of the isochemical amphibolites in its euhedral character and in the greater complexity of its zoning. Some of the plagioclase grains of the hornblende gneisses show carlsbad twinning in

addition to albite and pericline twinning. While albite and to a lesser degree pericline twinning are present in almost all the isochemical and metasomatic metamorphic rocks of the migmatite complex, only the plagioclase of the hornblende gneisses shows carlsbad twinning.

The hornblende of these gneisses is a brownish-green variety with a moderately strong pleochroism and X<Y=Z. The hornblende commonly shows either simple or multiple twinning. Due to the absence of suitably oriented grains no determination of the extinction angles of the hornblende could be made. The pleochroism of the hornblendes is summarized here.

Spec. No.	X	Y	Z
16	pale yellowish-green	greenish-brown	greenish-gray
17	pale greenish	greenish-brown	brownish-green
88	pale greenish-yellow	green (slightly brownish)	grayish-green (slightly bluish)
324	pale yellowish	brown	greenish-brown
478(2)	pale brownish-yellow	brown	brownish-green

All these hornblendes correspond to common types among the isochemical and the less strongly metasomatically altered amphibolites. All the hornblende gneisses contain biotite, and one specimen contains biotite to the exclusion of hornblende. The biotite in all these rocks appears to have formed from the biotization of hornblende. The biotite is generally synkinematic, but in two rocks it has crystallized statically after hornblende in small patches. The common biotite has X pale brownish yellow, Y and Z orange-brown to reddish-brown, but in one rock the biotite has X pale yellow, Y and Z dark brown. The biotite in several of the gneisses shows incipient retrogressive alteration to a positive chlorite with normal interference colors. Garnet is not present in any of the specimens studied but was observed at several outcrops in the field; in one outcrop the garnet occurs as large porphyroblasts some of which reach the size of small cherries. Many of the hornblende gneisses have been

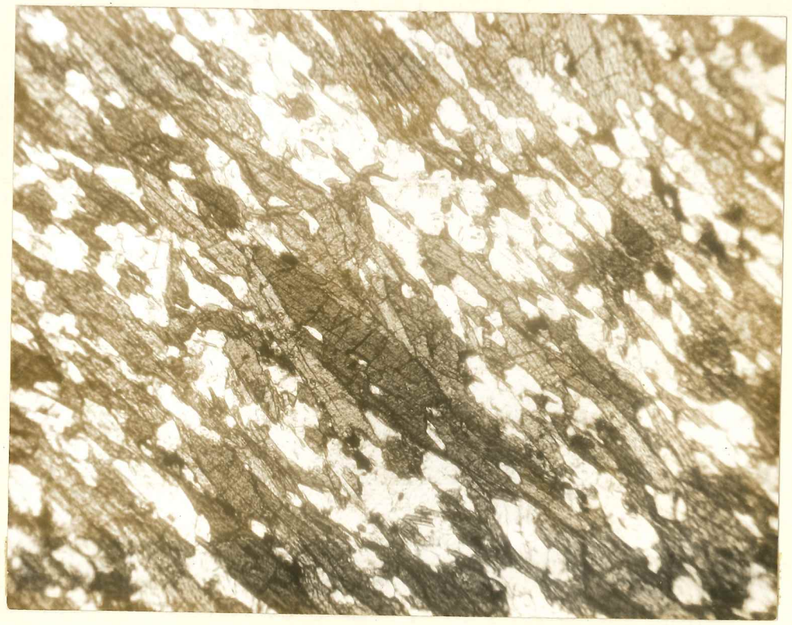
Fig. 32

Plane light. 40X. Ortho-amphibolite, brown hornblende and calcic andesine. Hornblende gneiss unit.

Fig. 33

Plane light. 40X. Ortho-amphibolite, green hornblende and sodic andesine. Helena Ridge crystallines.





strongly affected by retrogressive saussuritization and sericitization of the plagioclase. Iron ores and apatite are constant accessories in the hornblende gneisses. Zircon was observed in several of the gneisses, and secondary sphene is not uncommon in these rocks.

The occurrence of sodic andesine in the hornblende gneisses indicates crystallization at temperatures of either the kyanite zone or the high grade zone.

The pronounced contrast in the mineral composition of the hornblende gneisses and their parent amphibolites indicates a considerable metasomatic change in chemical composition. The mineralogical changes effected by the metasomatism are an increase in plagioclase (62% in the hornblende gneisses; 48% in the isochemical amphibolites), decrease in hornblende (8%; 49%), the appearance of quartz (22%) and biotite (7%), and the formation of a more sodic plagioclase (An_{34}; An_{45}). The increased amount and the more sodic composition of the plagioclase of the hornblende gneisses indicates a relative increase and probable introduction of sodium, though not of calcium, since the plagioclase of the hornblende gneisses is more sodic than the original plagioclase of the amphibolites and since calcium would be available from the elimination of hornblende anyway. The appearance of quartz indicates a relative increase and probable introduction of silica. The formation of biotite by biotization of hornblende indicates introduction of minor potassium. The great reduction in the amount of hornblende shows a relative decrease and probable removal of iron, magnesium, and possibly to a small extent calcium. The quartz dioritic hornblende gneisses of the hornblende gneiss unit show a much greater uniformity in texture and mineral composition than any of the metasomatic gneisses of the heterogeneous gneiss unit. This is thought to be a reflection of the uniform character of the original amphibolites, as a result of which a

persistent and rather uniform physical and metasomatic environment was able to develop a uniform product in contrast to the heterogeneous unit in which a similar metasomatism was unable to eliminate in any marked degree the heterogeneity of the original material.

Structure and Metamorphism

Structure

The general structural trend of the higher grade metamorphic rocks is N 40° W. This trend appears to be reliable even though it was established chiefly on the attitude of the schistosity, since the dips are generally steep and the foliation is parallel to the bedding where this could be determined, and since this trend accords with the axial trend of those minor folds observed and such b lineation as was observed. Both the isochemical metamorphic rocks and the metasomatic gneisses have participated in the same deformational history and minor folds in both rock types are frequently encountered in the field. The biotite schists and paragneisses of the heterogeneous gneiss unit, in particular, often show a very tight minor folding and crumpling of the schistosity; this is well displayed on the ridge between Red Mtn. and Black Mtn., and on the eastern part of "Lost Creek Ridge" where these folds plunge about 35° to the northwest. The great majority of the attitudes measured show very steep northeastward dips. Only in the area of Sloan and Bedal Pks. do the dips become more gentle. Such minor folds as were observed tend to be approximately upright, or to be slightly overturned to the southwest, although minor folds showing overturning to the northeast are not unknown. The distribution of the larger stratigraphic units does not reveal any major repetition by folding; however, local thickening and repetition by

minor folding are certainly important within these larger units, and especially within the heterogeneous gneiss unit. The present structural data suggest that the hornblende gneiss unit and the heterogeneous gneiss unit are distinct major stratigraphic units in concordant sequence. Whether their steep northeasterly dip is normal or overturned could not be definitely determined in the present area.

Evidence for Granitization

Several lines of evidence show that the trondhjemitic and quartz dioritic gneisses, and the gneissose diorites, as well as some of the directionless aplites and pegmatites of the migmatite complex, have been derived in place from the isochemical metamorphic rocks by replacement. The clearest evidence for this origin is found on the scale of individual outcrops where every gradation, both mineralogical and textural, may be traced between specific isochemical rock types and the associated migmatitic derivatives; space relations indicate that there can have been no forceful intrusion of magma. The same mineralogical and textural gradations are revealed by petrographic study. These relations have been described in detail above. The metasomatic origin of the gneisses is further confirmed by mineralogical evidence, especially by the frequent occurrence in the gneisses of relict metamorphic minerals (e.g., garnet, kyanite, main assemblage epidote, hornblende, accessory minerals, etc.) identical to the minerals in the associated isochemical rocks. The isochemical metamorphic rocks and the quartz dioritic gneisses are part of a single concordant structural unit which may be traced without interruption across the entire area of the migmatite complex. The original stratigraphy may likewise be continuously and uniterruptedly followed across the area, despite the fact that about 80% of the metamorphic complex consists of

quartz dioritic gneisses. Clearly the original stratigraphy could not be preserved intact under the forceful introduction of such huge volumes of granitic magma. The steeply dipping Circle Pk. marble, for instance, which is only about 300 feet thick and is in contact on both sides with very thick migmatitic gneisses, has been followed undisturbed for over five miles; this ribbonlike septum would clearly have been broken up if the adjacent granitic rocks had been intruded. It might be argued that the granitic gneisses are orthogneisses, intruded first as magmatic sills before or during the metamorphism of the original geosynclinal sediments and basic volcanics, and subsequently metamorphosed to orthogneisses. However, this does not account for the intergradation of the isochemical metamorphic rocks and the granitic gneisses, or for their space relations--on the scale of individual outcrops and also over the entire area--which exclude the possibility of the bodily injection of any large volumes of material, and most of all it ignores the constant association of specific types of gneisses with specific isochemical rocks. For instance, only quartz dioritic hornblende gneisses are found in migmatitic association with the isochemical and metasomatically altered amphibolites, only trondhjemitic biotite gneisses are found in association with the biotite schists and paragneisses, and only gneissose hornblende diorites and related rocks are found in association with the hornblendites. These associations are repeated without exception over and over in the area. Clearly a magma cannot be expected to seek out and intrude exactly those country rocks which it most closely approximates in chemical composition. The extreme mineralogical and textural heterogeneity of the migmatitic gneisses, especially in the heterogeneous gneiss unit is in itself an additional argument for granitization, for neither multiple intrusion nor differentiation in place appears capable of producing such varied contrasts in lithology. It

must be concluded that the migmatitic gneisses have formed by the metasomatic replacement in situ of the isochemical metamorphic rocks. Similar relations indicate that many of the small directionless aplitic and pegmatitic bodies have likewise formed by metasomatic replacement, although some of them appear to have become mobilized (dilation dikes), these rocks are for the most part later than the gneisses and have formed under static rather than synkinematic conditions.

Metamorphic Grade

In most cases no precise assignment of metamorphic grade could be given the present metamorphic rocks. However, from the general occurrence of plagioclase as calcic or more calcic than calcic oligoclase, it is clear that most of these rocks have formed at temperatures of either the kyanite zone or the high grade zone. Definitely belonging to the kyanite zone are the biotite schists, paragneisses, and metasomatic gneisses containing kyanite, the marbles and lime-silicate rocks with the association diopside-calcite-quartz-sodic andesine-zoisite (epidote), and those schists, gneisses, and amphibolites containing plagioclase of any composition from calcic oligoclase to calcic andesine associated with contemporaneous epidote. The only definite high grade rocks are those amphibolites with an average plagioclase composition as calcic as or more calcic than sodic labradorite. Indirect evidence indicates that the marbles and lime-silicate rocks of the Circle Pk. unit were all at one time crystallized in the high grade zone. And it is further probable that many, if not all, of the isochemical rocks and perhaps some of the metasomatic rocks which are immediately associated with the Circle Pk. marble were, like the Circle Pk. marble, once crystallized in the high grade zone. Two rocks can be shown to have crystallized in the cooler part of the medium

grade zone; these are two trondhjemitic biotite gneisses in which sodic oligoclase is associated with contemporaneous epidote. In the migmatite complex rocks of like metamorphic grade are not spatially distributed in such a manner as to indicate zones of progressive regional metamorphism; instead, they are irregularly and unsystematically scattered so that rocks of different metamorphic grade often occur very close together. This relation, together with the evidence that the Circle Pk. marble and probably other rocks, were first crystallized under one and later under a different set of physical conditions indicates a marked physical disequilibrium within the migmatite complex. In general it appears that crystallization at higher temperatures has been followed by recrystallization of many but not all of these rocks in response to lower temperatures. There appears to be a parallel between this and the phase of metasomatic metamorphism which is, in general, later than the isochemical metamorphism, since the metasomatic rocks are younger than the isochemical rocks which they replace. Even among various closely associated metasomatic rocks there is no uniformity in metamorphic grade, and hence no physical equilibrium, for in various metasomatic gneisses contemporaneous epidote is associated with plagioclase ranging from An_{12} and An_{34} in composition. Metasomatism, thus, appears to have operated through a considerable range of temperature (probably of progressively decreasing temperature). In spite of this general lack of physical equilibrium in the migmatite complex, equilibrium has at least locally been attained, especially in the Circle Pk. marble which shows the uniform association zoisite (epidote) and unzoned sodic oligoclase (An_{32}) throughout its entire outcrop belt. Why equilibrium has been reached here and not in the associated gneisses is not clear.

Nature of the Metasomatism

The following table shows in a very rough qualitative manner the chemical changes brought about by the metasomatism in each of the several isochemical rock types. The metasomatic changes represented here are based on the assumption that the metasomatism has proceeded without significant change in volume. This assumption appears to be justified by observation of the small number of outcrops where the volume relations could be established. Some exceptions, especially slight increase in volume, have been noted, however, and the assumption must remain provisional until fuller data are available from this area.

Original Rock	Silica	Na	K	Ca	Al	Fe	Mg	Metasomatic Equivalent
Heterogeneous Gneiss Unit								
Biotite Schist and Biotite Paragneiss		//	-	/		--	--	Trondhjemitic Biotite Gneiss
Hornblende-Biotite Paragneiss	//			-	-	--	--	Trondhjemitic Hornblende-Biotite Gneiss
Amphibolite	/	//	/			--	--	Metasomatically Altered Amphibolite
Amphibolite		//	//	/		--	--	Quartz Dioritic Hornblende Gneiss
Hornblendite	/	//	/			--	--	Hornblende Diorite
Hornblende Gneiss Unit								
Amphibolite	/	//	/			--	--	Metasomatically Altered Amphibolite
Amphibolite		//	//	/		--	--	Quartz Dioritic Hornblende Gneiss

// significant introduction
/ minor introduction
no significant change
- minor removal
-- significant removal

Although the metasomatism shows certain common features, which affect all the rock types, there is nevertheless a distinct over-all difference in its character for each individual rock type. Pronounced removal of iron and magnesium is characteristic of all the rocks, and major introduction of sodium is nearly as prevalent. Major introduction of silica has affected all the amphibolites and hornblende-biotite paragneisses, but not the biotite schists and paragneisses. Rather minor introduction of potassium, finding its mineralogical expression in the biotization of hornblende, is common except in the biotite schists and paragneisses where there is actual removal of potassium. In none of the rocks do calcium or aluminum show any conspicuous change in amount. Late, static metasomatism, insofar as this has been operative, does not differ in character from the synkinematic metasomatism which it generally follows. For a given rock type the kind of metasomatism is usually constant. The single exception is the amphibolites which may either be metasomatically altered to amphibolite richer in plagioclase and poorer in hornblende or may pass directly into quartz dioritic hornblende gneiss. Inasmuch as the first change may or may not precede the second, the character of the metasomatism as it affects the amphibolites appears to have varied both in space and time. The general uniform character of the metasomatism as it affects specific rocks even in widely separated areas suggests a uniform composition for the metasomatizing agent. The differential character of the metasomatism of the various rock types suggests that each rock type was able to satisfy its particular chemical requirements by selective precipitation of certain elements from the metasomatizing agent.

The Zoned Plagioclase

Zoned plagioclase is conspicuous in most of the higher grade metamorphic rocks, the metasomatic gneisses as well as the isochemical schists and amphibolites. Considerable attention was given to the zoning, since it records a number of features of metamorphic evolution important in the genetic interpretation of the rocks. One objective of the study was to compare both the composition of the plagioclase and the kind and range of zoning of the plagioclase of the various isochemical rocks to those of the related metasomatic gneisses. A comparison of the average composition of the plagioclase between related isochemical and metasomatic rocks would show some of the chemical changes brought about during granitization, and a systematic relationship of the range and kind of zoning between these two might provide supporting evidence for the metasomatic origin of the gneisses. The zoning is of further interest in that, apart from a forthcoming important contribution by Misch (Misch, 1954), little systematic study has been made of zoned plagioclase in metamorphic rocks; the literature contains many contradictory statements as to the occurrence and nature of zoned plagioclase in metamorphic rocks and several writers even maintain that zoned plagioclase is absent or at least uncommon in metamorphic rocks. The procedure was to determine the composition, and the kind and range of zoning in several, where possible 4 to 6, favorably oriented plagioclase grains in each rock. It was necessary to examine several grains, for the kind and range of zoning was commonly found to vary in the same rock. Thin sections of 107 metamorphic rocks containing plagioclase were examined. While obviously no sweeping pronouncements can be made on the basis of so few rocks, a number of generalizations based on trends in the kind and range of zoning of the plagioclase can be made for the

different rock types. Thin sections of 52 plagioclase-bearing isochemical metamorphic rocks, including biotite schists and paragneisses, lime-silicate rocks and marbles, and amphibolites were examined; all but 10 of these (7 of which were lime-silicate rocks and marbles) contain zoned plagioclase. Zoned plagioclase was determined in all but 5 of the 55 thin sections of metasomatic gneisses studied.

Almost all the plagioclase-bearing rocks studied contain both zoned and unzoned plagioclase crystals, or crystals showing different kinds of zoning. In one biotite schist, for instance, 6 individual crystals were determined, of which 3 show normal zoning, 1 shows reverse zoning, 1 oscillatory zoning with one recurrence, and 1 no zoning. Even in those rocks in which all the crystals have the same kind of zoning, the range in composition of the individual zoned crystals often varies widely. The zonal range in composition of the plagioclase in each rock and the kind of zoning determined for individual crystals in each rock has already been given in the description of the individual rock types. In characterizing the zoning of those rocks containing plagioclase grains which show different kinds of zoning, the most complex zoning observed was taken. Thus a rock showing both unzoned and reverse zoned crystals is considered to have reverse zoning, a rock with unzoned, normally zoned and reversely zoned crystals is considered to have oscillatory zoning with one recurrence (implied by the occurrence of both normal and reverse zoning), and a rock with unzoned, normally zoned, and oscillatory zoned crystals is considered to have oscillatory zoning. At least some unzoned crystals are present in most of the rocks containing zoned plagioclase, even in those in which most of the crystals are zoned; the number of unzoned crystals determined was not indicated on the above charts. The tabulation on the following page, summarized from the more detailed tabulations

	u	s	n	r	o
Heterogeneous Gneiss Unit					
Biotite Schist and Paragneiss	2	5	4	6	7
4% An An_{29}	-	5	14	14	5
Hornblende-Biotite Paragneiss	-	1	-	-	4
6% An An_{28}	-	1	-	7	5
Lime-Silicate Rocks and Marbles	7	-	-	-	-
0% An An_{32}	-	-	-	-	-
Diopside-Rich Quartz Dioritic Gneisses	-	-	1	-	2
12% An An_{32}	-	-	3	2	4
Amphibolite	1	-	1	5	4
13% An An_{45}	-	-	11	15	4
Hornblende Gneiss Unit					
Amphibolite	-	-	1	-	1
13% An An_{45}	-	-	4	-	1
Number of rocks with each kind of zoning	10	6	8	13	20
Number of each kind of zoned crystals	-	6	35	40	23

	u	s	n	r	o
Trondhjemitic Biotite Gneiss	3	1	3	4	10
5% An An_{27}	-	1	13	21	9
Trondhjemitic Hornblende-Biotite Gneiss	2	-	-	-	6
4% An An_{31}	-	-	3	6	6
Metasomatically Altered Amphibolite	-	-	-	-	7
10% An An_{36}	-	-	11	7	11
Quartz Dioritic Hornblende Gneiss	-	-	3	4	5
7% An An_{33}	-	-	12	20	4
Metasomatically Altered Amphibolite	-	-	2	1	-
9% An An_{34}	-	-	5	1	-
Quartz Dioritic Hornblende Gneiss	-	-	1	-	3
11% An An_{34}	-	-	8	1	6
	5	1	8	9	29
	-	1	49	54	32

u unzoned (number of unzoned crystals not given)
s simple zoning (either normal or reverse, trend undetermined)
n normal zoning
r reverse zoning
o oscillatory zoning

accompanying the description of the individual rock types above, shows the number of rocks with each kind of zoning for each of the major rock types (the upper row of numbers) and the total number of crystals showing each kind of

zoning determined (the lower row of numbers). The number of unzoned crystals determined is not given. Also shown in the tabulation are the average zonal range in composition and the average composition of the plagioclase for each rock type. Each of the metasomatic rocks is arranged in a column opposite its parent isochemical rock in order to permit comparison of the type of zoning and average plagioclase composition.

The principal characteristics of the plagioclase zoning in these metamorphic rocks are summarized here. This general summary is based in part on data already given in the description of individual rock types and in part on the above tabulation.

1. The zoning tends to be of rather simple character. Normal zoning, reverse zoning and oscillatory zoning with one recurrence are characteristic. Of the 92 rocks containing zoned plagioclase examined, only 5 rocks showed oscillatory zoning with two recurrences and only one showed oscillatory zoning with three recurrences. Only in the quartz dioritic hornblende gneisses of the hornblende gneiss unit is oscillatory zoning with more than one recurrence typical. The zoning of the metasomatic rocks tends on the average to be slightly more complex than that of the isochemical rocks, however, this difference is neither marked nor systematic.

2. Both the external form of the plagioclase and the internal form, as represented by the zoning, are typically anhedral. This applies to both the isochemical and metasomatic rocks. There is commonly little parallelism between the form of the outer boundary of a plagioclase crystal and the inner zone or zones. Adjacent zones, however, tend to be more nearly parallel than are more widely separated zones, and going out from the core of a crystal the successive zones become gradually more and more conformable with the rim of the crystal. Not infrequently the anhedral "core" of a plagioclase grain is

marginally rather than centrally located. This in some cases is due to truncation of one side of a plagioclase grain resulting from replacement, but in others seems merely to indicate asymmetric growth. The quartz-dioritic hornblende gneisses of the hornblende gneiss unit with their characteristic euhedral zoning are the only rocks which do not show anhedral zoning.

3. The sharpness of the transitions between adjacent zones varies considerably not only between different rocks but between different crystals in the same rock and even between different zones in the same crystal. The transitions may be abrupt or may be very slowly gradational.

4. Different plagioclase crystals in the same rock characteristically show different kinds of zoning and a variable zonal range in composition, and generally both zoned and unzoned crystals occur.

5. The zonal range in composition of the plagioclase is usually small and tends to be uniform for rocks of a given type. Those rock types with a more calcic average plagioclase composition show the widest zonal range in composition, and those with a more sodic average plagioclase composition show a smaller zonal range in composition. In keeping with this tendency the metasomatic rocks, which in general contain a plagioclase more sodic than that of their isochemical parent rocks, show a smaller zonal range in composition than their associated parent rocks.

