THE GEOLOGY AND PETROLOGY OF THE CRYSTALLINE ROCKS
OF THE
BECKLER RIVER-NASON RIDGE AREA, WASHINGTON

by

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INTRODUCTION

Location and Accessibility

The Beckler River-Nason Ridge area is a part of the Northern Cascade Mountains province of the State of Washington, and lies approximately halfway between the Puget Sound lowland on the west and the Columbia Plateau on the east (Figure 1). The center of the mapped area is about 60 miles east of Seattle. The Cascade Crest--the divide for east- and west-flowing drainage in the Cascade Mountains--bisects the mapped area. Plate A shows the topography of this part of the Cascade Mountains.

The area mapped is approximately triangular in shape, with maximum dimensions of about 25 miles from east to west and 15 miles from north to south. More than half of the mapped area lies west of the Cascade Crest, and occupies parts of King and Snohomish Counties (Plate A). The part lying east of the divide is within Chelan County. The mapped area is included in the Chiwaukum and Skykomish topographic quadrangles (48, a and c) of the United States Geological Survey.

Where ridges are composed of schist or migmatitic gneiss, a characteristic asymmetrical topography results (Plate IV). The northern slopes, as on Nason Ridge and in the Chiwaukum Mountains facing Nason Creek (Plate A), are "staircases" of near vertical cliffs separated by narrow, sloping benches. The southern slopes are considerably less steep. This asymmetry is typical of every ridge formed in schist, and presumably is the result of a more intensive glaciation on the wind- and sun-protected north slopes.

Previous Geologic Work

Geologically, most of the northern Cascades has been unknown, and only certain restricted areas have been studied. Previous work in the Beckler River-Nason Ridge area have been of a general reconnaissance type only. The results of this generalized work have been incorporated in the Geologic Map of the State of Washington (7). This map gives the approximate distribution of the granitic and metamorphic rocks in this area, but the description of the specific units and the boundaries of the various rock types are incorrect.

Some additional work has been done in adjacent areas. Before the end of the last century, I. C. Russell made several reconnaissance trips through the areas lying to the east and northeast (38, 39). W. S. Smith made a brief petrographic and physiographic study of the Skykomish River basin (43, 44, 45). Southeast of the Beckler River-Nason Ridge area, B. M. Page has done work involving structure, petrology, and physiography (30). Immediately east of Nason Ridge, C. L. Willis has made detailed structural and petrologic studies (51, 52).

Purpose of the Investigation

This study forms a part of a larger project to investigate the geology of the crystalline rocks between Stevens Pass and the Canadian Border

PLATE VIII

Vimy Ridge, the Cascade Crest, and Glacier Peak (10,436 feet) as seen from Robin Mt.

PLATE IX

The valley of the Little Wenatchee River from Benchmark Mt. Looking southeastward, Mts. Howard, Mastiff, and Rock form the prominences on Nason Ridge (right distance). The Entiat Mts. occupy the farthest distance. Cady Pass lies just to the left of Robin Mt. (foreground).

PLATE X

Sloan Peak (7,790 feet), Mt. Pugh (7,150 feet), and Mt. Baker (10,750 feet high and 67 miles distant) from Benchmark Mt. Looking northwest, the rocks in the right foreground are recent andesites capping the older metamorphic rocks of Benchmark Mt.

(Figure 1). This larger project, which emphasizes the petrology and structure of the crystalline rocks, was commenced by Peter Misch in 1948. Soon after--in 1949--the author commenced the study of the Beckler River-Nason Ridge area. A number of geologists, all of whom have worked at the University of Washington, are participating in this project. Their results, as well as the present paper, will be published individually as separate numbers in a series of contributions to the geology of the northern Cascades.

Concomitant with this Northern Cascades project, a number of graduate students at the University of Washington are engaged in studies of the Central Cascades. This latter project is under the general direction of Dr. Howard A. Coombs.

Procedure

Field work in the northern Cascades is restricted to a comparatively short summer season because of heavy winter snows which occasionally total 700 inches. Consequently, the author worked a total of seventeen weeks in the field during the summers of 1949 through 1952.