The general anhedral character of the zoning would appear to be the kind of crystal growth expected in a solid medium where the growth of each crystal is influenced by the resistance offered by its neighbors. The less typical euhedral zoning displayed by the hornblende gneisses of the hornblende gneiss unit is also considered to be crystalloblastic, inasmuch as euhedral zoning has been documented in some rocks of clearly metamorphic origin (Misch, personal communication). The diversity in the kind and range of zoning shown

by different crystals in the same thin section in part reflects the fact that not all the crystals have been cut through the center, and thus do not exhibit the full range in zoning, but to a much greater extent is believed to be only an expression of the duration of the period of crystal growth. If conditions in a given time interval are such as to favor the crystallization of oscillatory zoned plagioclase with one recurrence, only those crystals which grew continuously during the entire time interval will show the full oscillation. Those crystals which have grown during only part of the time interval may show only normal or reverse zoning, or even no zoning if the time of their growth was very short. The size of the different crystals also appears to reflect varying resistance to growth. The even-grained isochemical metamorphics, for instance, commonly contain zoned and unzoned crystals of the same grain size. The unzoned crystals clearly must have experienced conditions favorable to rapid growth, while the zoned crystals grew more slowly but for a longer time.

Misch (1953) has discussed the two principal controls in the development of zoned plagioclase. One is physical, chiefly temperature, and is based on the long-recognized fact that with progressively higher metamorphic grade an increasingly more calcic plagioclase becomes stable. Any rock containing plagioclase and potential anorthite in the form of anorthite-substitute-minerals (e.g., epidote, zoisite, scapolite, etc.) may under favorable conditions develop zoned plagioclase in response to rising temperature. In other rocks anorthite-substitute minerals plus more sodic plagioclase may form by breakdown of more calcic plagioclase in response to lower temperature. When this has occurred temperature-controlled zoned plagioclase may again form under favorable conditions. The other control is chemical. Here the presence of those particular constituents needed to form a certain zone of a zoned

plagioclase crystal is in part due to metasomatic addition and/or removal of certain chemical substances. A combination of these controls may of course also produce zoned plagioclase. The zoning in most of the present rocks does not appear to be temperature-controlled. This is indicated by the general absence of contemporaneous anorthite-substitute-minerals in the rocks. Anorthite-substitute-minerals are conspicuous only in the lime-silicate rocks and marbles, and in these rocks zoned plagioclase is lacking. Temperature control may be definitely excluded for those rocks containing normally zoned plagioclase or oscillatory zoned plagioclase in which the outer zone is more sodic than the penultimate zone; further, a temperature control is exceedingly improbable for reversely zoned plagioclase, and for oscillatory zoned plagioclase in which the outer zone is more calcic than the penultimate zone, for it is unlikely that the last bit of anorthite-substitute-mineral should, in so many cases, have been exactly consumed at the last instant of plagioclase crystallization. Only in those few rocks which contain minor anorthite-substitute-minerals can temperature control have participated in the development of the zoned plagioclase.

Since temperature changes have not controlled the development of the zoned plagioclase, the control must have been chemical. This chemical control has probably been to some extent modified in those rocks in which potential anorthite was available. In a number of rocks, for instance, hornblende has been biotized without the formation of epidote. In these anorthite may be assumed to have been directly released and to have immediately entered into the plagioclase crystallizing at the moment of release. Chemical control of zoning implies a relative change in the amount of calcium and sodium, and to a lesser extent aluminum, silica, and perhaps other substances in the active intergranular solution operating at any given time, with or without an

absolute change in the chemical bulk composition of the rock as a whole. In most cases the compositional changes in the intergranular solution required to produce the zoning need not have been large, and any associated changes in bulk composition may have been very slight. The balance of materials which might have been added and/or removed during growth of zoned plagioclase cannot be evaluated here; most probably, however, both addition and removal rather than addition or removal alone were involved. Growth of zoned plagioclase, like all crystalloblastic growth, involves continuous recrystallization in which less favored grains are broken down and the material set free is removed or more often used, sometimes in combination with newly added material, in the growth of newly crystallizing grains.

The close similarity in the character of zoning of the isochemical and metasomatic rocks clearly indicates crystallization under closely comparable environmental conditions and thus strongly supports the metamorphic origin of the quartz dioritic and trondhjemitic gneisses. Only the hornblende gneisses of the hornblende gneiss unit consistently show zoning of a character different than that of their parent rocks. Since the metasomatic gneisses are seen in many cases to have replaced the associated isochemical rocks, it may be asked whether the isochemical rocks have actively crystallized at the time of crystallization of the metasomatic gneisses or have remained inert during this time. This question cannot be answered with certainty on the basis of the present data. Identity of the plagioclase zoning in the isochemical and metasomatic rocks might suggest their simultaneous crystallization, however, this identity could equally well be explained by crystallization of the two rock types at different times under a changing physical-chemical environment fluctuating regularly between uniform limits. Only a detailed comparative study of the kind of zoning and the metamorphic grade of associated isochemical and

metasomatic rocks at a number of individual outcrops can provide the final answer.

The zoned character of the plagioclase clearly indicates that none of these rocks is in equilibrium. The occurrence of zoned plagioclase is perhaps somewhat surprising in view of the fact that most of these rocks, especially some of the biotite schists and amphibolites, are very sharply schistose and have experienced very intense penetrative deformation, for strong differential movement might be expected to promote crystallization of a uniform plagioclase. There appear to be two possible explanations for the preservation of the zoned plagioclase. One is that the zoned plagioclase crystallized after the end of the more intense penetrative deformation. The other is that the zoned plagioclase crystallized during the time of penetrative deformation but that the zoning was preserved because the differential movement in the rock was taken up chiefly by minerals other than the plagioclase. The preservation of zoned plagioclase would appear to indicate that ionic diffusion was not operative during the crystallization of these rocks.

The Helena Ridge Crystallines

On and near the summit of Helena Ridge (the 4500 foot ridge between Helena and Murphy Creeks), some eight miles west of the Straight Creek fault, is an area of about one square mile of medium grade metamorphic rocks comprising both amphibolite and hornblende gneiss. In lithology and metamorphic grade these rocks closely resemble the hornblende gneiss unit to the east. Further work will be required to clarify entirely the structural position of these rocks. On the south and west the crystallines are in contact with younger intrusive serpentinite and peridotite. Near this contact and within the serpentinite a single narrow zone of strongly sheared and mylonitized

diabase occurs. The relation of the crystallines to the Swauk formation occurring west of the peridotite is not known. On the east in Murphy Creek the crystallines are unconformably overlain by presumably tertiary conglomerates which may or may not be equivalent to the Swauk on the west. The relation of the Helena Ridge crystallines to the Gold Hill phyllite on the north end of Helena Ridge and in lower Murphy Creek is concealed in heavy timber and has so far not been definitely determined. The crystallines might conceivably be a block of higher grade metamorphics upfaulted through the Gold Hill phyllite, but are much more probably an erosive remnant of a large thrust sheet overlying the phyllite. The emplacement of these rocks may possibly even have involved the Swauk; if this is the case, then the conglomerates which rest unconformably on the crystallines in Murphy Creek are probably younger than the Swauk. Although the evidence is far from conclusive, the thrust hypothesis is favored over that of upfaulting. This is suggested by the occurrence of remnant klippen of medium grade metamorphic rocks nearly identical to the present rocks and belonging to part of a regionally extensive thrust sheet at several localities, both north and south of the present area (Misch, personal communication, and Yeats, unpublished Masters Thesis, 1956). The strongly sheared diabases occurring within the serpentinite could have been deformed during this thrusting, and the ultrabasic intrusions might be related to the thrusting. Toward the northern end of the ridge between Murphy Creek and Goodman Creek is a zone of mylonitic sedimentary and fine-grained basic igneous rocks which exceeds 1000 feet in thickness and is parallel in its attitude to the metamorphics on Helena Ridge and could well be related to such an overthrust. Near the base of this mylonite zone, just above the underlying Gold Hill phyllite, is what appears to be a tectonic slice of arkose, closely resembling arkoses of the Swauk formation several miles to the west; if these

rocks are indeed Swauk, thrusting would appear to be post-Swauk.

Amphibolites are the dominant rock type in the area of crystallines making up the northwestern part of the area, while hornblende gneisses comprise the southeastern part. The amphibolites show a very constant attitude throughout their outcrop area with an average strike of about N 40° E and an average dip of about 35° to the southeast. The amphibolites are fine-grained, rather uniform, greenish-black to black rocks showing a sharp foliation. Occasionally they exhibit a fine segregation banding of light colored, plagioclase-rich layers up to a few mm in thickness alternating with thicker dark hornblende-rich layers. The average estimated mode of five of these amphibolites is:

Hornblende	45%	(36-50%)
Plagioclase	53%	(49-61%)
Ores	1%	(0- 2%)

The hornblende is a green variety forming narrow elongate prisms which show a considerable size-variation in a single thin section. The hornblende is sharply oriented parallel to the foliation and generally also shows a marked linear parallelism. The irregular anhedra of even-grained plagioclase occupy the spaces between the hornblende grains, but some of the smaller hornblende crystals may be included in the plagioclase.

The hornblende is a green variety showing rather uniform optical properties in all the rocks studied. The extinction angle and pleochroism of the hornblendes of five of the amphibolites are given here. The intensity of absorption is generally moderate with X<Y=Z.

Spec. No.	Z:c	X	Y	Z
177	16°	yellowish	grass green	bluish-green
178	15°	pale greenish-yellow	bright grass green	bluish-green
179	15°	yellowish	grass green	grayish-green
180	16°	greenish-yellow	dark green	dark bluish-green
181	16°	greenish-yellow	grass green	green (faintly bluish)

The plagioclase of the rocks studied is rather sodic, being generally oligoclase-andesine or sodic andesine. The plagioclase is typically either unzoned or shows only very weak simple zoning. In one amphibolite normally zoned plagioclase with a zonal range in composition of about 6% An was determined. In another amphibolite plagioclase with simple zoning and an undetermined trend was observed. Most of the amphibolites contain accessory ores. Apatite was determined in two of the amphibolites and sphene in a third.

In several of the amphibolites plagioclase shows incipient alteration to fine-grained sericite. In one amphibolite the hornblende has in part been altered to a green chlorite with negative elongation and anomalous blue interference colors. In another rock some of the hornblende has altered to a colorless amphibole which shows higher interference colors than the hornblende.

The mineral composition of the amphibolites and their uniformity point to their derivation from igneous rocks of basic to intermediate composition. The mineralogy of the amphibolites affords no clear basis for determination of their metamorphic grade. They could belong either to the medium or high grade zone. The plagioclase of the amphibolites is relatively sodic; however, this is not critical, since no anorthite substitutes are present. The presence of green rather than brownish hornblende, however, points perhaps to the medium grade zone. It may be pointed out that the present amphibolites differ from chemically comparable amphibolites in the hornblende gneiss and heterogeneous gneiss units in several respects. They do not contain garnet, they have a more sodic plagioclase (An_{35} vs. An_{45}), and they contain different varieties of hornblende (green hornblende in elongate prisms vs. brownish hornblende in stubby prisms). These differences may reflect differences in metamorphic grade, inasmuch as the amphibolites occurring in the migmatite area to the east are known to belong, at least in part, to the high grade zone.

Hornblende gneiss is exposed in the southeastern part of the area of the Helena Ridge crystallines. They occur through only a very limited interval on the crest of the ridge but are found more abundantly on the east side of the ridge above Murphy Creek. Although the nature of the contact between the amphibolites and hornblende gneisses is not known, it appears to be fairly sharp and may possibly be tectonic as no migmatitic intergradations between the two rocks were observed.

The hornblende gneisses are coarsely schistose, quartz dioritic rocks which in their over-all appearance are strikingly similar to the gneisses of the hornblende gneiss unit but differ in the character of some of their minerals. The hornblende is uneven-grained, anhedral in form, and shows a rough orientation parallel to the schistosity; some of the larger crystals approach the larger plagioclases in size. The plagioclase is uneven-grained with large, roughly lath-shaped grains with irregular margins predominating. The plagioclase shows euhedral zoning which is often truncated at the grain boundaries. Smaller irregularly interlocking grains of plagioclase, quartz, and hornblende fill in between the larger hornblende and plagioclase grains. Although inclusions are not abundant in any of the minerals, the hornblende sometimes contains a few small inclusions of any of the other minerals. The average estimated mineral composition of two of the hornblende gneisses is: plagioclase 59%, hornblende 21%, quartz 17%, biotite 1%, chlorite 1%, iron ores 1%, and epidote 1%. The plagioclase typically shows euhedral oscillatory zoning. Plagioclase with as many as two recurrences was observed in one gneiss and plagioclase with as many as four recurrences in another. The transition between adjacent zones is partly quite rapid and partly slowly gradational. The range in composition of the plagioclase in two of these hornblende gneisses is:

OLDER SEDIMENTARY AND VOLCANIC ROCKS

Introduction

Three units of unmetamorphosed or only weakly metamorphosed pre-Tertiary sedimentary and volcanic rocks may be distinguished in the area. These rocks extend over 20 miles across the area in an east-west direction. These units have, in common, been very strongly deformed, with the development of tight folds. They have, however, been only very weakly metamorphosed, and recrystallization is for the most part confined to the finer-grained sediments in which slaty cleavage has developed. There is no perceptible variation in metamorphic grade within these rocks either along or across the strike. Neither the age of these units nor their mutual relations are entirely clear. The easternmost unit, here termed the window unit, consists almost entirely of sediments, among which slates and argillites are most prominent, although considerable limestone, arkose, and pebble conglomerate also occur. Volcanics were observed only locally. This unit is exposed in two windows beneath the Whitechuck overthrust, the upper plate of which consists of Gold Hill phyllite and Shuksan greenschists. The lithology of the window unit, together with the occasional occurrence of large crinoid stems, suggest a correlation with rocks of the upper Paleozoic (and at least in part lower Permian) Chilliwack series to the north. The Chilliwack series was first described by Daly (1910) on the Canadian side of the international boundary, and named after the Chilliwack Valley; more recently this formation has been mapped by Misch (1952 and oral communication) between the boundary and the Skagit Valley to the south. The window unit is separated from the other two pre-Tertiary units by Gold Hill phyllite of the upper plate and by a belt of Tertiary sedimentary and volcanic

rocks. The southwestern part of the area is occupied by the Canyon Creek unit, comprising a thick series of slates and ribbon cherts. In the absence of fossils the age of the Canyon Creek unit is not definitely known, but, like the window unit, may be upper Paleozoic (Permian?). In the northwestern part of the area, on Whitehorse Mtn., is a series of andesitic volcanics with which limestones, argillites, and other sedimentary rocks are associated. The lithology of this Whitehorse unit indicates a pre-Tertiary and probably also a pre-upper Jurassic age (see below). The relations of the Canyon Creek and Whitehorse units are not, at present, known, but could possibly be determined in the Mt. Bullon area.

The Window Unit

General Description and Structural Position

The window unit is a predominantly sedimentary sequence consisting chiefly of slates and argillites showing gradation to limey argillites and limestones on the one hand and siltstone, arkose, and conglomerate on the other. Ribbon cherts were observed at several localities and andesitic volcanics were found at just two places. The rocks of this unit occur in small outcrops over a wide area, and it is nowhere possible to observe them in a single continuous section. Thus it is not at all certain that they constitute one conformable sequence, or that rocks of several different ages are not present. Since, however, these rocks occupy the same structural position, show the same uniformly low metamorphic grade, and differ little in degree of deformation, and since the same lithologies recur even at widely separated outcrops, there is some justification in treating them here as a single unit. In addition to the sedimentary rocks, altered intrusive basic igneous rocks

ranging from diabase to gabbro and locally to serpentinite and quartz diorite are abundant in parts of the window unit.

The window unit was named for its consistent structural position as the lower plate of the Whitechuck overthrust. This name is only provisional and should be changed as soon as definite correlation can be made with a more suitable type section outside the area. The rocks of the window unit are exposed in two partial windows separated by a narrow belt of upper plate rocks. One window centers around the area at the mouth of the Whitechuck River, rocks of the lower plate being exposed on the lower south side of Whitechuck Mtn., on the lower north and west sides of Mt. Pugh, and in just one outcrop west of the Sauk River. The other window occupies a narrow band extending across two of the western spurs of Whitechuck Mtn. and north across the long ridge of Prairie Mtn. to the lower Suiattle River. The Whitechuck overthrust is a low angle thrust which truncates structures of both the upper and lower plates so that different rock types are found in contact at different places along the thrust. Upper plate phyllites of Gold Hill type are usually found at the contact, but it is clear from their considerable variation in thickness that they have themselves been truncated. In the western part of the area the phyllites at the thrust all belong to the Gold Hill unit, whereas some of the phyllites just above the thrust farther east may be intercalations in the Shuksan greenschist. The upper plate is thus truncated so that the Gold Hill phyllite overlies the thrust on the west and the Shuksan greenschist overlies it on the east. Where thick phyllites form the upper plate, tectonic wedges and slices of lower plate rocks varying from a few tens of feet to several hundred feet in thickness are commonly observed in the upper plate, generally in the first 1000 to 1500 feet above the thrust. Only one of these slices, the large one on the south side of Whitechuck Mtn., is

shown on the map. The occurrence of these tectonic slices testifies to the ease with which the phyllites yielded during thrusting. The consistent occurrence of phyllite at the thrust plane, even below the Shuksan greenschist, suggests, in fact, that these phyllites were dragged along the thrust plane as a lubricant, and the general absence of mylonites at the thrust reflects the ability of the phyllites to absorb the brunt of the differential movement resulting from the thrusting. The thrust relationship between the window unit and the Gold Hill and Shuksan units of the upper plate is believed to be consistent throughout the area, although this structure has to some extent been modified by later high angle faulting and weak folding. Three high angle faults cutting the thrust were mapped or inferred on the south side of Whitechuck Mtn., and others are doubtless present but could not be definitely established due to poor exposures and insufficient field data. On the east the Whitechuck overthrust is cut off by a much bigger high angle fault, the Straight Creek fault. The Canyon Creek and Whitehorse units on the west display the same metamorphic grade and deformational history as the window unit farther east and are believed to occupy the same structural position, belonging in the lower plate. Unfortunately these western units are nowhere in contact with the Gold Hill phyllite of the upper plate from which they are separated by a belt of Tertiary sedimentary and volcanic rocks. West of this belt of Tertiary rocks and west of the Tertiary Squire Creek quartz diorite, rocks of the upper plate do not reappear. There thus appears to be an important structural line, either a fault or a flexure, with the western block structurally higher, running somewhere through the belt of Tertiary rocks. If the upper plate of phyllite and greenschist is considered to be a single thrust mass completely isolated from its roots, as appears very probable, horizontal movement on the thrust plane must have exceeded nine miles in the

area. In any case a minimum of four miles horizontal movement on the thrust is clearly seen in the window at the mouth of the Whitechuck River.

Sedimentary Rocks

Argillites and slates are the most abundant rocks in the window unit. They are dark brown to black in color and often show a fine lamination marked by very thin lighter-colored silty layers. Most of these rocks possess some degree of slaty cleavage. In many cases this cleavage is parallel to the bedding, in others it cuts the bedding at an angle. A very few outcrops were observed in which the slaty cleavage had itself been folded with the incipient development of a second cleavage. Clastic grains of quartz, and generally also plagioclase are clearly visible in thin section and recrystallization is confined to the formation of some fine-grained sericite. Small amounts of carbonate are present in some of the slates. Since slates are the most prominent rocks in the lower plate, a brief summary of the criteria by which they may be distinguished from phyllites of the upper plate is presented here. 1. The phyllites appear lustrous and glossy reflecting relatively complete and coarse recrystallization of the original sediments. The slates have a duller appearance and are never fully crystallized, as clastic silt grains are visible in almost all thin sections. 2. Segregation veinlets and lenticles of milky vein quartz are conspicuous in many of the phyllites, but are absent in the slates. 3. Folded schistosity, either on a coarse scale or as a fine b-lineation, is typical of the phyllites but is uncommon in the slates. 4. The slates commonly show gradations to limestone or arkose and pebble conglomerate. The phyllite never grades into limestone and very rarely grades into sediments coarser than siltstone; when it does, these sediments are strongly folded and recrystallized. The association of slates with limestone, arkose,

conglomerate, ribbon chert, or nonmetamorphic volcanics, insofar as these are not in tectonic contact, clearly indicates lower plate slates. Association of phyllites with greenschist or blue amphibole schist indicates upper plate phyllites.

With increasing grain size the slates grade into siltstones, arkoses, and pebble conglomerates. In addition to quartz, most of these rocks have a high content of clastic plagioclase. Other constituents are detrital muscovite (in part recrystallized as sericite), biotite (partly chloritized), and epidote, and sometimes carbonate. The quartz and plagioclase characteristically form highly angular grains. The arkoses are megascopically identical to the Tertiary Swauk arkoses, apart from the presence of small quartz veinlets in the former. Distinction is not difficult in the field, however, for in the window unit the arkose beds and associated conglomerates seldom exceed 100 feet in thickness and show transitions to slate, limestone, and other rock types absent in the Tertiary arkoses. The conglomerates are not very coarse, the largest pebbles rarely exceeding two inches in their longest dimension. The commonest pebble types are light and dark gray chert pebbles, but pebbles of basic to intermediate and sometimes acidic volcanic rocks and granitic rocks are occasionally observed. A conglomerate of pea-sized andesite pebbles with a few limestone pebbles was observed on the Suiattle River road about one mile south of the Suiattle bridge. Some of these coarser-grained sediments have developed slaty cleavage, whereas others have not. This seems to indicate that the degree of penetrative deformation varied somewhat within the unit during its folding.

Limestone is abundant in the window unit, occurring most commonly as intercalations in the slates with which it intergrades. The limestone occurs as beds and lenses ranging from very small size to thicknesses of over 100

feet in a few cases. At least fifteen limestone bodies of moderate size were observed and many others are undoubtedly present. The locations of those noted are diagrammatically indicated on the map. Crinoidal limestone was noted at three localities; in the first outcrop on the Whitechuck River road about a mile and a half from its junction with the Sauk River road; at the end of a small logging road below and on the west side of the 3000 foot knob on the northwest ridge of Mt. Pugh; in the tributary of Dan Creek which flows west between the two northern of the three western spurs of the main ridge of Whitechuck Mtn., where the tributary is crossed by the upper of two logging roads. The crinoid stems are light in color in contrast to the dark gray limestone matrix. Many of the stems are quite large, some reaching as much as an inch and a quarter in diameter. These stems are very similar to large crinoid stems found in limestones of the Chilliwack series in the limestone quarry at Concrete some 30 miles to the north, as well as at several localities north of the Nooksack River (Misch, personal communication).