Aerial photographs were not available. Therefore, the mapping was accomplished by Brunton compass traverses aided by photographically-enlarged copies of the Chiwaukum, Glacier Peak, and Skykomish topographic quadrangles of the U. S. Geological Survey (48). In addition, part of the area is covered by lithographed copies of U. S. Corps of Engineers Northwest Sector photo-maps.

Because of the dense cover of timber and brush at the lower elevations (Plates V-VII), traverses generally were made to the highest peaks, along the main ridges, and along the canyons of the major streams.

Winter seasons were occupied in the preparation of thin sections from the more than 600 rock specimens collected, and in the petrographic studies of these rocks.

Acknowledgments

I am deeply grateful to Dr. Peter Misch, who supervised my work and not only offered friendly and invaluable criticism, but also constant encouragement. The petrographic analysis of the rocks of this area and their genetic interpretation follow the methods devised and perfected by Dr. Misch. I am under a lasting obligation to Dr. Howard A. Coombs and Professor George E. Goodspeed for their valuable advice and many courtesies. I am deeply appreciative of the many hours expended by Dr. Victor Clauson in teaching me--as well as many others--the art of preparation of petrographic thin sections. I am grateful to Dr. John C. Hazzard, Union Oil Company of California, for his ready assistance and encouragement. I wish to acknowledge the obligation I owe to Dr. Harold E. Enlows and the University of Tulsa for the use of petrographic microscopes and photomicrography equipment.

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Finally, I acknowledge the constant encouragement of three ladies: my wife, my mother, and Mrs. Carolyn Stockwell, former secretary of the Department of Geology.

PLATE XI

Typical alpine meadow terrain of the Cascade Crest, as seen north of Pear Lake. The Monte Cristo group lies in the distance to the northwest.

PLATE XII

Looking north toward Cady Pass from near Pear Lake. The nearest peak (left) is gneiss; the rocks to the right are schist. Glacier Peak lies in the distance.

PLATE XIII

Robin Mt. (left) and Saddle Gap. Cady Pass lies just beyond Robin Mt. Glacier Peak and the White River Glacier (right edge) in the distance. A large andesite dike is the source of the lighter-colored talus near the summit of Robin Mt. (upper left).

GEOLOGICAL SETTING AND OUTLINE OF BEDROCK GEOLOGY

Introduction

The Cascade Mountains of the State of Washington are a north to south trending range which, in the broadest sense, may be considered as a topographic unit. However, the rocks and the structures of the range vary greatly from place to place, and three major provinces can be recognized.

South of Snoqualmie Pass, which lies about 30 miles southwest of Stevens Pass (Plate B, 1-7), most of the exposed rocks are Tertiary volcanics (Culver, 6; Smith and Calkins, 42) which mask the older rocks and their structures. This area, mantled by volcanic rocks, is the Southern Cascade Mountains Province.

South of U. S. Highway 2 and Stevens Pass, and extending through the area of U. S. Highway 10 and Snoqualmie Pass, the rocks are mostly Tertiary sediments and volcanics. Locally, pre-Tertiary rocks are exposed. The largest mass of the pre-Tertiary rocks is the Mt. Stuart uplift (Smith, 41) the granitic rocks of which probably are coextensive with the granitic rocks of the Beckler River-Nason Ridge area. Other, smaller uplifts which expose pre-Tertiary rocks occur. One of these areas lies southeast of Snoqualmie Pass, and there the Easton schist (Smith and Calkins, 42) crops out. This terrane of dominantly Tertiary rocks, with subordinate pre-Tertiary rocks, is the Central Cascade Mountains Province.

North of Stevens Pass the Cascade Range is a complex mass of metamorphic, sedimentary, and igneous rocks which are dominantly of pre-Tertiary age. This terrane of older rocks forms the Northern Cascade Mountains Province.

The Beckler River-Nason Ridge area is centrally located in the southernmost part of the Northern Cascade Mountains Province. The rocks are

Chilliwack correlatives can be considered as being present. This isochemically metamorphosed sequence is definitely shown to be equivalent to the Skagit gneisses (Misch, 23) which are granitized correlatives.

Near Granite Falls, Washington, Thompson, Wheeler, and Danner (46) have described middle and upper Permian fusulinidae. In addition, Danner (Misch, 23) has discovered Permian fossils in a number of other localities in the western foothills of the northern Cascades.