Ribbon cherts were observed at only a few scattered localities in the window unit. One locality is on a shelf at 3200 feet at the end of a logging road on the southwest side of Whitechuck Mtn., another is in the south branch of Stujack Creek just above the forks. Ribbon cherts were also observed as tectonic intercalations in the Gold Hill phyllite on the northwest ridge of Mt. Pugh. The cherts are dark gray and purplish-gray to almost black in color. Individual bands range from about one quarter inch to an inch in thickness, the thicker layers generally being more typical. Where primary depositional contacts were observed, the cherts appear to be associated with slates and thin limestone beds.

Andesitic Volcanics

Andesitic volcanic rocks were observed at just two localities in the window unit. One is at the Suiattle River bridge about 12 miles north of Darrington. The rocks here are believed to be volcanic, as they include breccias and amygdaloidal types. Although these andesites are nowhere nearly as extensive as the andesites of the Whitehorse unit, they recall the latter in that both pyroxene-rich directionless types and pyroxene-poor varieties with trachytic structure are represented. The plagioclase is medium andesine and the pyroxene augitic. The other outcrop of andesitic volcanics was found about two miles up the Whitechuck River road. The rock examined is a sheared tuff containing a considerable admixture of calcareous and argillaceous sedimentary material; broken but unaltered grains of pyroxene and plagioclase are preserved in a fine-grained, strongly sheared matrix. Fine-grained amygdaloidal basic igneous rocks are exposed on a logging road along the second and larger of two small lakes of the northern end of the north ridge of Prairie Mtn. No thin sections have been examined, however, and the volcanic origin of these rocks is not certain.

Intrusive Igneous Rocks

Igneous rocks, commonly sheared and altered, are widespread as small intrusive bodies in the sedimentary rocks of the window unit. Basic igneous rocks, including diabase and gabbro are the dominant types, but quartz diorite and ultrabasic rocks are also found. These intrusive rocks are most abundant in the northern part of the outcrop area of the window unit, especially north of the Whitechuck River, but occur locally farther south as well. The largest intrusion lying between upper Dan Creek and the north ridge of Whitechuck Mtn.

occupies several square miles. Only this one larger intrusion is indicated on the map, the others are either too small to show, or their exact form has not been determined. Another large intrusion is found on the summit ridge of Prairie Mtn., and other prominent bodies occur on the northern part of the north ridge of Prairie Mtn. The fact that most of these intrusive rocks are confined to the lower plate of the thrust, as well as their mechanical deformation strongly suggests their emplacement prior to thrusting. A few occurrences of these rocks were noted in the phyllites of the upper plate. However, all of these appear to be in the immediate vicinity of the thrust plane and can perhaps be interpreted as tectonic slices of the lower plate. A single exception is the large intrusive mass east of upper Dan Creek, the western contact of which appears to be intrusive into the Gold Hill phyllite. Most of the intrusives have been involved in strong shearing movement which can possibly be correlated with the time of thrusting. This is at least clear on the north ridge of Prairie Mtn. where diabases have been directly overridden by upper plate greenschists with the production of more than a hundred feet of mylonite. Between the mylonitized diabase and the overlying greenschist is a narrow (5 to 15-foot) tectonic slice of phyllite. These relations are very clearly exposed at the end of a logging road just beyond two small lakes on the northern part of the north ridge of Prairie Mtn.

Altered diabases are the most abundant type represented among these intrusives. With increasing grain size these rocks grade into gabbros which locally become quite prominent. The diabases are brownish or greenish finely granular rocks. Almost all these rocks are traversed by crude shear planes, and cataclastic features such as crushed and bent plagioclase and uralite are apparent in most thin sections. Only exceptionally, however, as in the mylonites, have sharply parallel sets of shear planes been developed. A

considerable degree of recrystallization has accompanied shearing in most of these rocks, and except in a few rocks the original diabasic texture has been lost. The original plagioclase, though somewhat altered, has survived recrystallization in several of the diabases and the pyroxene has escaped complete uralitization in just a few of the rocks examined. The pyroxene has generally been altered to an often fibrous, uraltitic amphibole. The amphibole is generally green hornblende or a pale actinolitic hornblende, but actinolite and even tremolite, and a brown hornblende are occasionally noted. The amphibole commonly shows an irregular zoning marked by patches with differing pleochroism. Variable amounts of pennine formed from the pyroxene may also be present. The alteration of the plagioclase has not followed the same course in all of these rocks. In some rocks the original plagioclase is only slightly altered, either by sericitization or by the development of dark turbid material. In others the plagioclase has been saussuritized with the formation of epidote or clinozoisite and clear albite. In still other rocks rich in epidote, the albite component of the original plagioclase appears to have disappeared entirely, some of it having perhaps been taken up by the newly formed amphibole. The mylonitic diabases observed on Prairie Mtn. are less strongly recrystallized though much more strongly deformed than the other diabases. The plagioclase in these mylonites, though intensely crushed and bent with the formation of mortar structure, shows only sericitization. The pyroxene, however, has been completely transformed to chlorite with sharp parallel structure. Quartz makes its appearance in some of these mylonites.

Small occurrences of quartz-bearing igneous rocks were noted at several localities. Most are quite leucocratic, containing in addition to quartz much sericitized plagioclase and only minor chlorite. All are strongly sheared and the original textures have been largely destroyed. The relatively

coarse grain of some of these rocks suggests that the original rocks were quartz diorite rather than dacite.

Ultrabasic igneous rocks were observed at only two localities. Four and a half miles south of the Whitechuck River bridge the Sauk River road crosses a small stream in a precipitous gully. Here augitic pyroxenite is associated with serpentinite. Serpentinite and associated clinopyroxenite are also found on the upper part of the logging road on the second of the three western spurs off the north ridge of Whitechuck Mtn. These pyroxenites all show strong cataclastic deformation.

Unlike the associated sedimentary and volcanic rocks which are unmetamorphosed or at best have only been incompletely recrystallized in the lowest grade of metamorphism, the diabases and gabbros have recrystallized at temperatures which mostly correspond to low grade conditions but may in part approach medium grade condition, as is suggested by the presence of hornblende in some rocks. Since this recrystallization is confined to the basic intrusive rocks, it is probable that we are dealing with a kind of autometamorphism which was probably promoted by weak accompanying shearing. The general restriction of the basic intrusives to the lower plate indicates that the time of intrusion and autometamorphism was either prior to the emplacement of the thrust--during the main period of original deformation of the window unit--or at the time of overthrusting when local shearing movement was again active.

Structure

The rocks of the window unit have experienced at least three stages of deformation. To the first phase are correlated the major internal structures of the unit, rather tight northwest-trending folds, and the development of slaty cleavage, especially in the finer-grained sediments. The second phase

of deformation was that in which the Whitechuck overthrust, the relations of which have already been discussed, was emplaced. The final stage of deformation includes high angle faulting of the unit--clearly marked by displacement of the thrust plane--and probably also some folding of the thrust plane. The major structure produced during this final deformation was the Straight Creek fault, a high angle fault which cuts the thrust, bringing both upper and lower plate rocks in contact with medium and high grade metamorphic rocks on the east. Smaller faults cutting the thrust are observed on Whitechuck Mtn. The time of the original folding of the window unit is not clearly established but probably belongs in the post-Paleozoic and pre-upper Jurassic interval marked by an unconformity in the western part of the area. The time of thrusting is probably post-lower Cretaceous and pre-lower Tertiary. The high angle faulting is probably Tertiary.

Age and Correlation

The rocks of the window unit can probably be correlated with rocks of upper Paleozoic age farther north, including the Chilliwack series which is upper Paleozoic and at least in part of lower Permian age (Daly, 1910; Misch, 1952 and oral communication) and the associated Jackman Creek sediments east of Concrete (Misch, personal communication). Large crinoid stems found in the present rocks appear to be identical to those found at Concrete and elsewhere in limestones of the Chilliwack series. The small outcrops of andesitic volcanics occurring at the Suiattle bridge are very similar to and possibly correlative with andesites of the Whitehorse unit.

The Canyon Creek Unit

General Description

The name Canyon Creek was agreed upon by the writer and W. R. Danner for a thick series of sedimentary rocks comprising slates and argillites, ribbon cherts, and dark feldspathic sandstones which is widely distributed in the south and southwest parts of the Stillaguamish quadrangle. In the present area the dominant rocks in the unit are argillite and slate, and ribbon chert; the dark sandstones observed farther west by Danner (personal communication) appear to be absent. Less prominent in the unit in the present area are limestones which are usually associated with the ribbon cherts and basic igneous rocks which are found in the eastern part of the area. Although no attempt to subdivide the Canyon Creek unit has been made in the present area, this should be possible when the unit has been studied in more detail. In the westernmost part of the area, as on the eastern part of Green Mtn., the sequence is dominantly slate, and ribbon chert is subordinate. In most of the eastern part of the area ribbon chert is very prominent. One synclinal belt running from Big Bear Mtn. and Liberty Mtn. on the north to Ridge 5256 and Ridge 4257 on the south is more than two miles wide and consists almost exclusively of ribbon chert. The thickness of these cherts must measure in thousands of feet. This synclinal belt may be continued on the south, outside the present area, by a thick chert sequence exposed along the Schweizer Creek logging road. The Canyon Creek unit is believed to be unconformably overlain by siltstones of the Three Fingers unit (Jura-Cretaceous?) on the north. The relations of the Canyon Creek and Whitehorse units are not known. On the southeast the Canyon Creek unit is in contact with Tertiary arkoses of the Swauk formation, but it is not clear whether the contact is a fault or an unconformity. The Canyon

suggestion of relict schistosity is preserved by mimetically aligned biotite. Two of the hornfelses examined contain irregular poikiloblasts of what appears, because of its suggestive twinning, to be cordierite. One of the hornfelses appears to have formed from a somewhat dolomitic slate, for in addition to quartz, biotite, and plagioclase it contains a fine-grained brownish hornblende and a few anhedral porphyroblasts of a pyroxene, which appears to be hypersthene.

Ribbon Cherts

Ribbon chert is the one characteristic and distinctive rock type in the Canyon Creek unit. The layers most commonly range from a quarter inch to an inch in thickness and have an average thickness of about half an inch. Individual bands generally pinch and swell and can rarely be traced more than a few feet before pinching out entirely. The bands are separated from each other by narrow argillaceous partings which are much thinner than the bands themselves. The thickness of the individual ribbon chert sequences varies tremendously. Some ribbon chert horizons intercalated in slate comprise only a few tens of bands and are only a few feet thick; others like the thick sequence on Liberty Mtn. measure thousands of feet in thickness. These thick chert sequences provide a truly remarkable example of rhythmic precipitation of silica. The cherts are generally various shades of gray with dark gray the commonest color. Red chert is not uncommon and tan and green chert are occasionally observed. These latter colors were observed only in those parts of the area farthest from the quartz diorite intrusion, and it is possible that these colors have been lost elsewhere in incipient recrystallization caused by contact metamorphism. In the immediate area of the contact the cherts assume a streaky appearance, with alternating light brownish, quartz-rich,

recrystallized chert bands, and thinner, darker brown, biotite-rich layers representing the argillaceous partings. In thin section the chert is seen to consist of extremely fine-grained, turbid, cryptocrystalline silica. The turbidity results in large measure from tiny flakes of sericite which are sharply aligned parallel to the bedding and comprise 10 to 15% of the rock. In this turbid groundmass, and aligned parallel to the bedding, are small, clear lenticles consisting of many tiny silica grains which interlock in a highly irregular mosaic. These lenticles appear to be deformed radiolaria. Intersecting veinlets of more coarsely crystallized quartz traverse the rock irregularly. Some of these veinlets appear to have yielded slightly to shear folding. Like the associated slates, the ribbon cherts appear to have been subjected to penetrative deformation parallel to the bedding. This is indicated by the sharp parallelism of the newly-formed sericite grains with the bedding, the presumed flattened radiolaria, and the shear-folding of the crosscutting quartz veinlets. The first perceptible effect of contact metamorphism on the cherts is the development of extremely fine-grained brown biotite and the incipient coarser crystallization of quartz in irregular patches and veinlets. With further recrystallization the chert passes into a coarser-grained biotite quartzite. Uneven grain is characteristic of even the fully reconstituted cherts. Many of the hornfelsed cherts contained some calcareous and dolomitic admixture, which is usually reflected by the presence of minor plagioclase and sometimes also by that of tremolite-actinolite or diopside. Minor sericite and tourmaline are occasionally observed. Limestone is very locally associated with the ribbon chert, especially as small lenses. Many of these lenses measure only a few feet in length and a few inches in width. The largest lens observed is marble and occurs on the south side of Liberty Mtn. about 30 feet below the summit and measures 15 feet by 6 feet.

further field work will certainly reveal additional limestone bodies. Associated with the marble lens on Liberty Mtn. are lime-silicate rocks, including grossularite-fels and diopside-grossularite rocks which indicate high grade thermal metamorphism. Wollastonite-vesuvianite-diopside rocks were collected in float near the quartz diorite contact on the east side of Long Mtn.

Basic Igneous Rocks

Basic volcanic rocks may be represented in the eastern part of the unit on Long Mtn. and in the area of Marten Creek. Unfortunately most of these rocks have undergone contact metamorphism, and many of the original textures have been destroyed. Most of these rocks may be described as hornfelsed basalts or diabases. A blastophitic texture is often more or less distinctly preserved even in the more fully recrystallized varieties. Whether these rocks are truly volcanic interbeds in the unit or simply pre-quartz diorite intrusives is uncertain. Two of the basic igneous rocks examined in thin section had undergone strong penetrative deformation prior to hornfelsing, the original shear planes being marked by actinolite needles with sharp mimetic alignment. In one of these rocks, what appears to be an original fragmental volcanic texture has been preserved in spite of recrystallization. Although these rocks predate the period of deformation and low grade regional metamorphism which affected the Canyon Creek unit, it still cannot be definitely decided, with the exception of the one fragmental rock, whether the original rocks were volcanic or intrusive.

Structure

A very general description of the structure of the Canyon Creek unit must suffice until additional field work has been carried out. Further stratigraphic and structural data are needed, especially in the eastern part of the area. Locally the ribbon cherts show minor crumpling, with the development of small, tight folds having wave lengths in the order of half a foot to a foot. In general, however, these small folds are absent and it appears likely that the crumpling was effected during the accumulation and prior to the consolidation of the cherts. The only major structure definitely traced is a fairly tight syncline of ribbon cherts in a two-mile-wide belt running from Big Bear Mtn. and Liberty Mtn. on the north to Ridge 5356 and Ridge 4257 on the south. There is indirect evidence which suggests, however, that the phase of deformation which produced this structure is only the second of two major periods of deformation of the unit. The attitude of the foliation of both the chert and the intercalated slate is generally parallel to the bedding and is quite unrelated to the axial plane of the present syncline. This requires the assumption of an earlier phase of deformation in which the foliation was produced, probably in conjunction with the formation of large recumbent structrues. The later period of deformation can probably be correlated with the folding of the unconformably overlying Mesozoic (?) of the Three Fingers unit, now essentially preserved in a syncline which is the approximate continuation of the syncline in the Canyon Creek unit. Further investigation of this interesting problem is planned.

Age and Correlation

Apart from nondiagnostic radiolaria in some of the ribbon cherts, no fossils have been found in the Canyon Creek unit and the age of the unit remains uncertain. Danner (personal communication) considers the unit to be Mesozoic, but his evidence is by no means compelling. The writer prefers late Paleozoic and probably a Permian age, though again the evidence is not conclusive. A Permian age is supported by the similarity of the Canyon Creek unit with the Cache Creek Series (Dawson, 1896; Armstrong, 1949) of British Columbia in which ribbon cherts are very prominent and which is in large part of Permian age. Further, the outcrop belt of the Canyon Creek unit as mapped by Danner (personal communication) is parallel to that of the fossiliferous Stillaguamish Series of definite later Permian age. Although these units are separated by a fault there is no particular reason to suppose that they differ greatly in age. Several ribbon chert sequences, possibly correlative with the Canyon Creek unit, are known elsewhere in the Cascades. Among these may be mentioned parts of the Barclay Creek unit (Yeats, 1956) in the Mt. Baring area which I have also visited, and parts of the Wildcat "mylonitic schists" (quotation marks mine) (Bethel, 1951) which actually appear to be hornfelsed ribbon cherts in the area of the Middle and North Forks of the Snoqualmie River, and cherts associated with slates basic volcanics and minor limestone which Misch (personal communication) has mapped in the Baker Lake area south of the Skagit River and which the writer has seen while working with Misch. The writer has observed similar hornfelsed cherts on the south flank of Vesper Pk., north of the Sultan River in the upper Sultan Basin.

The Whitehorse Andesite Unit

On Whitehorse Mtn. and its long northwest ridge is a series of strongly folded, but little metamorphosed andesitic volcanic and sedimentary rocks. As the stratigraphic and structural relations of this unit have not been worked out in detail, only a brief description of the unit is presented here. Greenish, and locally light brown and reddish andesites are the dominant rock type. These are typically rather fine-grained pyroxene andesites consisting of small felted laths of plagioclase (most commonly near An_{36}, where the composition could be determined) among which are scattered abundant small grains of an augitic pyroxene. Most of the andesites are fairly even-grained, but a few show in thin section some tendency to a seriate porphyritic texture, especially in the plagioclase. Some of the andesites, notably those poorer in pyroxene, show a very pronounced tracytic texture marked by small sharply aligned plagioclase laths. Two of the rocks examined consist of a few scattered phenocrysts of plagioclase and a small amount of quartz in a glassy groundmass and should probably be classed as dacites. Some degree of hydrothermal alteration is observed in most of the andesites, but this is of a very low grade and the rocks are in no way to be thought of as metamorphosed. Alteration is most commonly confined to sericitization or carbonatization of the plagioclase and chloritization of the mafics. Some of these rocks experienced mild shearing prior to their hydrothermal alteration. Some of the andesites show a conspicuous development of secondary prehnite in small veinlets and irregular patches. The andesites are believed to be dominantly flows, although the uniformity of the sequence makes separation of individual units and determination of attitudes extremely difficult. A volcanic origin is supported by the occasional occurrence of amygdaloidal layers (generally

chlorite amygdales), and thin breccia horizons, and especially by the presence of thin but persistent sedimentary interbeds in the thick andesite sequence. It is probable, however, that intrusive igneous rocks, represented chiefly by diabases, are also present in the sequence. Near the Squire Creek intrusion these rocks show the usual contact metamorphism.

Sedimentary rocks are relatively subordinate in the Whitehorse unit. Most conspicuous among the sediments is a band, or more properly a series of discontinuous lenses, of limestone intercalated in the volcanics and extending at least three miles along the north flank of Whitehorse Mtn. In a northwesterly direction. A preliminary report on the economic possibilities of the limestone has been published (C. Popoff, 1949). Most of the limestone bodies mentioned in his report as well as several not mentioned were examined by the present writer. The individual bodies vary considerably in thickness. The thickest, occurring on Moose Creek in the northwestern part of the limestone belt, is approximately 400 feet thick through a distance of more than 1500 feet along the strike. Some of the smaller bodies do not exceed 30 feet in thickness. The band of limestone lenses strikes roughly N 45° W and appears to dip almost vertically. Sedimentary rocks are also exposed on the summit and along the crest of the northwest ridge of Whitehorse Mtn. Here the rocks are slaty argillites and sheared siliceous argillites, locally with a few very small limestone lenses. The trend of these rocks is northwest, dips generally being steep to the north. Between Buckeye Creek and Ashton Creek on the lower north side of Whitehorse Mtn. a group of black slates and argillites are exposed. The stratigraphic relations of these slates with the Whitehorse unit are not entirely clear but the two units may be conformable.

The general trend of the rocks is about N 45° W, parallel to the northwest ridge of Whitehorse Mtn. itself. The argillitic rocks of the unit

have reached the grade of slate and the andesites themselves are commonly somewhat sheared. This together with the prevalent steep to vertical dips indicates relatively strong deformation.

The age of the Whitehorse unit is uncertain but is clearly pre-Tertiary as indicated by the presence of thick limestone beds. A possible correlative is the Sauk Mtn. volcanics (Misch, personal communication) occurring near Concrete to the north. The middle-Jurassic Nooksack volcanics occurring in the area of the North Fork of the Nooksack River are another possibility, although no limestone beds are known in this unit.

THE THREE FINGERS UNIT

The greater part of Three Fingers Mtn. and its western ridge is composed of a series of arkosic siltstones. As examination of this unit was confined to a single traverse along the trail up the west ridge to the lookout on the south peak, the present description is necessarily incomplete and many of the conclusions expressed here must remain tentative. Further field work is planned.

The most typical rocks are siltstones and fine-grained arkosic sandstones with which occasional thin beds of pebble conglomerate are associated. A few thin beds of ribbon chert were also observed. The siltstones vary somewhat in color, ranging from light gray to dark gray and brown. In addition to quartz abundant clastic plagioclase is present in all these rocks. Quartz and plagioclase both occur as highly angular grains. Most of the siltstones contain a fairly high proportion of matrix consisting of minute clastic quartz and plagioclase grains together with much finely divided argillaceous material so that they approach the composition of graywacke. Most of the finer-grained rocks, and even some of the coarser ones, have undergone some degree of shearing, though this is not always apparent in hand specimen. In thin section the rocks are seen to be traversed by a system of roughly parallel, but irregular and poorly defined shear planes marked by filmlike concentrations of dark argillaceous material. Most of the rocks examined show some incipient static recrystallization due to thermal metamorphism by the adjacent Squire Creek quartz diorite. The matrix in these rocks is typically recrystallized to fine-grained pale brown biotite, sometimes with the development of small epidote grains. Veinlets of quartz with or without albite, and sometimes with an actinolitic amphibole, are commonly formed. Some of the siltstones have

developed irregular patches and veinlets of secondary prehnite. The arkoses differ from the more abundant siltstones only in their lighter color and coarser grain.

Thin beds of conglomerate were noted at several horizons. Some of these conglomerates have undergone weak shearing. The pebbles are generally small, less than an inch in their longest dimension, but reach 5 or 6 inches in a few cases. A wide variety of rock types are represented among the pebbles. Pebbles of fine-grained igneous rocks, especially andesites, but including also diabases and acidic rocks, are particularly common. Light and dark gray chert pebbles, together with dark slates and sheared siltstones, are also abundant. These latter, it may be noted, are the dominant lithologies in the adjacent Canyon Creek unit. Occasional pebbles of quartz diorite are also noted. Pebbles of metamorphic rocks are conspicuously absent.

A few thin beds of ribbon chert were observed on the Three Fingers trail on the sharp ridge about a mile west of the lookout. These cherts are dark and show a crude, coarse banding. The thickest of these chert beds does not exceed ten feet.