Daly has described Triassic fossils at Cultus Lake in British Columbia (8). However, Frebold's redetermination (9) indicates that these fossils are lower Jurassic in age. In addition, Triassic fossils have been found by Rice (37) in British Columbia, close to the Canada-United States border, and earliest Jurassic fossils have been described from British Columbia in localities lying within the Northern Cascade Mountains Province (Daly, 8; Frebold, 9).

In the "Limestone Belt" of Okanogan County, Washington, Misch (26) has found a sequence of locally fossiliferous rocks which grade into metamorphosed rocks which range from the chlorite to the sillimanite zones. The carbonate member of this section was considered to be probable Triassic in age by Waters and Krauskopf. Misch reported on the metamorphism of these rocks (26), and his collections of fossils indicate a probable upper Triassic age for the fossiliferous part of the section, thus confirming Waters' and Krauskopf's original determination (Misch, oral communication).

Cretaceous and earlier fossils have been described from the San Juan Islands by McClellan (22). The marine Nooksack formation of Misch (23; and oral communication) contains late Jurassic and early Cretaceous faunas. This formation is underlain by probable middle Jurassic geosynclinal volcanic rocks. The marine sedimentary rocks of the Nooksack formation grade into phyllites. Because of this low grade metamorphism of these Jurassic and Cretaceous rocks, Misch (oral communication) suggests that other metamorphosed rocks of medium and high grade may be older than these upper Jurassic and lower Cretaceous sedimentary rocks. However, evidence for this is inconclusive, especially since Misch (oral communication) has found upper Paleozoic volcanic and sedimentary rocks in a non-metamorphosed state north of the Nooksack Valley. Unfortunately, at no place has there been found a depositional contact between the upper Paleozoic rocks and the Mesozoic rocks. All observed contacts are tectonic.

Although the main synkinematic regional metamorphism of the northern Cascades is, according to Misch, probably pre-upper Jurassic, he reports that at some places a static metamorphism, associated with local granitization, is younger than the upper Jurassic-lower Cretaceous sequence. One locality is east of Ross Lake, Washington. Another, north of Jack Pass (Plate B, D-1), was found by H. Zwart (oral communication) of the University of Leiden. Zwart mapped an area northwest of the Beckler River-Nason Ridge area in 1954-55 while participating in the Northern Cascades project as a U. S. State Department post-doctoral research fellow.

Irrespective of the exact ages of the rocks involved and of the absolute age of periods of orogeny and of metamorphism, Misch believes (oral communication) that the following sequence of events can be considered as definitely established for the northern Cascades:

1. An early period of orogeny, with highly mobile forms of folding was associated with widespread regional metamorphism and synkinematic granitization;
2. A later orogeny, which affected upper Jurassic and lower Cretaceous rocks, as well as older rocks, was characterized

by folding and major overthrusting. These overthrusts were directed to the east-northeast on Jack Mountain, east of the Skagit gneisses (Misch, 23), and to the west-southwest in that area west of the Skagit gneisses which lies between the Canadian Border and Cascade Pass (Misch, oral communication). Thrusts directed to the west southwest also have been found near Darrington (J. Vance, personal communication), and in the region of Mt. Baring and Gunn Peak (R. Yeates, personal communication). This thrusting produced mylonitization and low grade retrogressive metamorphism, and, in the case of the Skagit gneisses, phyllonites were formed in the immediate vicinity of the thrusts. In connection with this thrusting, Misch found, south of Cascade Pass, that rocks originally of kyanite facies have retrogressed to the chlorite zone, with a local production of chloritoid. Misch also points out (23) that the phyllitic metamorphism of the Jurassic-Cretaceous sedimentary rocks belongs in this same phase and tends to be associated with the post-early Cretaceous overthrusting.

This sequence of events is rather definitely established. Less definite is the absolute age of these two major phases of orogeny. Misch (personal communication) believes the first phase is earlier Mesozoic in age. Although no Triassic rocks have been described in the northern Cascades of Washington, upper Triassic rocks are widespread immediately north of the international boundary in the Princeton map area (Rice, 37). These rocks are in part metamorphosed and synkinematically granitized in the same manner as the Skagit gneisses. If upper Triassic rocks are present in the "Limestone Belt" of Okanogan County, Washington, they have likewise definitely participated in the main orogenic metamorphism and granitization (Misch, oral communication). As suggested previously, this orogeny is probably earlier than the middle and upper Jurassic and the Cretaceous rocks. Therefore, this first orogeny probably occurred during latest Triassic or early Jurassic time.

Inasmuch as the Nooksack formation is composed of essentially conformable upper Jurassic and lower Cretaceous marine sediments (Misch, personal communication), there was no Nevadian orogeny in the northern Cascades.

The age of the second main orogeny which produced folding, large scale thrusting, some low grade metamorphic effects, and, in the case of pre-existing high grade rocks, some retrogression, is definitely post-early Cretaceous. Misch (23) believes that this orogeny pre-dates the Swauk formation which is of Paleocene age and may include rocks of latest Cretaceous age. Moreover, he believes that this orogeny is probably earlier than the late Cretaceous Nanaimo formation of Vancouver Island and the San Juan Islands. Thus, this second orogeny occurred in middle or early late Cretaceous time, and the orogeny that affected the Swauk and Nanaimo formations would be a third and less intense orogeny of still later date (Misch, 23). As mentioned above, some higher grade static metamorphism and granitization have, at least locally, occurred after the second main orogeny. In addition, many of the massive directionless granitic rocks of the northern Cascades, including, as in the Chilliwack batholith, statically granitized as well as mobilized and neomagmatic varieties, are later than the second (post-early Cretaceous) orogeny (Misch, 23), and are in part even later than the post-Swauk folding (Vance, Misch, personal communication).

In the Beckler River-Nason Ridge area there is no superposed retrogression which would indicate that this area had participated in the folding and thrusting of the second main orogeny. Regional considerations indicate that the thrust sheet of Mt. Baring and Gunn Peak must have gone over the Beckler River-Nason Ridge area, and that the root zone of the thrust must lie east of this area. Thus, the metamorphosed rocks of the Beckler River-Nason Ridge area apparently are the result of the early period of orogeny during which highly mobile forms of folding were accompanied by widespread regional metamorphism and synkinematic granitization.

Outline of Bedrock Geology

The crystalline rocks of the Beckler River-Nason Ridge area are mainly phyllites, schists, gneisses, and directionless granitoid rocks. The majority seem to have been derived from sediments through a metamorphism of regional extent. This metamorphism, which has affected most of the rocks of the northern Cascades, may be termed regional orogenic metamorphism. Moreover, these rocks have been subjected to a metamorphism which was contemporaneous with a penetrative differential deformation. That is, these rocks are the products of synkinematic metamorphism. The phyllites, and most of the schists, are the results of an isochemical metamorphism in which the chemical composition of the original sedimentary rocks has not changed materially during the period of metamorphism. The gneisses and the directionless granitoid rocks, on the other hand, have been changed significantly by the addition of chemical substances. Thus, these rocks are the resultants of a metasomatic metamorphism. In many of the gneisses there are repeated alternations or bands, with layers of granitic rock in juxtaposition to layers of definitely recognizable, isochemically metamorphosed schist. These heterogeneous rocks are termed migmatites, and the term migmatitic is applied to those rocks where a derivation from migmatites can be proved. This applies whether or not the final rock is granitoid in character.

Part of the schists and gneisses, and all of the directionless granitoid rocks, have undergone a static metamorphism--a type of metamorphism not accompanied by penetrative deformation. In the case of the rocks of the Beckler River-Nason Ridge area, this static metamorphism has followed a phase of penetrative deformation, both being continuous. Hence, the term post-kinematic metamorphism applies to these rocks.

In the discussions that follow the rocks of this area will be described in the order of ascending metamorphic grade.

Isochemically Metamorphosed Rocks

Those rocks which show only an isochemical metamorphism are the phyllites and the schists. More detailed descriptions of the phyllites and the several varieties of schist are reserved for later chapters. A sketch of these rock types is presented here.

Phyllites. The phyllites represent the lowest grade of metamorphism present in this area, and consequently they are most closely allied to the original sedimentary rocks. The phyllites are restricted to outcrops of limited extent in the westernmost part of the mapped area. Plate B shows the outcrop pattern of the phyllites.