The over-all structure of the Three Fingers unit is that of an open, northwest-trending syncline, probably with a few superposed minor folds. The Three Fingers unit appears to overly the Canyon Creek unit unconformably. At any rate it clearly truncates, apparently with a normal depositional contact, different members of the Canyon Creek unit; for on Meadow Mtn. it is in contact with the western belt of slates and subordinate cherts, while on the east it is in contact with cherts of the Liberty Mtn. synclinal belt, and north of Three Fingers it is again in contact with the chert member. Interpretation of the air photographs suggests that the present exposed contact is not everywhere an unconformity, but that the units are in fault contact in some places

(e.g., between Big Bear Mtn. and Three Fingers and at the northeast contact of the two units). As already discussed, the syncline in the Three Fingers unit appears to be a continuation of the syncline in the underlying Canyon Creek unit.

The Three Fingers unit is lithologically similar to and may be a correlative of rocks of Jura-Cretaceous age elsewhere in the Cascades. Among these are upper Jurassic and lower Cretaceous marine sediments, including the Nooksack formation of Misch (1956 and personal communication) between the Canadian border and the Skagit River, and equivalent rocks found by Danner (personal communication) southeast of the present area. The lithology of the formation, however, is not quite identical to that of the Three Fingers unit and the former is generally rich in marine fossils. The Three Fingers unit differs from and is older than the Swauk formation (early Tertiary) which occurs farther east in the present area. The Three Fingers unit differs from the Swauk in having a general predominance of finer-grained clastics and also in the occasional presence of ribbon chert, a lithology which is unknown in the Tertiary of the Cascades. Thus the Three Fingers unit is probably Mesozoic, possibly equivalent to the Nooksack formation or possibly somewhat younger.

ULTRABASIC AND BASIC INTRUSIVE ROCKS

Several intrusive bodies of ultrabasic and basic igneous rocks were mapped in the western part of the map area. These include two large ultrabasic dikes, several small serpentinite bodies, as well as several diabase and gabbro intrusions. Whether these rocks belong to one or several epochs of intrusion is not known. As the basic and ultrabasic igneous rocks occurring in the window unit farther east have already been described. They are not included in the present chapter.

The largest of the intrusive bodies studied is a vertically dipping dunite dike which has an average width of one-third mile and extends over six miles northnorthwest from Coal Creek on the south to the mouth of Helena Creek on the north. Farther north on Jumbo Mtn. several smaller dunite dikes and sills--ranging in thickness from about 10 feet to about 400 feet--were mapped. These smaller dikes are lithologically identical to and may be offshoots of the larger dike. Both the large dike and the smaller ones are intrusive into the Swauk formation and are thus of Tertiary age. It is probable that these dikes were emplaced in an essentially solid state. Contact metamorphic effects are inconspicuous in the wall rock of the dikes, indicating that temperatures were considerably less than those expected in an ultrabasic magma. The dikes have all been sheared with the development of a rough lenticular structure or foliation parallel to the dike walls. Several specimens of dunite from Jumbo Mtn. are strongly schistose. Emplacement in the solid state is strongly suggested in Coal Creek where the large dunite dike pinches out. Along what would be the continuation of the dike is a zone of slates and foliated arkosic siltstones (Canyon Creek unit?) which were dragged and faulted up during the emplacement of the dike. Isolated tectonic lenses of dunite are



Fig. 34

View east from the summit of Devils Peak. The long ridge in the center is the Coal Creek-Helena Creek dunite dike. In the middle distance are several ridges in the Barlow Pass volcanics. In the left background is Whitechuck Mtn.

found in the slates and lenses of slate in the dunite. An alternative explanation is that the dike was intruded into an altogether earlier fault zone. Dunite is the commonest rock type in these dikes. The dunite consists of fine- to medium-grained, even-sized, irregularly-shaped crystals of iron-poor olivine with a few scattered grains of iron ore. Most of the thin sections examined show some development of secondary minerals, presumably by metasomatism. Tremolite and talc are especially common. The tremolite occurs as scattered needles and clusters of radiating needles in the olivine and as tiny prisms in scattered patches and veinlets of very fine-grained talc. Certain zones in the dunite have been completely transformed into talc schist or talc-tremolite schist, implying metasomatic addition of silica and water in the first case, and silica, calcium, and water in the second case. Serpentine has not been widely developed in these rocks. Much of the alteration was probably complete before the emplacement of the ultrabasics. The unaltered dunites weather orange-brown, while the more strongly altered ultrabasic rocks are much darker.

A second large ultrabasic dike was mapped west of lower Marten Creek in the southwest part of the present map area where it has intruded the Canyon Creek unit. This dike appears to be about one-quarter mile wide and was followed a distance of two miles northnorthwest along the strike. The dike was not encountered on a traverse of Ridge 5256 just to the north, and presumably terminates not far north of the last observed outcrop. The present dike is directly on strike with and is almost certainly the same ultrabasic dike which has been mapped by Carrithers and Guard (1945) in the Sultan Basin south of the South Fork of the Stillaguamish River and traced to within three miles of the present dike. Whether this dike is of post-Swauk, that is, Tertiary age, like the dike described above, or is older is not known. The dike is older

than the post-Swauk quartz diorite intrusion of the Sultan Basin (a probable equivalent of the Squire Creek stock) by which it is cut. Only three specimens from this dike have been examined microscopically. One is an altered dunite containing about 50% olivine, 35% tremolite, 20% talc, and 3% iron ores. The rock has been sheared with the development of a rough schistosity and some cataclasis of the olivine. The tremolite occurs as isolated prisms and clusters of radiating prisms both in the olivine and in the talc which forms irregular patches in the rock. The tremolite and talc are less strongly deformed than the olivine and may have grown after the end of the main period of shearing. The other specimen studied is a schistose serpentinite consisting of about 95% roughly aligned antigorite flakes with about 5% of iron ores. The third specimen studied differs from any of the rocks found in the first group of ultrabasic dikes described above. It is a pyroxenite consisting of about 90% coarse-grained dark gray augitic pyroxene (2V ca. 60°), 8% antigorite and minor carbonate and iron ores.

Several small occurrences of serpentinite were observed in the Helena Ridge area. As a result of poor exposures in the heavy timber, none of these bodies could be mapped in detail. The largest body examined occupies an area of at least one square mile just south of Helena Ridge, where it appears to be intrusive into mylonitic diabases. These mylonitic diabases are themselves separated from the Helena Ridge crystallines (amphibolite and hornblende gneiss) by a steeply dipping ultrabasic dike about 200 feet in width. Another outcrop of serpentinite (not shown on the map) was observed on the north slope of Helena Ridge at an elevation of about 2800 feet. This last serpentinite body is probably intrusive into the Gold Hill phyllite, outcrops of which occur a few hundred feet farther north; its relations to the Helena Ridge crystallines a mile to the south could not be determined as no outcrops were

found. A further small outcrop of serpentinite (not shown on the map) was noted at an elevation of about 3000 feet on the ridge west of Goodman Creek where it is associated with greenish mylonitic rocks unconformably underlying the Tertiary Barlow Pass volcanics. The close association of all these serpentinite bodies with the Helena Ridge crystallines or with mylonites suggests that the serpentinites may be related to the emplacement of the Helena Ridge crystallines by thrusting. Three specimens from the largest serpentinite body were examined microscopically. These consist almost entirely of antigorite, iron ore amounting to a few per cent being the only other mineral present. In two thin sections excellent pseudomorphs of antigorite after olivine were observed.

Intrusive basic igneous rocks were observed at several localities along the ~~east~~ west (JAV) side of the outcrop belt of the large ultrabasic dike which extends northward from Coal Creek, along Helena Creek to Jumbo Mtn. It is not known whether these rocks are of Tertiary or of pre-Tertiary age, as their contact relations with the Swauk formation have not been established. Typical exposures of the altered diabase are found in Clear Creek and on the lower east slope of Jumbo Mtn. opposite the mouth of Helena Creek, and also on the Coal Creek logging road. The diabases of the latter outcrop appear to belong to a small intrusion in the upfaulted belt of slates and sheared siltstones which extends south of the termination of the big peridotite dike just to the north. The altered diabases are dark green, usually massive rocks. All, even the more thoroughly altered specimens, preserve a distinct ophitic or subophitic texture marked by prominent laths of plagioclase surrounded by pyroxene altered to uralitic hornblende. In these rocks plagioclase and its alteration products and the alteration products of pyroxene are approximately equal in amount. The plagioclase of the diabases may or may not be altered.

The unaltered plagioclase varies from An_{60} to An_{40} in the various specimens studied. Where altered, the plagioclase most commonly has been converted to albite plus epidote or albite plus carbonate. The pyroxene in most of the specimens studied has altered to a fibrous green uraltitic hornblende, but in a few specimens it has altered to pennine. Relict pyroxene was noted in only one specimen. Tiny needles of secondary green hornblende are often present in the plagioclase of the diabases, even where the plagioclase is otherwise unaltered. Abundant secondary sphene was noted in most of the specimens studied. Many of the altered diabases have been somewhat sheared and some, especially those on Helena Ridge and those west of Helena Ridge in Helena Creek, have been very strongly sheared and even become mylonitic. The presence of less strongly deformed small fragments of diabase in some of these strongly cataclastic and mylonitic rocks clearly shows their derivation from diabase. Much of the long north ridge of Jumbo Mtn. is composed of gabbro. Two thin sections of gabbro examined consist of about equal amounts of augitic pyroxene which occurs as large, slightly uralitized, well-formed crystals and of plagioclase which has been altered to a very fine-grained turbid aggregate rich in clinozoisite.

Altogether younger than the above rocks is a small body of gabbro which is intrusive into the Barlow Pass unit (Eocene ?) in the area of the forks of upper Falls Creek. The gabbro is exposed in an area of perhaps one square mile, but has not been mapped in any detail and is not indicated on the map. The gabbro appears to be relatively uniform, consisting of conspicuous laths of plagioclase up to a quarter inch in length and set in a matrix of small matted fibers of a green uralitic hornblende. The plagioclase laths show both albite and carlsbad twinning. The plagioclase has an average

composition of about An_{55} and shows some oscillatory zoning with a normal trend and only a small zonal range in composition. Uralitic hornblende also fills narrow cracks and fissures traversing the gabbro.

THE SWAUK FORMATION

General Description and Structural Relations

Continental sediments are exposed in a two-mile-wide northnorthwest-trending belt extending from the area at the head of the South Fork of the Stillaguamish River on the south, with one gap across the valley of the Stillaguamish, to Devils Peak, Helena Peak, and Jumbo Mtn. on the north. These sedimentary rocks include silty shale, arkose, and conglomerate and are correlated with the Swauk and the synonymous Chuckanut formation of McLellan (1927) which is mainly of Paleocene age. The unit has been moderately strongly folded. Outcrops of similar rocks, but with much more limited areal distribution, were noted at two other places; since the correlation of these rocks with the main Swauk belt is uncertain, they are discussed separately.

The structural relations between the Swauk and some of the adjacent units were not definitely established. It was not clear whether its contact with the Canyon Creek unit in the Deer Creek area is a fault or an unconformity; four miles to the south, however, Carithers and Guard (1945) have described a fault between what appear to be the southern continuations of these units. The nature of the contact of the Swauk on Jumbo Mtn. with the black slates and argillites (these may be conformable with the Whitehorse unit) in the lower Buckeye Creek-Ashton Creek area is likewise unknown. On the Coal Creek logging road and in lower Coal Creek a narrow belt of argillite, slate, sheared siltstone and altered diabase appear to have been upfaulted into the Swauk; these rocks are similar to the slates and sheared siltstones of the Canyon Creek unit, both lithologically and in their very low metamorphic grade, and are tentatively referred to this unit even though no

ribbon cherts were found. The Squire Creek quartz diorite is clearly intrusive into the Swauk, the contact being well exposed at a number of places between Devils Peak on the south and Jumbo Mtn. on the north. The Swauk is also intruded by a big dunite dike which averages half a mile in width and is at least six miles long, and in the Jumbo Mtn. area, by several smaller dunite dikes. The relations of the Swauk and the Gold Hill phyllite were not observed but must be unconformable. Much of the eastern contact of the Swauk is with the Tertiary (probably Eocene) Barlow Pass volcanics. Indirect evidence strongly suggests that the Barlow Pass unit overlies the Swauk unconformably. Locally, however, the two units appear to be in fault contact as on Lewis Peak in the southernmost part of the area.

Description of the Rocks

The Swauk of the present area comprises silty shales, arkoses, and conglomerates, and all their intergradations. The relative proportion of these rocks varies considerably from place to place, and it is difficult to give any but an extremely general statement as to their relative abundance. In general, however, arkose is most prominent and silty shales almost as abundant, while conglomerate is less widespread. The typical silty shales are dark in color and commonly show many fine laminations. In thin section all show a high content of angular clastic quartz, and generally also plagioclase. These coarser clastic grains are set in a matrix of finely divided argillaceous material and finer silt grains. With increasing grain size the amount of matrix diminishes and the argillites pass into lighter-colored arkosic siltstones and arkoses. In these rocks, along with quartz, angular plagioclase grains are always abundant, in almost all cases enough so as to justify their classification as arkose. Apart from quartz and plagioclase, lithic

fragments, especially chert may also be conspicuous in the coarser-grained arkoses. Clastic muscovite and somewhat less biotite are generally conspicuous in the matrix. Cross-bedding is occasionally noted in the arkoses. Small strings and thin bands of pebbles are common in the arkoses. Where the pebbles locally become more abundant, the arkoses pass into conglomerate. Most of the pebbles are light to dark gray chert. The largest pebbles observed measure about 6 inches in their longest dimension.

Most of these rocks are very strongly indurated. Much of this induration is due to hornfelsing by the intrusive Squire Creek quartz diorite, and thin sections of most rocks collected within half a mile of the intrusive contact show at least some degree of recrystallization. The first effect of recrystallization is the new formation of very fine-grained brown biotite in the finer-grained sediments and in the matrix of the coarser sediments. With further recrystallization the biotite becomes increasingly coarser, and the larger quartz and plagioclase grains are finally affected so that the original clastic texture is gradually lost. Very near the contact, in the highest grade of metamorphism reached, only the conglomerates, in which recrystallized chert pebbles can usually be recognized, preserve any original textures. Hornfelsed conglomerates are especially well exposed on the summit ridge of Devils Peak. The completely recrystallized arkoses often show a peculiar texture in which small well-formed laths of simply twinned plagioclase together with small biotite flakes are scattered among larger, uneven-sized, sutured grains of plagioclase and quartz. Irregular porphyroblasts of tourmaline, commonly the blue and brown varieties in zonal arrangement, are often observed in the hornfelses. In some of the hornfelses the tourmaline is so abundant as to suggest the metasomatic addition of boron. An unusual type of hornfels was collected just above the first waterfall in the prominent stream

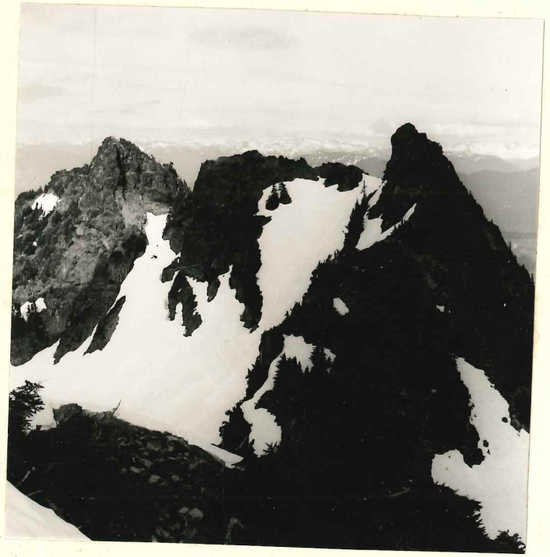
Fig. 35

Synclinally folded Swauk at the headwaters of the South Fork of the Stillaguamish River. The peak in the background is Del Campo. Looking south from Mt. Dickerman.



Fig. 36

Swauk on the summit ridge of Jumbo Mtn. Left, North Peak, right, Middle Peak, as seen from the South Peak.



running northwest off Jumbo Mtn. which joins Squire Creek about three miles up the Squire Creek trail. This rock is a sillimanite hornfels and is believed to be a contact metamorphic shaley bed of the Swauk formation. The sillimanite is a fibrous variety occurring in bundles of roughly radiating needles arranged in bands which appear to be mimetic after either bedding or foliation. Between the sillimanite bands are bands of very fine-grained quartz and pale brown biotite. Some of the higher grade hornfelses contain fine-grained muscovite which has apparently formed by retrogressive alteration.

Origin of the Sediments

The lithology of the unit, with its predominant arkoses and silty shales and subordinate beds and lenses of conglomerate, combined with the occasional presence of cross-bedding and fossil leaves, suggests a floodplain environment of deposition. The predominance of quartz and plagioclase among the detrital constituents points to derivation of the sediments from a granitic terrane. The general absence of granitic pebbles in the conglomerates indicates that the source area was far removed from the area of deposition. The predominance of chert pebbles in the conglomerates is possibly explained by assuming a more local derivation of the chert, as from the chert-rich Canyon Creek unit.

Structure

The Swauk formation of the present area is part of a long, narrow, northnorthwest-trending belt of continental sediments extending over 50 miles with several gaps from the type area south of Mt. Stuart to the present area, thence almost 50 miles farther with a few more breaks to the Bellingham area where the same unit has been called the Chuckanut formation (Weaver, 1937).

The Swauk appears to owe its preservation in this narrow belt to faulting and in part to sharp downfolding. Throughout most of the present area the Swauk formation is characterized by steep dips and relatively strong folding which considerably exceeds the intensity of folding of the overlying Tertiary. Strikes average northnorthwest paralleling the outcrop belt of the unit. The relative complexity of the structure, combined with inadequate exposures and insufficient field data, made it impossible to trace individual folds in many parts of the area. Faults must likewise be present within the unit, but they were impossible to distinguish. In the southernmost part of the area, at the head of the South Fork of the Stillaguamish River, the structure is relatively simple, being an open syncline with limbs inclined at about 45°. The Swauk section here has a thickness of at least 4000 feet. Just north of the present area in the Mt. Higgins area, folds are also of an open type (Jones, personal communication). These structures are contrasted to the relatively strong folding in most of the present area, thus a variation in the intensity of folding along the strike is indicated. Locally in the present area the Swauk has experienced exceptionally strong deformation. This is will illustrated at the upper end of the Deer Creek logging road and in the valley of Deer Creek just below the road. Here the finer-grained silty shales have been sheared to slates which have subsequently been thermally metamorphosed to spotted hornfels. Other features indicative of strong deformation noted here are tight minor folds in laminated silty shale, and also the "intrusion" of chert pebbles into adjacent argillaceous layers.

Correlation and Age

Fossil leaves of angiosperms, found in several places in the present sequence, clearly indicate a Cretaceous or younger age for these rocks. As the leaves have not yet been determined, no more precise dating can be given at present. Correlation of the present sedimentary sequence with the Swauk formation as established by Smith (1904) in the Mt. Stuart area appears probable from the lithologic similarity of the rocks, even though the continuity in their outcrop belt is broken by several gaps. Correlation with continental sedimentary rocks of the Chuckanut formation farther northwest is likewise probable, although the outcrop belt again is discontinuous. The only other possible correlative unit in the Mt. Stuart region would be the continental Roslyn formation also established by Smith (1904) in the Mt. Stuart area. Correlation with the Roslyn formation is considered less likely, however, for the Roslyn, together with the concordantly underlying Teanaway basalt, unconformably overlies Swauk which has been moderately strongly folded and the Rosyln has been only more weakly folded itself. The relatively strong folding of the present rocks more nearly corresponds to the degree of folding of the Swauk than of the Roslyn. In addition, Alexander (1956) feels that the Swauk formation and the Camas formation (which he considers a correlative of the Roslyn) can be distinguished on a lithologic basis, the Camas being cheifly an arkose unit, while shale and conglomerate also enter prominently in the Swauk. If he is correct in this, the present rocks more nearly resemble the Swauk. The Swauk formation is, on the basis of its flora, generally considered to be mainly Paleocene, but to include perhaps some upper-Cretaceous and lower Eocene rocks as well. The evidence for this age assignment has been summarized by Willis (1952).

The Murphy Creek Sediments

Pebble conglomerates which may possibly be equivalent to the Swauk formation were observed just west of Murphy Creek some two miles east of the main Swauk belt. These conglomerates unconformably overlie amphibolite of the Helena Ridge crystallines. The unconformity is well exposed in a small stream gully on the east side of Helena Ridge about 400 feet above the junction of the stream with Murphy Creek and about two and one-half miles map distance above the mouth of Murphy Creek. Nearly 300 feet of conglomerates are exposed here. The conglomerates strike about N 30° W and dip 55° NE as does the contact with the unconformably underlying amphibolites. The same relations are found, though not so clearly exposed, about two thirds of a mile northwest along the strike of the conglomerate. The pebbles average perhaps two inches in their maximum dimension and occasionally reach 4 or 5 inches. There is little matrix in the conglomerate, though a few thin arkosic and gritty layers are present. At least 50% of the pebbles in the conglomerate are milky vein quartz. Since these quartz pebbles are identical to the vein quartz of the Gold Hill phyllite just to the east, and since occasional pebbles of phyllite were noted in the conglomerate, it appears certain that these pebbles were derived from the Gold Hill unit. It is interesting to note that no pebbles of the underlying amphibolite are present in the conglomerate, even in the first few inches above the unconformity. Exposures are very poor east of Murphy Creek but much float of arkose and silty shale were observed; these sediments could possibly represent a sequence conformably overlying the conglomerates. These rocks are all represented as Swauk on the map, although there is no conclusive evidence for this correlation.

An isolated occurrence of arkose, very similar to the typical Swauk arkoses, was found on the ridge between Murphy Creek and Goodman Creek about a mile and a half south of the Sauk River just above an old logged-off area where there is an abrupt steepening of slope. The rocks are massive medium-grained arkoses with occasional layers of small chert pebbles. These rocks are exposed through a vertical interval of about 300 feet and appear to be tectonically intercalated near the base of a very thick mylonite zone which itself overlies the Gold Hill phyllite. These arkoses, again, may or may not be equivalent to Swauk. The significance of these arkoses in connection with the age of the possible thrust emplacement of the Helena Ridge crystallines has already been discussed.

THE SQUIRE CREEK QUARTZ DIORITE

General Description

A stock of quartz diorite occupies an area of somewhat more than 30 square miles in the western part of the map area. The name Squire Creek was taken from the more picturesquely named of the two major creeks draining the quartz diorite area. The maximum relief in the quartz diorite is nearly 5000 feet. Interestingly the general elevation of peaks within the stock is considerably less than that of the neighboring peaks outside the contact which form a surrounding ring of high summits. The stock is a roughly elliptical body, the longer axis of which trends about N 30° W, approximately parallel to the structural trend of the adjacent country rocks. The country rock of the stock includes early Tertiary arkoses, conglomerates, and argillites on the east (Swauk formation ?), pre-Tertiary cherts and slates of the Canyon Creek unit on the south and southwest, pre-Tertiary siltstones and arkoses of the Three Fingers unit on the west, and pre-Tertiary andesitic volcanics and sedimentary rocks on Whitehorse Mtn. to the north.