The prevailing strike of the phyllites is northwest to southeast, and most are minutely isoclinally folded. The folds are uniformly overturned to the southwest. The majority of these rocks are sericite-chlorite phyllites, and are representative of the low grade zone or epizone (Grubenmann, 19) of regional metamorphism.

Smith (45) has designated the phyllitic rocks in the vicinity of Skykomish and the Beckler River-Nason Ridge area as belonging to the Peshastin formation. The Peshastin formation of Peshastin Creek is a dark phyllitic slate which locally, as determined by Misch (personal communication), has been subjected to a low grade contact metamorphism with the resultant local production of a chiastolite schist. However, there is no faunal or lithic basis for correlating the Skykomish Basin phyllites with the geographically distant type Peshastin, especially in view of the fact that phyllites in the northern Cascades range in age from Paleozoic to Cretaceous. Therefore, the phyllites of the Beckler River-Nason Ridge area are not designated as belonging to the Peshastin formation. Rather, they are described simply as pre-Tertiary (i.e., pre-Swauk) phyllites.

Schists. The schists are one of the most common groups of rocks cropping out in the Beckler River-Nason Ridge area. They do not form one well-defined and continuous belt, but occur in many parts of the mapped area (Plate B). The schists crop out most extensively east of the Cascade Crest, and they are the dominant rock type in the area east of Pear Lake (Plate B, D-6), on Mt. Fernow (Plate B, I-8), and on Rock Mountain (Plate B, G-10). There are also lesser bodies of schist west of the Cascade Crest. Specifically, these occur on the southwest and south flanks of Evergreen Mountain (Plate B, E and F-3), on the east flank of Capitan Peak (Plate B, H-5), and on Robin Mountain (Plate B, B-5).

The largest single area of schists is that in the vicinity of Rock Mountain. Here they form a belt up to two and one-half miles wide, and in the mapped area they have been traced for almost twenty miles along the strike. This schist unit, however, is not restricted to the mapped area. Similar schists have been described about ten miles to the southeast in the vicinity of Chiwaukum Creek (Page, 30), and Misch (personal communication) has observed these schists in the valley of the Whitechuck River, over thirty miles to the northwest.

Both east and west of the Cascade Crest the schists also occur as smaller bodies enclosed or intercalated in gneisses or directionless granitoid rocks (Plate B). Whether occurring in large units, or as intercalations in other rocks, or as limited remnants in granitic rocks, the schists invariably are gradational with the adjacent rock types.

Schists crop out at both the highest and the lowest elevations in the area. The Chiwaukum Mountains, lying south of the mapped area (Plate A), are composed of schist, and attain elevations in excess of 8,000 feet. Rock Mountain, the bulk of which is schist, is one of the culminations of Nason Ridge, and exceeds 7,300 feet in elevation.

The prevailing strike in the schists is northwest to southeast, as it is in the phyllites. The schists generally are folded isoclinally, and it is probable that any larger structures not readily visible are also isoclinal folds. Generally the schists have a steep northeasterly dip, and the folds typically are overturned to the southwest.

The schists are extremely variable in composition, and for convenience they have been divided into three groups. The largest group is that of the biotite-quartz schists, many of which have an aluminum excess indicated by the presence of kyanite and staurolite in the mesozonally metamorphosed rocks, and sillimanite in the katazonally metamorphosed rocks (Grubenmann, 19). A less extensive group is that of schists in which hornblende is a major constituent. Finally, there are very subordinate bands of schistose amphibolite intercalated in the more abundant biotite-quartz or hornblende-bearing schists.

Though the schists are variable in composition and texture, they are rather uniform in appearance. Generally they weather to a dirty reddish-brown color, and apart from the subordinate amphibolites, it is difficult to distinguish the various types of schist in the field. The major groups to be described have been differentiated by petrographic methods.

Page has mapped the same schists immediately south of the Nason Ridge area, and he named them the Chiwaukum schist. He (30, figure 4) describes this unit as.......

> "foliated rocks ranging from phyllite to fine gneiss. Varieties include gray quartz-biotite-graphite schist, hornblende-quartz-feldspar schist, garnet-quartz-biotite schist, and fairly abundant green schist, commonly composed largely of hornblende, actinolite, chlorite, and talc."

Recently the term, Chiwaukum schist, has been used in the sense of any pre-Tertiary metamorphic rock. The writer believes that both Page and more recent workers have used the term Chiwaukum in too broad a sense, actually meaning nothing but pre-Tertiary schists of various kinds. The term, if used at all, should be restricted to the aluminum-excess sequences of schists found at Page's type locality on Chiwaukum Creek. If so restricted, the term could be applied to the kyanite, staurolite, and sillimanite schists of the Beckler River-Nason Ridge area.

Gneisses and Directionless Granitoid Rocks

The gneisses and directionless granitoid rocks of this area generally are transitional with the isochemically metamorphosed schists. These granitoid rocks are the result of both a synkinematic and a postkinematic metamorphism involving the metasomatic addition of chemical substances. The terms granitic and granitoid are used in this paper in the broad sense of any granular rock with a composition ranging from diorite to granite.

The migmatitic gneisses are the variety of granitoid rocks which is most closely allied to the schists. These gneisses typically are thinly-banded, with alternations of fine-grained, dark-colored schist and coarser-grained, light-colored gneiss. These heterogeneous rocks are clearly migmatites which show all transitions between definitely recognizable isochemically metamorphosed schist and metasomatically-derived granitic gneiss, and they demonstrate an incomplete process of granitization.

The most extensive outcrops of the migmatitic gneisses occur along Nason Ridge (Plate B) and in the northern part of the area between Grizzly Peak (Plate B, E-5) and Cady Pass (Plate B, B-5). Future field work probably will demonstrate that the Nason Ridge outcrops and the Cady Pass outcrops can be connected to form one broad belt.

Smaller areas of these migmatitic gneisses crop out both east and west of the Cascade Crest (Plate B). The most extensive of these smaller areas extends from west of Barrier Peak (Plate B, I-6) to the vicinity of Silica Mountain (Plate B, D-3).

Coarser-grained gneisses of granitoid composition are subordinate to the migmatitic gneisses in areal extent. These gneisses, unlike the migmatitic gneisses, are not prominently banded. Rather, the foliation generally is defined by slight variations in composition, with thin stringers of a higher mafic mineral content alternating with less mafic-rich zones. Moreover, a part of the foliation is defined locally by a preferred orientation of part of the minerals. Locally, it is only this slight preferred orientation of the mafic minerals which distinguishes these gneisses from directionless granitoid rocks.

The granitic gneisses generally form narrow bands, and show all possible gradations between migmatitic gneisses on one side and directionless granitoid rocks on the other. On Barrier Peak (Plate B, I-7) and around Pear Lake (Plate B, C-5), these gneisses are the dominant rock type. The lineation of these gneisses and their subordinate included bands of schist and migmatitic gneiss parallels the adjacent, more clearly-foliated rocks. In all cases the granitic gneisses are completely gradational with adjacent migmatitic gneisses and directionless granitoid rocks.

The directionless granitoid rocks are the most abundant rock in the Beckler River-Nason Ridge area. They range in composition from diorite to granodiorite, but quartz diorites are most common. These granitic rocks form the bulk of the central and southwestern parts of the mapped area, and their most extensive area of outcrop lies west of the Cascade Crest (Plate B). The directionless granitic rocks generally are entirely gradational with adjacent gneisses and schists. Significant exceptions to this occur on Mt. Fernow and on Beckler Peak.

The mapping in the Beckler River-Nason Ridge area shows that the quartz diorites in the vicinity of Stevens Pass (Plates A, B) are probably a northern prolongation of the Mt. Stuart batholith, first described by Smith (41). This poses an interesting problem, inasmuch as the quartz diorites of the Stevens Pass area are largely of replacement origin, whereas the southern part of the Mt. Stuart batholith is clearly intrusive. Thus, migmatites form the northern border of the Mt. Stuart batholith, and there is the seemingly anomalous situation of one side of the batholith being migmatitic, and the other, intrusive. Misch (28) describes a similar situation with regard to the Chilliwack batholith in the northwesternmost Cascades. There, the east side of the batholith is the locus of a static recrystallization of the Skagit gneisses, which themselves are the products of a synkinematic granitization of schists and amphibolites. Yet, on the western side of the Chilliwack batholith there are intrusive contacts, and even isolated intrusive stocks have been produced west of the main western contact of the batholith. Misch (personal communication) ascribes these relationships to mobilization of material of migmatitic derivation.