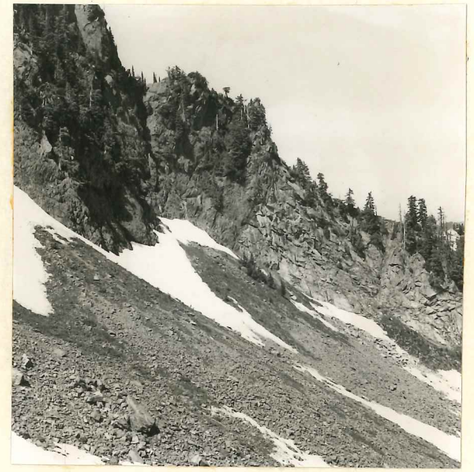
The quartz diorite is a massive, light-colored, medium-grained rock. In hand specimen it shows white plagioclase crystals as the most abundant mineral, together with clear quartz, irregular black plates of biotite, and black hornblende crystals which partly show regular crystal outlines. On steep bare slopes where well exposed, the quartz diorite shows a coarse slabby jointing parallel to the surface and sometimes also a steeply dipping joint set striking approximately N 60° E. The light gray quartz diorite contrasts sharply with the reddish-brown country rock hornfelses, and the sharp contact of the two often can be traced visually even from a distance of several miles.

Fig. 37

Contact of the Squire Creek quartz diorite and chert and slates of the Canyon Creek unit on the northeast ridge of Liberty Mtn.

Fig. 38

Intrusive contact between the Squire Creek quartz diorite and ribbon cherts of the Canyon Creek unit one mile north of Three Fingers.



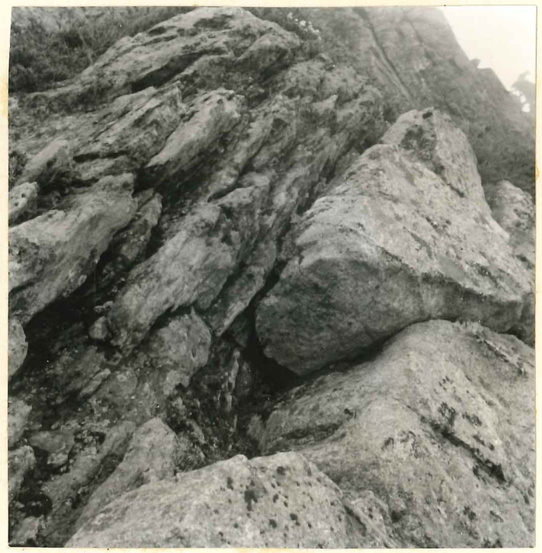


Fig. 39

Right, pinnacles of the Squire Creek quartz diorite. Left, the Whitehorse unit on the southeast ridge of Whitehorse Mtn. Contact indicated by dashes.

Fig. 40

Devils Thumb seen from Helena Peak. The lower part of photo is Squire Creek quartz diorite. The upper ridge of Devils Peak is Swauk. The long ridge in the left center of the Coal Creek-Helena Creek dunite dike. Glacier Peak is seen in the distance on the left.





The contact of the stock is uniformly sharp wherever examined. Perhaps the most striking feature of the quartz diorite is its uniformity. There is very little variation in grain size, mineral composition, or texture within the stock, even at the contact, and the fine-grained basic inclusions which are quite abundant in the stock have a rather uniform distribution.

The quartz diorite is considered to be of igneous origin. This seems to be particularly indicated by the uniformity of the quartz diorite and by its universally sharp contacts. Nowhere was any transition from country rock into quartz diorite observed. Metamorphism of the country rocks is virtually restricted to a narrow aureole of thermal metamorphism at the contact of the quartz diorite. Textures are dominantly magmatic.

Petrography

Mineral Composition and Classification

The modes of five specimens of quartz diorite, collected at widely separated points within the stock, were determined with the integrating stage. The modes are as follows:

Spec. No.	402	405	409	419	423	Average
Andesine	62	53	49	58	55	55
Quartz	18	26	27	25	26	24
K-feldspar	1	4	10	4	6	5
Biotite	11	10	8	7	8	9
Hornblende	7	7	5	5	4	6

Under Lindgren's classification, in which a quartz diorite must have a ratio of plagioclase : potash-feldspar in excess of $7\frac{1}{2}$: 1, all but one of these rocks fall under quartz diorite. Under Wahlstrom's classification, which is preferred by the writer for its more even division of the granitic rocks, with a plagioclase : potash-feldspar ratio of 5 : 3 and the dividing line between

Fig. 41

Plane light and crossed nicols. 40X. Oscillatory zoning marked by tiny inclusions in two plagioclase individuals forming a coalescent plagioclase group. Note the matching of zones across the contact of the two crystals. That these are not the same crystal is indicated by their differing cleavage and optic orientation. Note the greater thickness of the zones on 001 and the lesser thickness of 010 on the larger plagioclase crystal. Note how a crystal face has been added on the larger plagioclase grain in the upper part of picture as zoning progressed outward (euhedral disharmonic zoning).

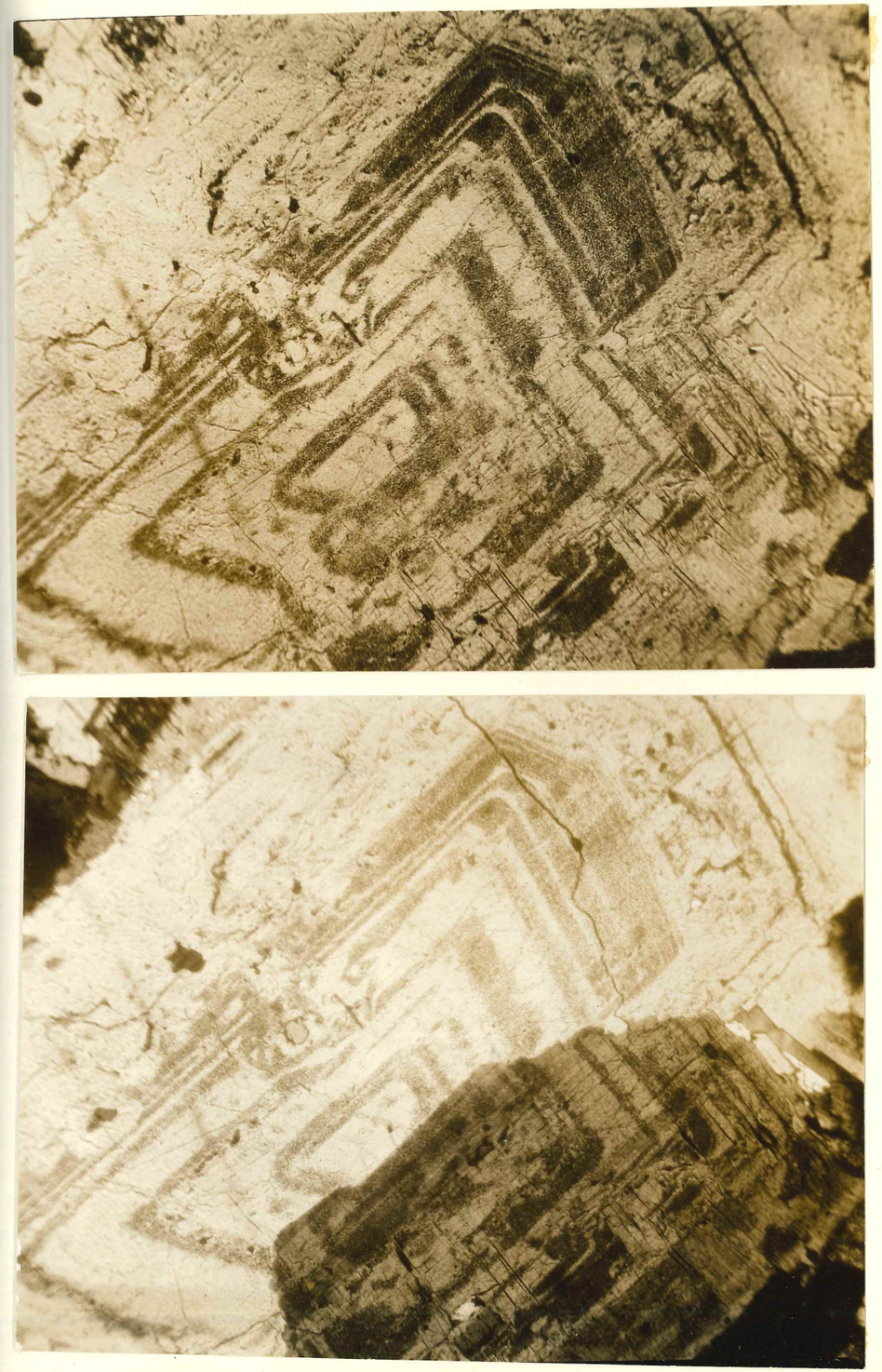


Fig. 42

Crossed nicols. 40X. Three oscillatory zoned plagioclase individuals in a coalescent group. Individual zones may be traced across grain boundaries. Some of the zones are anhedral along part of their perimeter.

Fig. 43

Crossed nicols. 50X. A coalescent group consisting of two intergrown zoned plagioclase crystals. Individual zones continue without interruption across the grain boundaries. These two grains began as small adjacent crystal nuclei. Where in contact only with magma, these growing crystals added euhedral zones; the irregular line of contact of the two crystals resulted from their mutual interference.





1. Form and size of crystals. The general tendency of the plagioclase is toward a more or less euhedral, lathlike form. The individual plagioclase crystals vary considerably in size, and the texture is actually porphyritic, though this is not conspicuous in hand specimen. The larger plagioclase crystals are the largest mineral grains in the rock, often reaching 6 or 7 mm in length, while some of the smaller plagioclase crystals scarcely reach 1 mm and compare in size with the quartz and other minerals.

2. Groups of coalescent plagioclase crystals. Very frequently the plagioclase occurs as groups of two, three, or even more individual crystals, rather than as a simple individual lath. These are not merely glomerophyritic aggregates which drifted together after crystallization, for the individual parts of a group often appear to be complexly intergrown along irregular boundaries. Two, three, or even more parts of what is seen from its optical continuity to be a single plagioclase crystal may be completely isolated from each other in the plane of the thin section, but are believed to be connection in the third dimension. Individual crystals in a group show euhedral zoning. At the contact of the different crystals there is an abrupt angular bend in the zoning, although distinctive individual zones can be followed across the different crystals. It must, therefore, be assumed that the individual crystals crystallized simultaneously coalescing into a tightly-knit group. The irregular boundaries where individual crystals of a coalescent group are in contact reflect the mutual interference of the various crystals during their growth, while the euhedral oscillatory zoning indicates freedom of growth in any direction away from simultaneously growing adjacent crystals.

3. Zoned plagioclase. The plagioclase of the Squire Creek quartz diorite is characterized by its striking zoning. The zoning of the interior of the crystal is typically euhedral and oscillatory. As many as 15 or 20

recurrences (30 or 40 zones) are common and sometimes as many as 50 recurrences (100 zones) are observed. Around the oscillatory zoned interior of the crystal is a narrow outer rim with normal zoning. The oscillatory zoning and the normal zoning and their interpretation are discussed separately here.

(a) Oscillatory zoning. Although the zoning of the plagioclase has not been plotted graphically as Rodick (1955) and Yeats (1956) have done in their theses, cursory inspection shows a number of features of the oscillatory zoning to be in agreement with those described by Yeats. Among these features are the following. (1) Zonal boundaries generally show a very rapid transition, although infrequently boundaries appear to lack conformity, being surfaces of corrosion and resorption. (2) Alternate calcic and sodic zones respectively tend to maintain a rather constant composition through a considerable number of recurrences. Commonly a number of recurrences at one composition are followed by more recurrences at a slightly more sodic or calcic composition. (3) There appears to be no constancy in the width of the individual zones. (4) The zoning has an over-all euhedral character. However, some of the zones may be anhedral. Yeats finds the anhedral zones to be confined to the interior part of the oscillatory zoned portion of the plagioclase crystals. In the present rocks the anhedral zones show no systematic position; they may occur in the interior, in the intermediate, or in the outer part of the interior oscillatory zoned portion of the plagioclase crystal. In none of the plagioclases observed does the entire crystal show anhedral oscillatory zoning. The anhedral zoning is usually restricted to one side or one part of an otherwise euhedral zone. In a few cases the anhedral zoning appears to have been caused by small included mineral grains

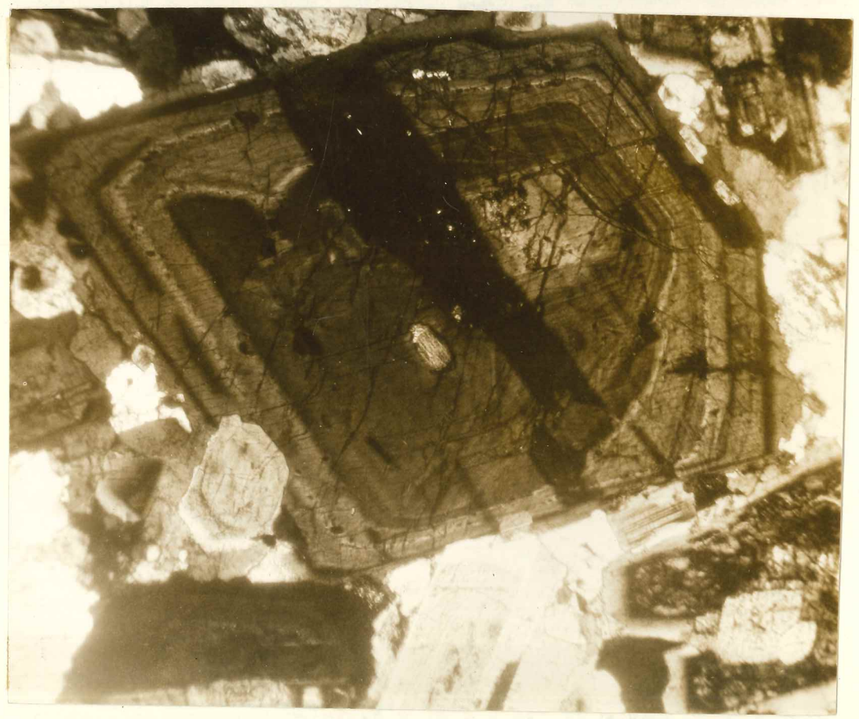
Fig. 44

Crossed nicols. 40X. Oscillatory zoned andesine. The crystal face which is well developed in the interior zones (just left of center) has become progressively smaller in the outer zones and is very poorly developed in the outermost zones. Toward the upper margin of the broad face 001 the oscillatory zoned plagioclase has been deflected in its growth around a small plagioclase inclusion and caused to grow normal to 010 instead of normal to 001 as in the interior of the plagioclase grain; the gap above the inclusion was later filled by oligoclase of the normally zoned rim.

Fig. 45

Crossed nicols. 40X. Oscillatory zoned andesine with a narrow outer rim of normally zoned oligoclase. Some of the zones are anhedral through part of their perimeter. The anhedral zones are succeeded by euhedral zones (anhedral disharmonic zoning). The development of oscillatory zoning near the crystal margin, at the upper right, was little affected by the small plagioclase inclusion.





to the sodic zones, as was observed by Yeats. (7) Inclusions in the plagioclase are common in the oscillatory interior portions of the plagioclase crystals, but do not appear to be confined to this area. (8) The composition of the oscillatory interior of the plagioclase crystals is generally medium or calcic andesine, but occasionally is as calcic as sodic labradorite. The composition of the oscillatory interior of the plagioclase bears no apparent relation to the size of the crystal. Small crystals with only a few oscillations were observed with a core as calcic as sodic labradorite, while larger crystals with many oscillations may have a core of only medium andesine. (9) Yeats notes that "zoning (oscillatory) usually does not extend to the center of the crystal" and that "extension of oscillatory zoning to the center may mean that the thin section does not penetrate to the center of the crystal." The writer's observations do not particularly seem to support this conclusion for the present rocks; however, final judgment is withheld until the rocks can be examined in more detail.

(b) Normal zoning. (1) The oscillatory interior portion of the plagioclase crystals is invariably succeeded by a normally zoned narrow outer rim. The normally zoned rims consist of oligoclase. The most sodic composition reached in the outermost part of the rims ranges from An_{22} to An_{15}. (2) The outer margins of the plagioclase crystals, although more or less euhedral in their general outline, are irregular and indented in detail, and thus only roughly preserve the more perfectly euhedral form marked by the zoning in the interior of the crystals. This irregular form is interpreted as the result of magmatic crystallization at a relatively late stage at a time when mineral

are generally irregularly rounded in outline and most often are confined to the inner parts of the oscillatory interior. In a few instances the cracking has involved only a ringlike outer portion of the oscillatory interior. The cracked area may involve several individual crystals in a composite group of plagioclase grains.

5. Twinning. Albite twinning is prominent in most of the plagioclase crystals. Carlsbad twins are commonly also conspicuous. Pericline twinning is only occasionally observed and generally is absent. A peculiar feature which may be related to albite twinning was observed in a number of plagioclase crystals. This is the occurrence of abundant, small, isolated, rectangular patches in parallel optical and crystallographic orientation both with each other and with definite and continuous albite twinning lamellae in the crystal. These may perhaps be regarded as incipiently forming albite twins. Emmons and Mann (1953) have noted and discussed the elimination of zoning by twinning in plagioclase. Yeats (1956) has noted similar features in plagioclase of quartz diorites in the Skykomish River area. Examination of the present rocks, however, failed to disclose any comparable relationship. In determining this point only plagioclase crystals cut perpendicular to the albite twinning, giving equal illumination in both sets of twins, were considered. This was done in order to prevent possible misinterpretation of the relative composition of the plagioclase due to differences in extinction angle in the two sets of twins. Dozens of such crystals were examined. In all of these, zoning proved to be equally sharp and well preserved in both sets of twins, and not a single example of twinning destroying zoning was observed. As a result of decrease in extinction angle, twinning is inconspicuous in the normally zoned rim plagioclase, and therefore twinning lamellae followed out from the plagioclase core often seem to disappear in the zone of

Fig. 46

Crossed nicols. 40X. Oscillatory zoned andesine with a narrow rim of normally zoned oligoclase. The small squarish light-colored patches are in parallel optic orientation with the albite twin lamellae and may be a peculiar kind of twin.

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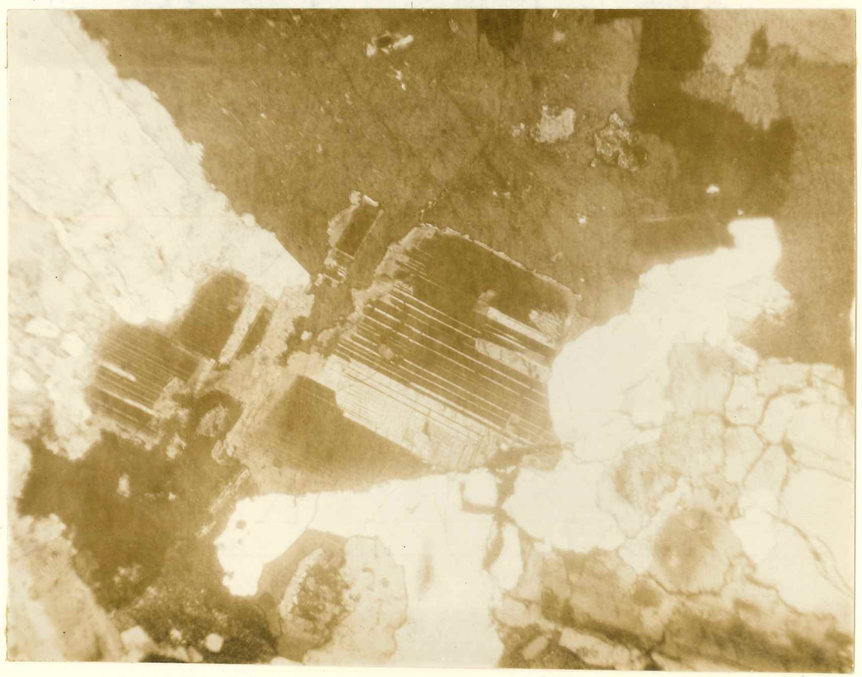




Fig. 48

Crossed nicols. 40X. Replacement of several of the outer zones of oscillatory andesine by the oligoclase rim (just above center).

rim plagioclase.

6. Inclusions in the Plagioclase. Small inclusions of earlier mineral grains are common in the oscillatory interiors of some of the plagioclase crystals. Of these, plagioclase is the most prominent, occurring as small roundish grains, some of which must be part of once larger grains, as they show abruptly truncated oscillatory zoning. Small grains of green hornblende are somewhat less common as inclusions, and tiny grains of a colorless clinopyroxene, sometimes wholly or partially uralitized, are occasionally observed. These minerals are smaller than and clearly predate the corresponding minerals which occur outside the oscillatory plagioclase cores, and which are correlated to the main period of magmatic crystallization of the quartz diorite. Any of the chief mineral constituents of the quartz diorite may project into the normally zoned rim of the plagioclase crystals.

The Other Minerals

The characteristic mafic minerals of the quartz diorites are hornblende and biotite. The hornblende occurs as somewhat irregular, poorly-formed prisms which may lack a regular basal termination. Both simple and multiple twinning are common. The hornblende is a green variety in which the pleochroism is rather variable. Areas of differing absorption are commonly observed within a single crystal in an irregular patchy distribution. The general pleochroism is X yellowish, Y grass green, Z slightly bluish, grayish-green, and X<Y<Z. However, the pleochroism may vary considerably in quality and also in intensity and some varieties have a very pale, bleached appearance. The biotite occurs in two ways, as small irregular, nonoriented plates associated with and generally included in hornblende, and as irregular, individual plates occurring independently of the hornblende. The biotite associated with the hornblende has clearly replaced the latter, and possibly even

the biotite which is not obviously related to hornblende may have formed similarly. The pleochroism of the biotite is quite uniform in all the rocks studied, with X golden yellow, Y and Z very dark brown (sometimes with a deep orange hue), X<Y=Z.

Quartz, and the less prominent potash-feldspar, occur as irregular grains filling the interspaces between the larger plagioclase grains and including the smaller hornblendes and biotites, and to some extent each other. Some of the quartz and potash-feldspar have replaced the other minerals. Small potash-feldspar grains are often prominent as inclusions in the quartz. The potash-feldspar is generally perthitic, the sodic plagioclase component occurring as very fine-grained, more or less regularly arranged stringers. The potash-feldspar has a negative sign and characteristically shows a surprisingly small 2V, estimated in different specimens as from 20° to 30°.

Apatite and zircon are characteristic accessory minerals in the quartz diorites. The apatite is present as numerous well-formed crystals. The zircon forms larger grains than the apatite, but is much less abundant. Pleochroic halos around zircon in biotite are either very inconspicuous or absent. In some of the quartz diorites poorly-formed granules of secondary sphene and iron ore have developed along with pennine and sometimes epidote in the chloritization of biotite.

Order of Crystallization and Interpretation of Texture

The oldest minerals in the quartz diorites are the small plagioclase, hornblende, and pyroxene grains occurring as inclusions in the oscillatory zoned central portions of some of the larger plagioclase crystals. These inclusions are clearly of an altogether earlier generation than the corresponding mineral phases making up the bulk of the quartz diorite. The inner

portion of the plagioclase crystals, typically showing oscillatory zoning, crystallized next, and this was followed by the crystallization of the normally zoned oligoclase rim. The period of crystallization of the hornblende, biotite, quartz, and potash-feldspar overlapped the time of crystallization of the rim plagioclase. This is indicated by the somewhat irregular, embayed outline of the rim plagioclase in contact with these minerals. These irregular margins appear to reflect differential resistance to growth resulting from the interference of the increasingly larger and more numerous crystals in the rocks in the more advanced stages of crystallization of the quartz diorite. That growth of the quartz and potash-feldspar has outlasted growth of the rim plagioclase is suggested by the general interstitial position of these two minerals between the plagioclases. Biotite, insofar as this has formed as a replacement of hornblende, is later than the hornblende. Apart from these observations, textural evidence does not clearly separate the time of crystallization of the hornblende, biotite, quartz, and potash-feldspar. In summary, the textural features of the rocks indicate that, although some of the minerals are seen to have replaced the other minerals--such as quartz and potash-feldspar as indicated by deep penetration and truncation, and biotite as indicated by its association with hornblende--the principal textures of the quartz diorite can be explained by simple crystallization from an igneous melt. This interpretation does not apply, however, to the small grains of plagioclase, pyroxene, and hornblende which are included in the plagioclase ores and are remnants of an altogether earlier chapter in the evolution of the rock.

Aplite Dikes

Aplitic dikes are widely distributed in the Squire Creek stock. The dikes are very narrow, rarely exceeding a foot in thickness, and they may extend only a few hundred feet before pinching out. The aplites vary somewhat in appearance but are mostly very fine-grained, leucocratic rocks, generally pink, but sometimes light gray in color. The dikes do not appear to extend outside the quartz diorite into the country rock. As only three specimens of aplite were studied petrographically, the present description is necessarily brief and cannot be considered standard for all aplites in the stock. All three of the aplites examined are of a very acidic composition. The estimated average mode of two of the aplites is: quartz 45%, potash-feldspar 40%, oligoclase 15%, with minor brown biotite (partly chloritized), secondary iron ores, and sphene. These two rocks differ slightly in grain-size but otherwise are texturally quite similar. They consist of fairly even-grained quartz, potash-feldspar, and oligoclase interlocking in an irregular mosaic. In one of these aplites a few of the potash-feldspar grains are euhedral against quartz; otherwise all the minerals are anhedral. The potash-feldspar is perthite with the same surprisingly small -2V (around 25°) characterizing the perthite of the host quartz diorite. The plagioclase is oligoclase with fine, narrowly spaced albite twins and is either unzoned or has weak simple or oscillatory zoning with one or two recurrences. A very few irregular flakes of brown biotite are present. Hornblende is absent. These two aplites consist, then, of the latest minerals to crystallize in the quartz diorite itself, suggesting that the aplites are a late magmatic differentiate which migrated from an almost fully crystalled quartz diorite into newly forming fractures and joints in the latter. The fine-grained and irregular texture of

the aplites appears to have arisen in part as a result of a rather short period of crystallization during which the crystallization of all of the individual minerals overlapped considerably, and possibly in part by replacement. Pegmatites, it may be noted, appear to be completely lacking in the stock. The third specimen examined, because of its texture, should probably not be termed an aplite, although it does not differ from the other aplites in mode of occurrence. It is made up of about 50% spherulites which are composed of radiating fibers of a mineral or minerals with low relief, lower first order interference colors, and a rather dusty appearance. The material composing the spherulites is presumbaly alkaline feldspar. The spherulites are set in a fine-grained, somewhat turbid groundmass containing numerous small laths of plagioclase, a few larger plagioclase phenocrysts, and small scattered grains and clusters of quartz grains. Minor amounts of secondary chlorite, epidote, and sericite occur irregularly in the rock.

Basic Inclusions

Small, dark inclusions are widespread in the Squire Creek quartz diorite. They are generally rounded in form, being either equidimensional or slightly elongate, and seldom exceed a foot in their maximum dimension. The inclusions occur rather uniformly throughout the quartz diorite and are not lithologically related to any of the exposed wall rocks of the stock. The inclusions are dark in color and are typically finer-grained than the enclosing quartz diorite. They vary somewhat in appearance, especially in grain size and darkness, the latter property depending apparently on the coarseness of recrystallization and the degree of replacement by the quartz diorite. The coarser-grained inclusions are generally more leucocratic than the finer-grained ones. Many of the coarser-grained inclusions contain scattered

plagioclase porphyroblasts which resemble the igneous plagioclase of the quartz diorite proper, but which have probably formed by replacement through the action of metasomatizing solutions from the quartz diorite on the basic inclusions. Biotization of hornblende characterizes the inclusions just as it does the quartz diorites. Only one thin section of a basic inclusion was studied petrographically. The mineral composition of this rock is approximately 54% plagioclase, 33% hornblende, 9% biotite, 3% iron ores, and 1% epidote. The texture is blastophitic, with small, irregularly-disposed laths of plagioclase showing both albite and carlsbad twinning enveloped in green hornblende which appears to be pseudomorphic after pyroxene. The hornblende, a green variety, is apparently identical to that of the quartz diorite and has in part been replaced by brown hornblende and minor epidote. No prophyroblastic plagioclase has developed in this inclusion, although the inclusion has been irregularly and marginally replaced by both quartz and potash feldspar. The uniform distribution of the basic inclusions in the quartz diorite and their dissimilarity to any of the various wall rocks of the stock indicates that they have been carried up with the quartz diorite magma. The ultimate origin of the basic inclusions remains obscure. Their basic composition, fine grain, and in some cases their relict ophitic texture suggests that they may be basic volcanic or hypabyssal rocks accidentally incorporated in the magma at depth. If the inclusions were an earlier differentiate of the same parent magma which produced the quartz diorite, they would have crystallized at depth and would presumably be coarser-grained. The texture of the inclusions does not support the view that they are simply rocks which have escaped an anatexis which produced the quartz diorite magma itself.

Contact and Structural Relations of the Squire Creek Stock

The contact of the Squire Creek stock was observed excellently exposed at three places. These were just west of the summit of Helena Pk., on the northeast ridge of Liberty Mtn., and northeast of Three Fingers. The contact is very sharp, generally as a knife edge, at all these places, though locally there is a narrow zone, up to a few cm thick, in which the hornfelsed country rock has been somewhat feldspathized. At many other places the quartz diorite contact was observed, even from a distance of several miles, to be likewise very sharp. The contact generally dips between 45° and 65° away from the stock except on the north where it is approximately vertical, and on the northeast on Jumbo Mtn. where it dips about 80° into the quartz diorite. The inferred upward extension and upward flattening of the dip suggests that the stock has not been long deroofed. Dikes and other offshoots of the quartz diorite are few and do not extend far into the wall rock. Although, as already mentioned, the small basic inclusions in the quartz diorite were not derived from the presently exposed wall rocks of the stock, but were brought up from below, definite inclusions of wall rock are occasionally observed in the quartz diorite. Some of these inclusions are quite large blocks with a maximum dimension of from 5 to as much as 80 feet. All the country rock inclusions observed were localized at the contact, generally within 100 feet, and some of these blocks can still be matched with irregularities in the country rock contact from which they broke loose. The paucity of these inclusions of wall rock appears to exclude stoping as a major process in the emplacement of the stock, and the localization of the inclusions in the immediate vicinity of the contact indicates a rather high degree of viscosity for the quartz diorite mass at the time of emplacement. Internal structures,

dating from the time of emplacement of the quartz diorite, are either absent or very inconspicuous. A diligent search failed to reveal any flow structures or alignment of basic inclusions even at the contact of the stock. No mapping of joints and aplite dikes was undertaken.

More detailed knowledge of the country rock structure will be needed in order to establish the structural control responsible for the location of the stock. The N 30° W trend of the major axis of the stock closely parallels the tectonic trend of the adjacent country rocks. The eastern contact of the stock lies along the approximate northward extension of a major fault between a younger (Swauk) arkose-conglomerate-argillite unit and much older (Paleozoic ?) sedimentary rocks (Cretaceous or younger, and Mesozoic or Paleozoic according to Carithers and Guard, 1945). Similarly, the eastern boundary of the northern part of a large quartz diorite intrusion in the area of the North Fork of the Skykomish River lies along the possible southern extension of this fault. This, then, is a possible control, although the presence of this fault has not yet been definitely established in the present area. The trend of the contact at the eastern and western boundary of the stock approximately parallels the strike of the country rock, indicating that shouldering aside of the country rock, insofar as this has occurred, has not conspicuously modified the original country rock structure. Indeed, shouldering aside may have played only a minor role in the emplacement of the quartz diorite. At the north and south contacts of the quartz diorite the country rock strikes directly into and is abruptly cut off at the contact of the stock, indicating that the emplacement was here accomplished by faulting and suggesting that upfaulting of the roof was an important mechanism in emplacement. On the other hand, the general downward widening of the stock would appear to limit the part played in emplacement by upfaulting of the roof. The observed amount of country rock

deformation attributable to the emplacement of the quartz diorite actually seems too small to provide the necessary room for the stock. Downward displacement of the country rock by stoping is a tempting hypothesis but must be rejected because country rock inclusions are absent in the quartz diorite, except very locally at the immediate contact. Moreover, the presumed stoped country rock blocks can hardly be supposed to have sunk to unexposed depths when the heavier basic inclusions have been carried up by the quartz diorite.

Contact Metamorphism

The Squire Creek stock is surrounded by an aureole of contact metamorphism. The width of the aureole varies considerably and contact effects are observed at distances ranging from about one-third mile to, in a few instances, over a mile from the exposed contact, the greater distances presumably reflecting a more gentle inclination of the contact. The various types of hornfels produced are not described here as this has already been done for the rocks of the individual units involved. The first mineralogical indication of contact metamorphism in most of the wall rock sediments (arkoses, cherts, slates) is the appearance of very fine-grained reddish-brown biotite, and in the dolomitic sediments and basic igneous rocks the incipient formation of greenish actinolitic hornblende. With increasing proximity to the quartz diorite higher grade mineral assemblages develop, and the rocks gradually become coarser-grained and more completely reconstituted. At least some of the rocks at the contact are true high grade hornfelses. Examples are a wollastonite-vesuvianite-diopside rock collected from float on the east side of Long Mtn. and a garnet diopside rock from the summit of Liberty Mtn.

An interesting phenomenon clearly related to the contact metamorphism is tourmalinization. This tourmalinization, which has affected representatives

of each of the various types of wall rocks, is most conspicuous near the contact, though isolated instances were observed over half a mile away. The tourmaline occurs as veinlets along fractures in the hornfels and as porphyroblasts within the hornfels itself. The tourmaline forms both well-developed prisms and irregular porphyroblasts. A brown variety appears to be most common, but blue tourmaline and zoned crystals with a blue core and a brown rim are also observed. Tourmalinization suggests metasomatic addition of boron, at least in those rocks in which tourmaline becomes an important constituent. The most startling example of boron-metasomatism observed is a hornfelsed siltstone which contains about 65% tourmaline. Sulfide mineralization of the wall rock is widespread near the contact, but although considerable exploration has been accomplished since the early part of the century, as evidenced by numerous abandoned prospect pits and adits, no continued interest has been shown in any of these properties.

A single example of what appears to be small-scale local granitization was observed. A narrow and precipitous gully occupied by a small stream descends the east side of Long Mtn. west of Deer Creek. The base of this gully is about one-quarter mile from the exposed quartz diorite contact and is easily reached from near the end of the Deer Creek logging road by crossing Deer Creek on a bridge and following the small tributary to the base of the gully. Outcropping at the base of the gully is a directionless dark hornblende-plagioclase rock, probably a hornfelsed basaltic dike. In the hornblende-plagioclase hornfels are irregular small bodies and patches of a very leucocratic aplitic rock. Within the aplite are angular fragments of the hornblende-plagioclase rock. With increasing amount of feldspar these fragments exhibit all transitions to the aplite. This, coupled with the spatial relations of the aplite and the hornblende-plagioclase hornfels which appear

to rule out forceful intrusion of the aplite, suggests that this is a replacement breccia. The aplite is clearly later than the hornfelsing and the metasomatizing solutions are assumed to have been derived from the quartz diorite.

Origin of the Quartz Diorite

Both field and petrographic evidence point strongly to an intrusive emplacement and a magmatic origin of the quartz diorite. The strongest evidence for intrusive emplacement is the universally sharp contact and the absence of transitions from country rocks to quartz diorite. Even the arkoses at the eastern contact of the stock which already closely approximate a quartz dioritic composition, have escaped granitization and have simply recrystallized as hornfels. This speaks little for the efficacy of magma-derived hydrothermal solutions in bringing about granitization. The remarkable uniformity of the quartz diorite even in contact with very diverse wall rocks further strengthens this argument. The geological environment of the stock is not one of extensive higher grade regional metamorphism as characterizes most areas of granitization; on the contrary, the country rocks were either unmetamorphosed or had undergone only incipient metamorphism, that producing slates, prior to the emplacement of the quartz diorite. As typifies igneous intrusive bodies, the stock is surrounded by a narrow aureole of thermal metamorphism which is genetically related to the quartz diorite itself. The texture of the quartz diorite appears to be best interpreted as almost wholly magmatic. The speculative question as to the ultimate origin of the quartz diorite magma is not discussed here.

Age and Correlation

The Squire Creek quartz diorite is probably correlative with lithologically similar quartz diorites in the Sultan Basin and in the area of the North Fork of the Skykomish River to the south. Like these latter--(Carithers and Guard, 1945), (H. J. Zwart, personal communication), and (R. S. Yeats, personal communication)--it is of Tertiary age in that it intrudes a leaf-bearing arkose-conglomerate-argillite unit (Swauk) of early Tertiary or possibly of late Cretaceous age. Since the quartz diorite is nowhere in contact with Tertiary volcanics younger than the arkose unit, it cannot be determined whether it is of early Tertiary or, like the Snoqualmie granodioritic and quartz dioritic intrusions, of mid-Tertiary age.

THE BARLOW PASS VOLCANICS

General Description and Structural Relations

The Barlow Pass unit is a thick and varied series of volcanic rocks with local interbeds of sedimentary rocks. Andesite and basalt flows predominate among the volcanic rocks, but acidic flows and fragmental volcanics are also present. Interbedded sediments include arkoses, arkosic siltstones, and locally pebble conglomerates. The unit exceeds 4000 feet in thickness. No detailed stratigraphic study of these rocks has been made. The unit would lend itself to detailed mapping, however, for several widespread and highly distinctive members are present. The unit has not been strongly folded in the present area, and dips commonly do not exceed 35°. The name Barlow Pass volcanics was chosen for the well-exposed, though incomplete and not wholly representative section exposed at Barlow Pass on the main highway through the area. More complete sections are well exposed on the steep faces of Stillaguamish Pk., Mt. Forgotten, Mt. Dickerman, and Twin Pks.

The unit is believed to overlie all adjacent units unconformably, including the Swauk on the west, the Gold Hill phyllite on the north and east, and the window unit locally on the east. Although the actual contact was not observed, the unconformity between the Barlow Pass and Gold Hill units is very apparent at their northern boundary. Here the Barlow Pass rocks are folded into a shallow north-south-trending syncline with limbs inclined at about 30°; individual beds in the volcanics may be followed almost continuously across the axis of the syncline just above the contact with the phyllite. The eastern contact of the volcanics and the Gold Hill unit was not observed and appears in most places to be covered by Quaternary deposits of the Sauk River

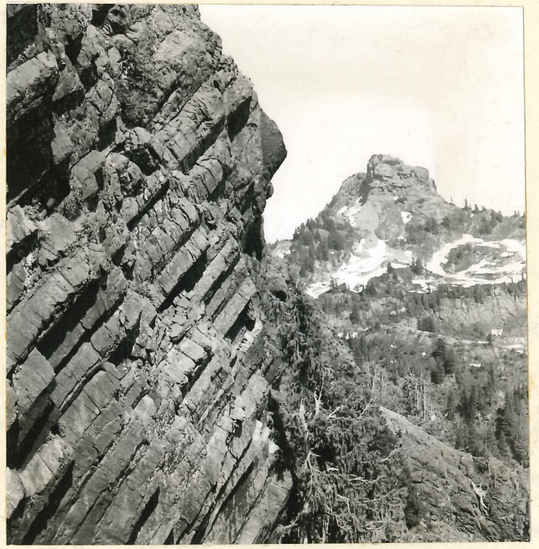
Fig. 49

Shallow syncline in the Barlow Pass volcanics of Stillaguamish Peak, looking north from Mt. Dickerman.

Fig. 50

Columnar jointing in basalts of the Barlow Pass volcanics on Stillaguamish Peak. The basalt flow dips at about 30°. Twin Peaks in the background.





valley. Although the contact of the Barlow Pass unit with the Swauk north of the South Fork of the Stillaguamish River was nowhere actually observed, the unconformable relationship is clear from the structural relations of the two units. The Swauk on the west is strongly folded and shows consistently steep dips, whereas the topographically higher Barlow Pass unit on the east has a uniform dip of 25-35° eastward. The contact relations are somewhat obscure here, partly because thick arkoses which resemble the Swauk are interbedded near the base of the volcanics, and partly because the Swauk has been cut by several large andesitic and basaltic dikes which without careful study could be mistaken for the volcanics. The relations may also have been somewhat complicated by faulting. Further evidence for the unconformable relation of the volcanics with the Swauk and the Gold Hill phyllite is the consistent presence on the north and west of a very distinctive acid flow at a single stratigraphic horizon near the base of the volcanics. At least locally the Barlow Pass unit is in fault contact with the older rocks. The Barlow Pass and Gold Hill units, for instance, are cut by several small high angle faults at their northeastern contact. Structural relations on Lewis Pk. indicate that the Barlow Pass unit is there in fault contact with the Swauk.

H. Zwart (personal communication) has mapped the southern continuation of the Barlow Pass unit into the Monte Cristo area, but considers the unit to underlie the Swauk unconformably, the exact reverse of the relations observed in the present area. I have not visited Zwart's type locality for the unconformity and am, therefore, not qualified to evaluate his evidence. It would seem possible, however, that Zwart was actually dealing with two volcanic sequences, one older and one younger than the Swauk. It is certain that at least the northern part of Zwart's volcanics is equivalent to the present Barlow Pass unit and is thus younger than the Swauk. Spurr (1901) considered

these Monte Cristo volcanics to be of Tertiary age.

The Andesitic Volcanics

Andesitic volcanics appear to be the most common rock type in the Barlow Pass unit, although they do not greatly surpass basalt in amount. The andesites occur chiefly as flows, but are also abundantly represented by pyroclastics, especially by tuffs and relatively fine-textured breccias. The lavas are generally green in color and are commonly amygdaloidal, but reddish and brownish types are also observed. The fragmental andesites are sometimes green, but more often are dark brown in color.

The andesites are quite distinct from the associated basalts, both mineralogically and texturally. The augitic pyroxene present in most of the andesites is always distinctly subordinate to the plagioclase, whereas pyroxene is usually almost as abundant as plagioclase in the basalts. The plagioclase of the phenocrysts in the andesites usually ranges from An_{35} to An_{45} in composition, and the more fine-grained groundmass plagioclase is still more sodic. In the basalts the plagioclase is generally labradorite. The plagioclase of the andesites is generally unzoned. The andesites exhibit considerable textural diversity, although all are very fine-grained. Perhaps the most common type is a holocrystalline pyroxene andesite consisting of tiny felted laths of plagioclase with small intergranular crystals of clinopyroxene and some iron ore. This type sometimes shows a slight tendency to porphyritic texture, although never in hand specimen; the phenocrysts of plagioclase often show a seriate tendency, and though usually few are always more numerous than the pyroxene phenocrysts. Differing slightly from this type is a pyroxene andesite containing variable amounts of turbid, altered, intersertal matrix rich in chloritic material. The greater the amount of matrix in rocks of this

type, the smaller the amount of pyroxene. Also quite common are pyroxene-free types consisting of small plagioclase laths and a relatively large amount of intersertal matrix. Some rocks of this type show a tendency to trachytic structure. Amygdales may be present in any of these types. Chlorite is the commonest mineral in the amygdales, but carbonate, quartz, prehnite, and epidote were also noted. Chlorite commonly forms the outer part of the amygdales, the inner part being occupied by one or more of the other minerals.

Andesitic tuffs and breccias appear to be the most abundant fragmental volcanic rocks in the Barlow Pass unit. The commonest types are lithic tuffs and relatively fine-grained breccias. Any of the rock types just described may occur among the rock fragments, but the most common lithic fragments are various dark vitrophyres.

Basalts

Basalt is the second most common rock type in the Barlow Pass unit. The basalts occur almost exclusively as flows, some of which show excellent columnar jointing. The basalts are dense, dark gray and dark brown to almost black rocks which are easily distinguished from the andesites, even in hand specimen. A few specimens are coarse enough to be termed diabase. Mineralogically and texturally the basalts are quite different from the andesites. The plagioclase of the basalts is generally labradorite (An_{60} to An_{45}) which shows normal zoning and in a few cases oscillatory zoning. Both augitic and pigeonitic pyroxene were noted. In the basalts the pyroxene tends to be nearly equal to the plagioclase in amount.

The textures of the basalts are quite variable. A common type is poikilophitic. In thin section certain small areas show a subophitic texture, while others show an intersertal texture in which a fine-grained pleochroic

greenish-brown or orange-brown micaceous mineral with moderate birefringence together with dusty iron ores forms the matrix. There appear to be all gradations between the orange-brown and greenish-brown minerals and a further gradation to a green chlorite-like mineral with weaker birefringence. These mineralogical gradations are often observed within single grains and between different grains in a single thin section. The pleochroic minerals with moderate birefringence occur in amygdales as well as in the intersertal matrix. The optical properties of these minerals very nearly fit bowlingite or xylotile (A. N. Winchell, H. Winchell, 1951). These minerals appear to have formed as an alteration of glass or pyroxene, except in the amygdales where they were probably deposited by volatiles early in the cooling of the basalt. Another common variety of basalt contains small grains of pyroxene and minor iron ores in irregular intergranular patches and the greenish-brown mineral with moderately strong birefringence or a green chlorite in intersertal patches. A few small phenocrysts of plagioclase, with or without pyroxene phenocrysts, may be apparent in thin sections of this type of intergranular-intersertal basalt. In only a few of the specimens studied was the texture wholly intergranular or wholly intersertal. A single specimen was collected in which a porphyritic texture was conspicuous in hand specimen. The phenocrysts are normally zoned glomeroporphyritic plagioclase (An_{68} to An_{50}) showing a distinct tendency to asterism. The phenocrysts are set in a matrix of small plagioclase laths among which are dispersed intergranular pyroxene and fine-grained intersertal chlorite. The diabasic types show an ophitic or subophitic texture with small irregularly scattered intersertal patches of the orange-brown or greenish-brown moderately birefringent mineral.

Acidic Volcanic Rocks

Acidic volcanic rocks were observed at a number of outcrops in the Barlow Pass sequence. These rocks occur chiefly as flows some of which are very thick; at least one flow averages about 350 feet in thickness. Detailed stratigraphic study will be necessary to determine how many of the acidic flows are actually present. One member, the thick flow already mentioned, is characteristically present in the lower part of the volcanic sequence, generally occurring at about 800 feet above the inferred base. What appears to be this same flow was observed near the west, northwest, north, and northeast boundaries of the volcanics. At least one and possibly two more similar flows were observed higher in the section on the western part of the outcrop area of the volcanics. Since little work has been done on the volcanics of the eastern part of the area occupied by the Barlow Pass volcanics, it is quite possible that the acidic flows are also present there.

The acidic volcanics are dense light-colored rocks. There is often considerable variation between different specimens of the acidic volcanics, even within a single flow. Colors range from tan to pale grayish or greenish and white. Spherulites are visible in some hand specimens and occasionally reach about one-half inch in diameter. A fine lamination or banding marked by slight differences in color and texture is often noted in the acidic volcanics. The banding may characterize a flow from top to bottom or may be present in only part of a flow but is apparently never entirely lacking. The present limited field observations indicate that the banding often does not parallel the attitude of the flow itself. The dip of the banding in particular is generally much steeper than the dip of the flow. Some of the banded acidic volcanics show extremely complex plastic flowage folding. The folds may be

either tight or open and range from almost microscopic size to several feet in wave length. The folds commonly die out or abruptly change their strike when followed along their axes. Similar banding in rhyolites of the Yellowstone Park area has been interpreted by Iddings (1899) as flow banding which developed in a highly viscous magma just prior to its solidification. According to Iddings, banding of this type is characteristic of many acidic lavas. Iddings has attributed the folding of the flow banding to steep initial slopes below the lava flows. The folding of the banding in the present rocks is clearly not tectonic, for the Barlow Pass sequence has itself been only rather gently folded.

The textures of the acidic volcanics as seen in thin section are highly variable. In most cases, however, the textures may be described as some combination of several common textural elements. Spherulites composed of fibrous crystals of alkaline feldspar are present in almost all the thin sections examined. Some of the spherulites are quite regular in form and may be bounded by circular perlitic cracks. These regular spherulites are very clear and consist of tiny radially arranged fibers. Other spherulites are only imperfectly formed, consisting of bundles of irregularly radiating fibers making up only a small sector of a sphere; these spherulites may be either larger or smaller than the regular spherulites with which they are associated and are usually rather turbid from small inclusions. A further textural element in many of the acidic volcanics consists of small, irregularly articulating, often even-sized grains of a mineral with lower first order interference colors and a moderately low relief. These grains are too turbid to permit positive identification, but are probably alkaline feldspar. Some of these grains appear to consist of many small feldspar fibers arranged in parallel fashion rather than radially as in the spherulites. Small bands consisting of

fibers arranged perpendicular to the length of the bands were observed in several thin sections. Quartz is present in many of the acidic volcanics in small clear clusters and patches of irregularly joined grains or in relatively sharply defined bands. Tiny irregularly disposed feldspar microlites, as well as tiny flecks of a colorless to pale green, moderately birefringent secondary mineral were noted in the more fine-grained, turbid portions of several thin sections. In a few thin sections one or two small plagioclase phenocrysts were observed. The textural diversity of the acidic volcanics results from different arrangements of the above elements all of which may vary in relative amount and size. The banding is marked by a parallel arrangement of these elements. Textures often change abruptly across perlitic and other cracks.

The acidic volcanics appear to be best interpreted as devitrified acidic glass. This is supported by the presence of perlitic cracks in several of the specimens studied. Whether the rocks are of rhyolitic or dacitic composition cannot be determined without chemical analyses.

Intercalated Sedimentary Rocks

Sedimentary rocks including arkose and siltstone, and locally pebble conglomerate, form numerous intercalations in the volcanic sequence. The thickness of the interbeds varies considerably. One bed near the base of the volcanics on the East Fork of upper Coal Creek is at least 300 feet thick. Several other beds measuring at least 100 feet, and many others measuring a few tens of feet in thickness were noted. As these individual beds were not mapped, their lateral extent is not known. One very extensive conglomerate bed, however, appears to be consistently present at a certain horizon in the volcanics. This conglomerate consists wholly of poorly sorted angular to slightly rounded pebbles of milky vein quartz and phyllite derived from the

Gold Hill unit. The pebbles range from about one-quarter inch to two inches in average size in different specimens. Float of this conglomerate was noted in all the major streams draining the area of the volcanics. The bed itself was observed at only one outcrop, at about 4000 feet elevation on the ridge between upper Goodman Creek and the Sauk River, where it occurs well above the base of the section.

Arkoses are the most abundant rocks among the sediments. They are gray to tan rocks differing little in their lithology from the Swauk arkoses of the area. Under the microscope angular to subangular grains of quartz predominate, whereas plagioclase grains are less abundant. Small chert granules are present in some of the coarser-grained arkoses. The matrix of the arkoses consists of smaller grains of clastic quartz and plagioclase together with clastic biotite, muscovite, chlorite, and sometimes carbonate cement. Epidote and/or sphene may be prominent among the heavy minerals. Narrow bands and stringers of chert pebble conglomerate are found in some of the coarser arkoses. Interbedded with the arkoses are fine-grained, dark, arkosic siltstones. Well-preserved fossil angiosperm leaves were collected from siltstones in an arkose interbed about two and one-half miles up the Dickerman Mtn. trail where the trail crosses a small stream.

The arkoses intercalated in the Barlow Pass volcanics are interpreted to be fluviatile deposits like the lithologically similar Swauk arkoses of the present area. Because of the absence of granitic pebbles, these quartzofeldspathic sediments are inferred to have been derived from a relatively distant source area. The pebbles in the conglomerates which are almost exclusively light and dark gray chert may be of more local origin. The occurrence of river-laid sedimentary rocks is significant in that it implies notable downwarping during the accumulation of the Barlow Pass sequence, for such

rocks could only have been deposited in a topographically low area. This is supported by the general absence of volcanic debris in the interbedded sediments, indicating that the volcanics were not being actively eroded in the present area between the outpouring of the various flows. However, the local picture during the accumulation of the volcanic series was not entirely one of subsidence. The vein quartz-phyllite pebble conglomerate already described is, in its uniform character and in the angularity of its pebbles, clearly of local origin. Only by rapid local uplift, probably accompanying tectonic movements, could this material have been made available for erosion and deposition as an interbed in the volcanic sequence.

Structure

In the present area the Barlow Pass volcanics have been only rather weakly folded. Dips in general do not exceed 35° and in most places are much gentler. The only prominent structure which could be traced for any distance is a shallow north-south-trending syncline running from the summit of Stillaguamish Pk. northward to the ridge at the head of Goodman Creek. The structure of the eastern part of the volcanics has not been studied in any detail. Locally the unit has been faulted. Several small high angle faults cut the Barlow Pass volcanics and the Gold Hill phyllite at their northeastern contact. Structural relations indicate that the Barlow Pass unit is in fault contact with the Swauk on Lewis Pk.

Age and Correlation

The Barlow Pass unit is younger than the Swauk formation which it overlies with angular unconformity in the present area and thus appears to be of Eocene or younger age. That the unit may be Eocene in age is suggested by

its marked dissimilarity to volcanics of the Keechelus type which are for the most part considered to be of late Eocene-Oligocene age, or to any other younger volcanics in the Cascades. Further, the present rocks are rather strikingly similar to arkose-volcanic sequences of well-established Eocene age in the Cascades farther south. The Naches formation (Smith and Calkins, 1905) consisting of arkoses and interbedded basalts, and locally of rhyolites, resembles the present rocks in its volcanic-arkose association, though andesites appear to be absent and arkose is more prominent than the present section. R. Foster (personal communication) who has remapped a part of the Snoqualmie area for a Ph.D. thesis at the University of Washington, considers the Naches formation to be a probable correlative of the Eocene Teanaway basalt (Smith, 1903) rather than of the Swauk as had been suggested by Smith and Calkins (1905). The Teanaway basalt of the Snoqualmie quadrangle (Smith and Calkins, 1905) consisting of basalt, andesite, arkose, and some rhyolite is lithologically rather similar to the Barlow Pass unit. R. Foster (personal communication) considers this part of the Teanaway to be a probable equivalent of the Naches formation.

THE ROUND LAKE VOLCANIC BRECCIAS

Andesitic breccias are widely exposed at and north of Round Lake on the western end of Lost Creek Ridge. Field work was confined to a single traverse across the southeastern part of the area on the Lost Creek Ridge trail, but interpretation of the air photos shows these rocks to have an areal extent of more than four square miles. The volcanic neck cuts the hornblende gneiss unit of the higher grade metamorphics. At Round Lake the contact of the andesite breccia with the hornblende gneiss unit is well exposed and dips nearly vertically through a vertical distance of 1000 feet. The contact has not been examined farther north where it extends through a vertical distance of about 3000 feet. At many places along the contact fragments of the wall rock (hornblende gneiss) have been broken off and incorporated into the breccia. These inclusions are most abundant within 100 feet of the contact. The inclusions range in size from fragments of microscopic dimensions to large blocks many feet in diameter.

The steep contacts of the breccia and the wall rock make it clear that this is a volcanic pipe, presumably the conduit of an ancient volcano and is not a volcanic accumulation built up above an old erosion surface. The size of the pipe suggests that the volcano itself was a very large feature. The level of the surface upon which the volcano was built was higher than that of the highest rocks presently exposed in the pipe, but not necessarily much higher, since a relatively shallow depth would seem essential to the formation of the fragmental volcanics.

In the area of Round Lake the rocks composing the volcanic pipe consist almost exclusively of andesitic breccias. The breccias vary considerably in color including greenish, grayish, tan, and brown varieties, and also in

texture ranging from rather fine-grained types which might be termed tuff-breccias to coarser breccias with blocks up to several feet in diameter. Most of the blocks are highly angular. Seven specimens were collected in the Round Lake area and examined microscopically. Six of these specimens are andesite, the seventh is a leucocratic basalt. The andesites examined are rather fine-grained rocks showing considerable textural variation. Variants include porphyritic and nonporphyritic types, others showing trachytic textures, still others with nondirected textures, as well as various representatives of these types which differ only in grain size. All the andesites are rich in plagioclase. The plagioclase phenocrysts of the porphyritic andesites range from An_{35} to An_{45} in composition in different specimens and are unzoned or show only weak normal zoning. The composition of the more abundant tiny laths of groundmass plagioclase in both the porphyritic and nonporphyritic types could not be determined. Saussuritization of the plagioclase is common. None of the andesites studied contains any pyroxene. In one specimen pyroxene phenocrysts have been pseudomorphosed by chlorite. In all the other specimens pyroxene probably never crystallized, the basic material being present in a turbid, chlorite-rich matrix. One specimen of andesite collected near the contact is rich in quartz and plagioclase xenocrysts derived from the wall rock. The one basalt specimen studied consists of approximately 60% plagioclase (An_{60} to An_{48}) with oscillatory zoning and a normal trend and a seriate porphyritic texture, 35% augitic pyroxene (including chlorite pseudomorphs), and 3% iron ores. Because of its leucocratic character this rock might equally well be classed as an andesite.

Twelve miles south of the present area in the Monte Cristo district Zwart (personal communication) has mapped a sequence of thick-bedded breccias measuring 1500 feet in thickness. The breccias are almost flat-lying, but

possess a slight southward dip, possibly initial dip. A part of this unit had been mapped earlier by Spurr (1901). These breccias rest on an erosion surface of very low relief at an elevation of about 5500 feet. These deposits originally covered at least 6 square miles, and probably much more. The greater part of the fragmental material consists of angular unsorted andesitic debris entirely similar to the andesites of the Round Lake breccias. Other fragments include schists and hornblende gneisses identical to the wall rock of the breccia pipe at Round Lake. The writer has examined the flat-lying breccia beds of the Monte Cristo area on both Columbia and Kyes Peaks and has found the fragmental material to be very similar to the breccias of the Round Lake area. Recently completed geologic mapping of this part of the Cascades by several workers associated with the University of Washington has not disclosed any source for the breccias other than Round Lake pipe. The only feature comparable to the Round Lake pipe in this part of the Cascades is a small breccia pipe, less than one-quarter square mile in area, about 10 miles south of Monte Cristo (Yeats, personal communication). This pipe could not, however, have supplied the hornblende gneiss and other metamorphic fragments which are so prominent in the breccias at Monte Cristo. The breccias were probably transported to their present site as mud flows off the now vanished volcano at Round Lake.

The breccias at Monte Cristo overlie with angular unconformity older volcanic rocks (probable correlatives of the Eocene Barlow Pass volcanics) and a mid-Tertiary quartz diorite stock intrusive into the volcanics. The complete erosive destruction of the superstructure of the Round Lake volcano contrasts sharply with the much less extensive erosion of even the oldest of the younger Washington Cascade volcanoes (cf. the Black Buttes, Coombs, 1939). Insofar as the dating of these younger volcanoes as Pleistocene is correct,

the Round Lake volcano must be pre-Pleistocene. This evidence together with the undeformed character of the young breccias near Monte Cristo suggests a late Tertiary and possibly a Pliocene age for both the old volcano and the flat-lying breccias to the south.

The relations at Monte Cristo indicate that the breccias there were deposited in a mountainous or hilly area, an early Cascade Range, probably with less relief than the present-day Cascades, prior to at least one installment of later Cascade uplift. The surface of low relief upon which the breccias in the Monte Cristo area now lie was clearly not developed at its present level of 5500 feet, but at a much lower level and has subsequently been uplifted. That this particular surface was not a peneplain, but of more local extent is clear, inasmuch as nearby peaks rise more than 2000 feet above its level (e.g., Sloan Pk. 3 miles away is 7790 feet high) and in that there is no evidence of local faulting or warping in the area subsequent to the deposition of the breccias. The surface upon which the breccias were deposited is interpreted to have been a local valley floor in mountains, an early Cascade Range, with at least several thousand feet of relief. A subsequent episode (or several episodes) of Cascade uplift elevated the breccias to their present position.

QUATERNARY HISTORY

Pleistocene Deposits

Pleistocene deposits, including glacial till, outwash, and lakebeds mantle much of the surface in the present area, and are especially abundant in the major river valleys. Although examination of these deposits has been spotty and largely incidental to study of the older rocks, it is felt that a few observations here will be of value to future workers primarily concerned with glacial problems. The Pleistocene history is complex, involving both continental and alpine glaciation as well as major drainage changes. The following outline briefly summarizes and gives the writers tentative interpretation of the principal feature observed.

The general sequence of events of the last glacial stage in the Sauk River area has been alpine glaciation, by Cascade valley glaciers, followed by the movement of glaciers from the lowlands to the north and west into the mountains. The form of the major river valleys (Sauk, Suiattle, Whitechuck, North and South Forks of the Stillaguamish) was produced by the earlier alpine glaciation. This is indicated by the deep troughlike form of the valleys, where this has not been obscured by later deposits, and especially by the presence in many till deposits of rock types of certain eastern derivation. Light and dark gray and occasionally red Glacier Peak andesite pebbles, and the abundant presence of pebbles of crystalline schists and gneisses in till clearly indicates derivation from the east. Such till is found abundantly to an elevation of 3500 feet on the ridges south of the lower Suiattle River and on the ridges around and west of the lower Whitechuck River, and scattered erratics occur to even higher elevations on these ridges. The valley glaciers

of this time must have been very powerful and active.

Sharply set off from the alpine glaciation performed by the Cascade valley glaciers, and distinctly later, is the advance of ice from lowlands to the northwest up into the mountains. Startling relationships in the Whitechuck River valley indicate that this ice moved up the valley of the Whitechuck River to at least 7 miles above its mouth and within 17 miles of the Cascade crest. At an elevation of 2200 feet, on an old logging road two miles east of Crystal Creek, alluvium is exposed which is considered to be reworked glacial till. Rock types which occur only west of the Straight Creek fault, three miles further west, are conspicuous in the alluvium, implying up-valley glacier movement. This interpretation is strengthened by other evidence in the Whitechuck River valley. The youngest glacial deposits in the valley are lacustrine silts and clays. These overlie till deposited by valley glaciers (as indicated by the presence of distinctive pebble types). These relations indicate the impounding of a lake in the valley, which could only have been accomplished by ice moving up the valley. The surprising point illustrated by these relationships is not so much that ice moved up the valley, but that alpine glaciers were so inconsequential at this time. It has been clearly demonstrated that the maximum advance of continental ice considerably post-dates the maximum of alpine glaciation along the front of the Northern Cascades largely through the work of Mackin (1941), but the full extent of the decline of the alpine glaciers has perhaps not been fully appreciated. The relations in the Whitechuck River valley are of unusual interest and deserve further, more detailed study. Evidence on Squire Creek, one mile above its junction with Buckeye Creek and two miles southwest of Darrington, indicates that ice from the north or west reached this point. Here lake silts and clays have been deformed by ice moving south up Squire Creek.

The latest glacial events, the retreat of the continental glaciers which had advanced into the mountains, are well documented in the valleys of the North and South Forks of the Stillaguamish River in the western part of the Sauk River area. Here glacial till which may be either of northern and western derivation, or alpine origin (deposited by Cascade valley glaciers), but which is at least in part Cascade, as indicated by distinctive pebble types, is extensively overlain by lake silts and clays. These deposits accumulated in lakes formed by blocking of the lower valleys of these rivers by the retreating ice to the northwest. Related to these same lakes are deltaic deposits built by streams marginal to the continental ice, just west of the Sauk River area, between Deer Creek and Boulder River on the North Fork of the Stillaguamish River and in lower Canyon Creek on the South Fork of the Stillaguamish River. It is probable that all the glacial deposits mentioned were developed in a single broad late Pleistocene stage. The area was surely affected by earlier Pleistocene glaciation as well, even though no definite earlier glacial deposits have been recognized in the area. Bryant (1955) in the Snowking area immediately to the north, has been described a deeply weathered till.

Pleistocene Drainage Changes

Several interesting drainage changes are believed to have been effected by glaciation. The most significant change was the diversion of the Suiattle (and possibly also of the Sauk) north into the Skagit River from an earlier western course out the valley of the North Fork of the Stillaguamish. This is believed to have been accomplished by lowering of the divide between the Skagit River and the present Suiattle drainage by glaciers moving south; further erosion of this channel may have been accomplished by streams,



Fig. 51

Roadcut in fill terrace of Glacier Peak ash. Note layers of pumice pebbles. Near the mouth of the Whitechuck River.

including the Skagit River, marginal to the continental ice seeking outlet to the south by way of the Sauk River and the North Fork of the Stillaguamish River. At the time of higher advance of the continental glaciers, the marginal streams probably found outlet to the south and west by way of the upper Sauk River, Barlow Pass (2400 feet) and the South Fork of the Stillaguamish River. Barlow Pass itself is believed to have been formed earlier by the spilling out to the west across a low divide of ice from a large valley glacier occupying the valley of the upper South Fork of the Sauk River.

Recent Ash Fill Terraces and the Glacier Peak Eruption

Thick fill terraces consisting largely of river-laid volcanic ash and pumice cover large areas along the Suiattle, Whitechuck, and Sauk Rivers. These deposits are clearly related to a cataclysmic eruption of Glacier Pk., as they are essentially restricted to the rivers draining the area of the peak. The volcanic material is considered to be airfall debris washed off the hillsides in such volume by rains into the streams and rivers that these were forced to aggrade. The deposits have their greatest thickness on Glacier Pk. itself and in general thin away from the mountain. According to Ford (personal communication) deposits of this eruption reach a thickness of 1000 feet on the east side of Glacier Pk. and a thickness of 500 feet on the west flank. The writer has traced remnant terraces of the pumice fill from the western flank of Glacier Pk. with a few gaps down to the mouth of the Whitechuck River where the fill covers an area of more than a square mile. The height of the terraces above the present level of the Whitechuck River decreases from about 400 feet, east of the mouth of Camp Creek, to only about 150 feet at the mouth of the Whitechuck River. Isolated remnant patches of the terraces were noted along the north side of the Suiattle River, and also along the Sauk River

between the mouth of the Whitechuck River and Darrington. There are two very large fill areas, one around Darrington and one at Sauk Prairie around the mouth of the Suiattle River; these two have a combined area of about 12 square miles. The fill material is bedded and fairly well sorted at most outcrops. These characters together with the fact that these deposits are confined to the major river valleys and that the surface of the terraces slopes regularly downstream with the profile of a low gradient stream indicates that the deposits are river-laid. With increasing distance from Glacier Pk. the quantity of rock material other than pumice and ash increases in the fill. Locally, as at the mouth of the Whitechuck River, large rounded boulders, some of which reach 8 feet in diameter are found in poorly sorted phases of the deposit; these coarse materials were apparently carried locally by strong threads of current. The two larger fill areas, one at the mouth of the Suiattle River and the other at Darrington, take the form of large fans built on broad relatively gentle surfaces. The Darrington fan which was deposited by the Sauk River extends far west into the present drainage of the North Fork of the Stillaguamish River. The Sauk must, then, have discharged westward during much of the time of filling and may in fact have discharged westward in post-Pleistocene time prior to the time of filling, although a northward course at that time is equally possible. That the Sauk now drains northward to join the Suiattle appears anomalous, in that it passes through a much narrower valley than the one leading westward. Knowing that the Sauk discharged to the west during much of the time of filling, its present position can be explained only by assuming that the river happened, quite fortuitously, to be flowing north on the eastern margin of the fan at the time filling ceased and downcutting began. The Sauk Prairie surface around the present mouth of the Suiattle River was built as a fan by the Suiattle River. It appears probable, however,

that the Suiattle occupied its present northward course immediately prior to filling, for the valley leading north was already there as a heritage of glacial drainage change and it is unlikely that the river was diverted out the North Fork of the Stillaguamish River drainage in the post-Pleistocene pre-fill interval.

Ash which originated in the same Glacier Pk. eruption, but which has been not reworked and deposited by water, has been preserved on many of the gentler high wooded ridges, usually between 2000 and 4500 feet, in the area, as well as in scattered patches on the gentler wooded slopes. It has been washed off all the steeper, rocky ridges and slopes. The ash is probably present throughout most of the area but went unnoticed by the writer until his last month in the field. The ash layer is light gray. It typically lies directly below the surface overlying a brownish soil layer and being covered only by a thin veneer of evergreen needles and other organic material. It was observed on most of the wooded ridges on Whitechuck Mtn. and Prairie Mtn.; on the crest of these ridges where it has not been thickened or thinned by reworking, it averages 2 to 3 inches in thickness. Its thickness elsewhere in the area is not known. While engaged in geologic mapping during the summer of 1956 just south of the Skagit River about 30 miles north and slightly west of the present area, the writer observed the same ash layer but with an average thickness of only one half to three quarters of an inch. This thinning to the north towards Mt. Baker indicates that the ash was derived from Glacier Pk. and not from Mt. Baker.

The ash terraces unconformably overlie the youngest Pleistocene deposits in the area. The great eruption of Glacier Pk. has been dated at about 6700 years ago by Rigg and Gould (unpublished MS) on the basis of

carbon-14 analyses of peat overlying and underlying the ash layer in Washington peat bogs. Carithers (1945) and Rigg and Gould have shown the ash layer to be widely distributed in the state of Washington as well as north and east of the state.

OUTLINE OF STRUCTURE

General Statement

This chapter is an integration of structure already presented in the descriptions of the various individual rock units. The reader is referred to these earlier descriptions for further structural details.

Internal Structure and Structural Position of the Metamorphic Rocks

Two broad metamorphic units differing sharply in metamorphic grade were distinguished in the Sauk River area. Each of these units was in turn subdivided on a lithologic basis into two smaller units. The lower grade unit includes the Gold Hill phyllite which comprises well crystallized black phyllites with subordinate greenschist and blue amphibole schist beds, and the Shuksan greenschist consisting chiefly of greenschist and blue amphibole schist with some phyllite intercalations. The metamorphism of the low grade unit is believed to be essentially isochemical and of uniform grade throughout. Folding is of a mobile type, and the schistosity has, itself, characteristically been folded. The Gold Hill phyllite and the Shuksan greenschist are considered to be essentially conformable, although their contact has locally been modified by later thrust faulting. In the present area the low grade rocks form a large thrust sheet overlying nonmetamorphic sediments which are at least in part of upper Paleozoic age. The thrust can be shown to have moved horizontally at least four and probably nine miles in the present area. This thrust, the Whitechuck overthrust, truncates structures of both the upper and lower plates. The upper plate is truncated in such a way that it consists entirely of Gold Hill phyllite on the west and chiefly of Shuksan greenschist

on the east. The presence of thin tectonic slices of the Gold Hill phyllite below the greenschist at the main thrust plane suggests that the upper plate has moved from east to west. The Whitechuck overthrust is correlated with Misch's Mt. Shuksan thrust and is believed to have formed during the period of middle to earlier late Cretaceous thrusting established by Misch (personal communication) south of the Canadian border.

The second major metamorphic unit includes rocks formed in the hotter part of the medium grade zone as well as some rocks formed in the high grade zone. Most of these rocks have been strongly feldspathized and granitized under synkinematic conditions. Two major subunits were mapped. One subunit, tentatively named the heterogeneous gneiss unit, consists of isochemical biotite schists, ortho-amphibolites, and more locally of hornblendite and marble, together with somewhat more abundant trondhjemitic gneisses, quartz dioritic gneisses, and diorites. These latter occur in intimate migmatitic association with the first three isochemical rock types named and are believed to have formed from these metasomatically. The eastern part of this unit is equivalent to the Green Mtn. unit of Bryant (1955). Zwart has mapped the extension of the heterogeneous gneiss unit south of the present area. The other higher grade metamorphic subunit, provisionally named the hornblende gneiss unit, consists dominantly of rather uniform quartz dioritic hornblende gneiss together with lesser amounts of migmatitically associated ortho-amphibolite from which it has been metasomatically derived. The hornblende gneiss unit has been mapped by Zwart immediately south of the Sauk River area. Several lines of evidence show that the gneisses of the two higher grade metamorphic units have formed from the isochemical rocks by granitization in place: there is a complete mineralogical and textural intergradation between the isochemical metamorphics and the gneisses with which they are associated;

the spatial relations of the isochemical rocks and the gneisses preclude the intrusion of magma; there is a constant and unvarying association of specific kinds of gneisses with specific isochemical rocks; the pre-granitization stratigraphy has been preserved intact and may be traced continuously across the area, even where the original rocks have been almost completely transformed to gneiss. Small dikes and irregular bodies of directionless aplite and pegmatite formed in late-kinematic to post-kinematic time; some of these have formed by replacement, while others are intrusive and may represent mobilized migmatitic material. The two higher grade units show an essentially uniform structure and metamorphic grade and are believed to be concordant. Folds are of a mobile type and folded schistosity is characteristic. The main body of higher grade metamorphic rocks on the east is separated from the low grade metamorphics and from nonmetamorphic sedimentary rocks on the west by the Straight Creek fault which dips steeply to the east and has a throw exceeding 5000 feet. This fault is younger than the Whitechuck overthrust which it cuts. North of the area the Straight Creek fault dies out (Bryant, 1955), and along the Cascade River there is an uninterrupted sequence of progressive metamorphism from low grade metamorphic rocks which are the stratigraphic equivalents of the present low grade rocks to rocks which are isograde with the present higher grade metamorphics and like them have in part been granitized (Misch, personal communication). It is probable that the higher grade rocks of the Sauk River area formed during this same metamorphism. One small area of higher grade metamorphic rocks, including amphibolite and hornblende gneiss, was found on Helena Ridge 8 miles west of the Straight Creek fault. The available evidence is not conclusive but suggests that these Helena Ridge crystallines are a remnant of a regionally extensive thrust sheet which is now known from the Canadian border, where Misch in 1955 found klippen

(personal communication), to the Skykomish area on the south, where Yeats (1956) found large klippen, and which roots west of Mt. Eldorado far to the east (Misch, personal communication). In the present area the thrust is believed to be structurally higher than the Whitechuck overthrust and like this latter is probably of middle to earlier late Cretaceous age.

Neither the age nor the time of the metamorphism of the parent rocks of any of the metamorphic units in the present area is known. There is thus far no satisfactory correlation of any of the Cascade metamorphic units with rocks of the pre-Tertiary nonmetamorphic sequence in the Cascades. There are three main possibilities for the age of the main Cascade metamorphism. One is a pre-Cambrian or early Paleozoic metamorphism, earlier than the nonmetamorphic upper Paleozoic of the Cascades. The second is an early or middle Mesozoic metamorphism, corresponding to the folding of the upper Paleozoic prior to upper Jurassic time; this folding is believed to be marked by a major unconformity in the present area. Misch (1952 and personal communication) considers an early to earlier middle Mesozoic age of the major regional metamorphism and the associated synkinematic granitization as most likely and believes that certain metamorphic rocks in the Marblemount-Cascade River area can be loosely correlated with known late Paleozoic rocks. The third possibility, and perhaps the least likely, is a middle to early late Cretaceous metamorphism, corresponding to the folding of the Jura-Cretaceous Nooksack formation. Misch (1952 and oral communication) believes that this possibility can be ruled out for the large-scale and higher grade regional metamorphism, since metamorphism of the Nooksack formation and the roughly equivalent Dewdney Creek formation is, apart from very late, local higher grade metamorphism, is of low grade and dynamic character.

Internal Structure and Structural Position of the Older Sedimentary and Volcanic Rocks

Three units of essentially nonmetamorphosed, but strongly deformed pre-upper Jurassic sedimentary and volcanic rocks have been distinguished in the present area. Metamorphism in these rocks is incipient and does not exceed the stage of the development of slaty cleavage. These units all are structurally below the two thrusts already described. As these three units were nowhere observed in contact, their relative ages and structural relations are not known. From their structure and uniformly low metamorphic grade it appears that they owe their main deformation to the same period of orogeny. Provisional correlation on lithology and sparse fossil content indicates that upper Paleozoic (Permian ?) and possibly also lower Mesozoic rocks are present. The main folding of these rocks is considered to be pre-middle Jurassic.

The easternmost of these units, the window unit, consists chiefly of slates and argillites but includes limestones, siltstones, arkoses, and pebble conglomerates, together with local ribbon cherts and andesitic volcanics. Intrusive basic igneous rocks are locally prominent in the unit. The window unit is considered to be at least in part of upper Paleozoic age. In the present area the window unit forms the lower plate of the Whitechuck overthrust.

The Canyon Creek unit consists of a thick and highly distinctive sequence of slates and ribbon cherts, with minor limestone. This unit is tentatively correlated with other thick ribbon chert sequences in the Northern Cascades and is considered to be most probably of upper Paleozoic (Permian ?) age. The Canyon Creek unit can be shown to have undergone at least two periods of strong deformation. The first period of folding is earlier than rocks

of probable Jura-Cretaceous age which are believed to overlie the unit unconformably. In this early folding large isoclinal recumbent structures appear to have been produced. The later folding involved the unconformably overlying sediments and produced large open folds.

The Whitehorse unit consists dominantly of andesitic volcanics, believed to be chiefly flows, together with interbedded sediments including slates, argillites and limestones. One discontinuous vertically dipping limestone band was traced for two and one-half miles along the strike. The Whitehorse unit may possibly be of upper Paleozoic or lower Mesozoic age.

Structure of the Three Fingers Unit (Mesozoic)

The Three Fingers unit consists of arkosic siltstones, together with subordinate arkoses and pebble conglomerates, and occasional thin ribbon chert beds. Structural evidence strongly suggests that these rocks lie with angular unconformity on the slates and ribbon cherts of the Canyon Creek unit. On the basis of its lithology and structural position the unit is considered to be Mesozoic, possibly equivalent to Misch's Nooksack formation of upper Jurassic to lower Cretaceous age. The unconformity below the Three Fingers unit is believed to indicate a major period of deformation in early or middle Mesozoic time. The Three Fingers unit, together with the underlying Canyon Creek unit has been folded into an open syncline. Regional relationships (Misch, personal communication) suggest that this folding was of middle to early late Cretaceous age. The thrusting which produced the Whitechuck Mtn. overthrust and the probable thrust of the Helena Ridge crystallines is believed to have taken place in a late phase of this orogeny, after the Nooksack formation and its equivalents had already been folded.

Structural Position of the Swauk Formation (Paleocene)

On the basis of its angiosperm flora, lithology and structure, a thick unit of continental arkoses, silty shales, and conglomerates in the present area is correlated with the Swauk formation (Smith, 1903) which is now considered to be mainly of Paleocene age. The present Swauk is believed to overlie the Gold Hill and Canyon Creek units unconformably, although at least locally they are in fault contact. In the present area the Swauk has experienced moderate to rather strong folding. One small area of pebble conglomerates, with associated arkoses and silty shales is isolated from the main Swauk outcrop area; these rocks unconformably overlie amphibolites of the Helena Ridge crystallines and are probably equivalent to the Swauk. The folding of the Swauk occurred prior to the accumulation of the unconformably overlying Barlow Pass volcanics which are believed to be of Eocene age. The formation of the Straight Creek fault and possibly also the folding of the Whitechuck overthrust can probably be correlated with the folding of the Swauk, for only weaker deformation has affected the Barlow Pass unit and younger rocks in the present area.

Basic and Ultrabasic Intrusive Activity

Basic and ultrabasic intrusive rocks are common in the western part of the map area. The basic intrusives comprise both diabase and gabbro. These are commonly sheared and altered. Some of these basic igneous rocks may be younger than the Swauk, but most appear to be older. One small body of gabbro has intruded the Barlow Pass volcanics which are believed to be of Eocene age. Two large dunite dikes were mapped. One of these is younger than the Swauk which it cuts. The other dike may be of the same age or older. One large and

several small serpentinite bodies of uncertain age were mapped.

Eocene Volcanism (The Barlow Pass Volcanics)

The Barlow Pass volcanics consist predominantly of andesitic and basaltic flows together with some acidic flows and interbedded sediments. The intercalated sediments are arkosic and locally contain an angisperm flora. The sequence is about 4000 feet thick. The Barlow Pass unit is younger than the Swauk which it overlies with angular unconformity. The volcanics have been rather gently folded and dips generally do not exceed 35°. On the basis of its flora, unconformable position above the Swauk, and lithology, the unit is considered to be Eocene and probably equivalent to the Teanaway (Smith and Calkins, 1905) and the Naches (Smith and Calkins, 1905) formations in the Snoqualmie quadrangle.

Tertiary Granitic Intrusive Activity (The Squire Creek Quartz Diorite)

A large quartz diorite stock cuts the Canyon Creek, Whitehorse, Three Fingers, and Swauk units in the western part of the map area. The uniformity of the quartz diorite together with its systemmatically sharp contacts and magmatic textures point to an igneous origin. The stock is surrounded by an aureole of thermal metamorphism which extends from one-third mile to a mile from the contact. Structural evidence suggests emplacement of the stock by forceful intrusion. The quartz diorite cuts the Swauk and is thus of Tertiary age.

Late Tertiary Volcanism (The Round Lake Breccias and Cascade Uplift)

The higher grade metamorphic rocks at and near Round Lake in the eastern part of the area are cut by a steep-walled body of andesitic breccias which is believed to fill the conduit of an ancient volcano. Nearly flat-lying, thick-bedded breccias occurring at Monte Cristo, 12 miles south of the breccia pipe (Zwart, oral communication), are believed to have been derived from the degradation of this old volcano and deposited as mudflows. Beneath the breccias at Monte Cristo is an erosion surface of very low relief which lies at an elevation of 5500 feet. Since this erosion surface could not have developed at its present level, Cascade uplift subsequent to the deposition of the breccias is indicated. This erosion surface is believed to have been local, probably a river valley rather than a peneplain, since present nearby peaks rise as much as 2300 feet above its level and since there does not appear to have been any significant folding or faulting since the deposition of the breccias. Thus an early Cascade Range was already present before the breccias were deposited, and before the volcano at Round Lake was built. Inasmuch as the breccias at Monte Cristo unconformably overlie mid-Tertiary quartz diorite and the stage of dissection of the Round Lake volcano suggests that it is pre-Pleistocene, these deposits are considered to be of later Tertiary age. Uplift of the old Cascade erosion surface may then have occurred in late Tertiary and/or Pleistocene time.

Quaternary Glaciation and Volcanism

Plestocene deposits, including till, glaciofluvial, and lacustrine sediments, are widespread in the major river valleys of the Sauk River area. Two episodes of glaciation both probably of late Pleistocene age, have been

recognized. The first phase was one of alpine glaciation which shaped the present river valleys; till and glacial erratics from this time are found in abundance to elevations of 3500 feet and locally up to a thousand feet higher. The alpine glaciation was followed by the advance of continental ice from the north and west into the mountains to within 18 miles or less of the Cascade crest. The Suiattle River is believed to have been diverted during glaciation from an earlier westward course into its present northward course into the Skagit River.

Recent deposits include thick ash and pumice fills in parts of the Suiattle, Whitechuck, and Sauk River valleys. The ash unconformably overlies the youngest Pleistocene deposits in the area and represents the reworked and stream-laid ejecta of a gigantic ash and pumice eruption of nearby Glacier Peak which occurred 6700 years ago (Rigg and Gould, oral communication). The Sauk River may have been diverted off the fan which it built with this ash from an earlier westward course to a northward course out to the Skagit River.

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VITA

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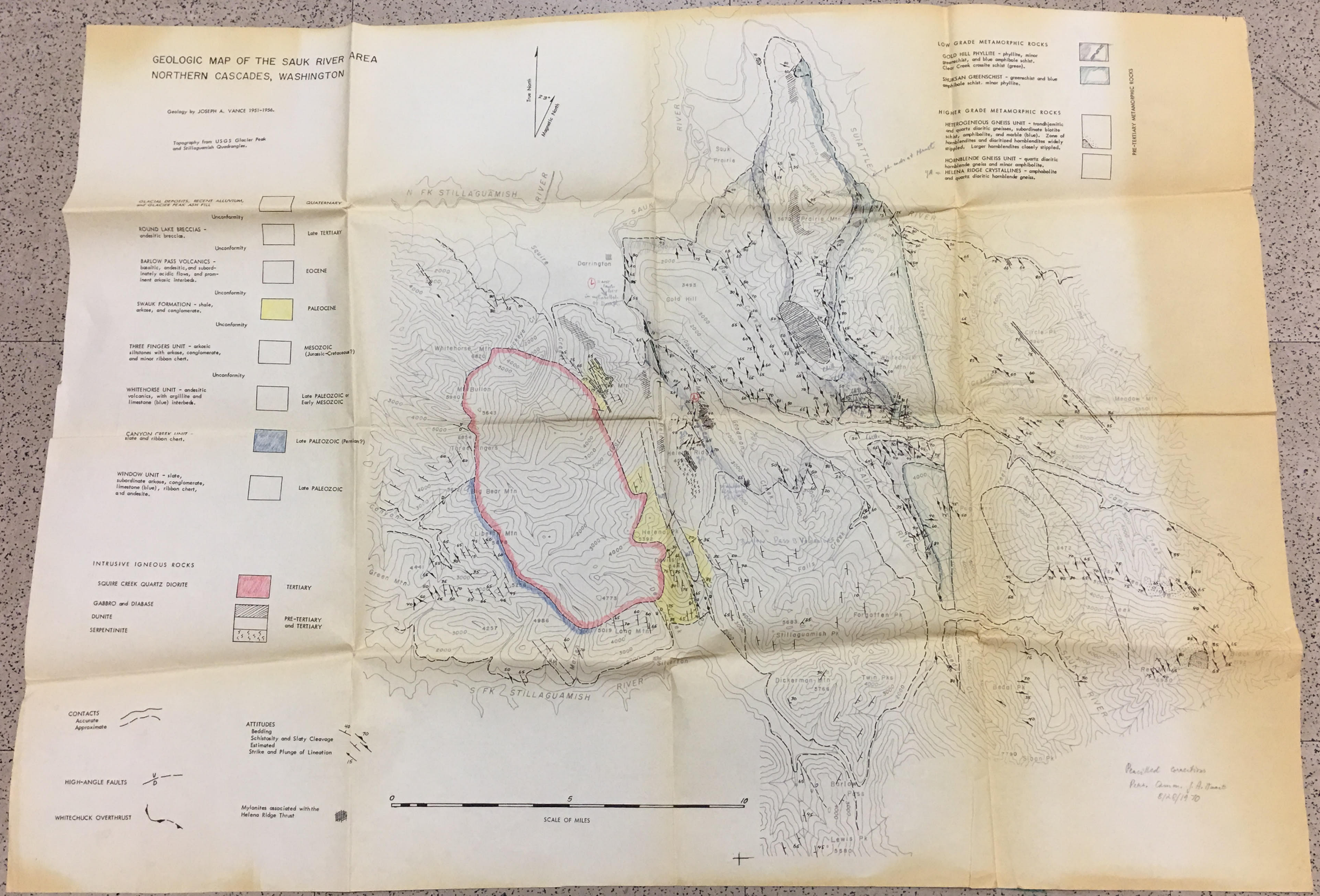
GEOLOGIC MAP OF THE SAUK RIVER AREA
NORTHERN CASCADES, WASHINGTON
Geology by JOSEPH A. VANCE 1951-1956.
Topography from USGS Glacier Peak and Stillaguamish Quadrangles.
True North
Magnetic North
GLACIAL DEPOSITS, RECENT ALLUVIUM, and GLACIER PEAK ASH FILL
QUATERNARY
Unconformity
ROUND LAKE BRECCIAS - andesitic breccias.
Late TERTIARY
Unconformity
BARLOW PASS VOLCANICS - basaltic, andesitic, and subordinately acidic flows, and prominent arkosic interbeds.
EOCENE
Unconformity
SWAUK FORMATION - shale, arkose, and conglomerate.
PALEOCENE
Unconformity
THREE FINGERS UNIT - arkosic siltstones with arkose, conglomerate, and minor ribbon chert.
MESOZOIC (Jurassic-Cretaceous?)
Unconformity
WHITEHORSE UNIT - andesitic volcanics, with argillite and limestone (blue) interbeds.
Late PALEOZOIC or Early MESOZOIC
CANYON CREEK UNIT - slate and ribbon chert.
Late PALEOZOIC (Permian?)
WINDOW UNIT - slate, subordinate arkose, conglomerate, limestone (blue), ribbon chert, and andesite.
Late PALEOZOIC
INTRUSIVE IGNEOUS ROCKS
SQUIRE CREEK QUARTZ DIORITE
TERTIARY
GABBRO and DIABASE
DUNITE
SERPENTINITE
PRE-TERTIARY and TERTIARY
CONTACTS
Accurate
Approximate
ATTITUDES
Bedding
Schistosity and Slaty Cleavage
Estimated
Strike and Plunge of Lineation
HIGH-ANGLE FAULTS
WHITECHUCK OVERTHRUST
Mylonites associated with the Helena Ridge Thrust
0
5
10
SCALE OF MILES
LOW GRADE METAMORPHIC ROCKS
GOLD HILL PHYLLITE - phyllite, minor greenschist, and blue amphibole schist. Clear Creek crossite schist (green).
SHUKSAN GREENSCHIST - greenschist and blue amphibole schist, minor phyllite.
HIGHER GRADE METAMORPHIC ROCKS
HETEROGENEOUS GNEISS UNIT - trondhjemitic and quartz dioritic gneisses, subordinate biotite schist, amphibolite, and marble (blue). Zone of hornblendites and dioritized hornblendites widely stippled. Larger hornblendites closely stippled.
HORNBLENDE GNEISS UNIT - quartz dioritic hornblende gneiss and minor amphibolite.
HELENA RIDGE CRYSTALLINES - amphibolite and quartz dioritic hornblende gneiss.
PRE-TERTIARY METAMORPHIC ROCKS
N FK STILLAGUAMISH RIVER
SAUK RIVER
SUIATTLE RIVER
S FK STILLAGUAMISH RIVER
Darrington
Gold Hill
Whitehorse Mtn
Mt Bullon
Three Fingers
Big Bear Mtn
Liberty Mtn
Helena Pk
Long Mtn
Silverton
Green Mtn
Prairie Mtn
Whitechuck Mtn
Circle Pk
Meadow Mtn
Forgotten Pk
Stillaguamish Pk
Dickerman Mtn
Twin Pks
Bedal Pk
Sloan Pk
Barlow Pass
Lewis Pk
Pencilled corrections
Pers. Comm. J. A. Vance
8/28/1970