Miscellaneous Rocks

In addition to the above, there are very subordinate lime-silicate rocks and andesites. The lime-silicate rocks crop out only on Robin Mountain (Plate B, B-5) and on West Cady Ridge (Plate B, B-4); the andesites occur as a flow capping the summit of Bench Mark Mountain (Plate B, B-4) and as a large dike on Robin Mountain.

GEOLOGY AND PETROLOGY OF THE CRYSTALLINE ROCKS

Isochemically Metamorphosed Rocks

Low-grade Rocks

Phyllites

Distribution and structure. The lowest grade metamorphosed rocks exposed in the Beckler River-Nason Ridge area are phyllites. These rocks are of limited areal extent, and they are restricted to the westernmost part of the mapped area (Plate B). Here they crop out east of the lower Beckler River and east of its confluence with the Tye River. The most extensive exposures are in a belt (Pl. B, F-2) which crosses the southwestern spur of Evergreen Mountain and the Rapid River, and then passes transitionally into biotite-quartz schists. The maximum width of this belt across the strike is about 2,000 feet, and its longitudinal extent is at least two miles. A second belt of phyllites crops out about one-half mile south of the confluence of Rapid and Beckler Rivers (Plate B, G-2). A third area in which scattered outcrops of phyllite occur is on the southwestern spur and south flank of Beckler Peak (Pl. B, I-2). This phyllite is well-exposed in a road cut on U. S. Highway 2 about one-half mile east of the junction of Tye and Foss Rivers (Plate B, J-2).

The phyllites generally are poorly exposed. They are not resistant and are easily weathered and eroded. Thus they do not have a distinctive topographic expression. Moreover, the phyllites crop out only at elevations of less than 3,500 feet. Consequently, they usually are masked by the timber and brush prevalent at these lower elevations. The best exposures are in cuts along the Beckler and Rapid River roads, in a short cut along U. S. Highway 2, and in the lower canyon of the Rapid River (Plate B).

The prevailing strike of the phyllites is northwest to southe as it is for most of the foliated rocks of this region. The exception prevailing strike is at the foot of Beckler Peak (Pl. B, J-1) where fa has complicated the structure and produced attitudes which are at vari with the regional strike.

Most of the phyllites are folded isoclinally, the folds bei turned to the southwest. Most of the folds are of small amplitude, a an inch or two from crest to trough. These small folds may be minor tures on the flanks of larger, concealed isoclinal folds. The attitu the phyllites and adjacent schists along the lower Rapid River sugges the phyllites form part of the southwest flank of a major northwest-p syncline (Plate B, F-2 and 3).

The phyllites cropping out near the confluence of the Rapi Beckler Rivers are flanked by biotite-quartz schists into which they The phyllites here typically are of a uniform dark-grey color, with making the foliation planes lustrous. On the southwest spur of Beck the phyllites have undergone later, cross-cutting shearing through spaced high angle faulting. As a result they are shattered, deeply and characteristically of a rusty-brown color.

Description. Most of the phyllites are thinly-foliated a pronounced banding. The banding is an alternation of dark-grey to litic material and thin laminae of quartz. These light and dark ba visible the details of structure in these rocks (Plate XIV). Local are segregation lenticles of quartz up to 12 inches long and 4 inch The majority of these lenticles are curved and occupy the crestal folds.

The following mineral assemblage is typical of the majority of the phyllites: quartz, 60%; sericite, 15%; chlorite, 5%; graphite, 5-10%; and magnetite, 5%. In addition, biotite is present in those phyllites which are transitional with the biotite-quartz schists. The biotite then forms up to 20% of the rock, with an accompanying reduction in the amount of sericite and chlorite.

Accessory minerals include apatite, clinozoisite, and plagioclase. The plagioclase is usually albite, but oligoclase (average, An_{30}) is always present in the biotite-bearing varieties of phyllite. Some specimens of phyllite show traces of epidote, muscovite, tourmaline, and zoisite. The muscovite is more coarsely crystallized than the sericite of typical specimens. Deeply weathered specimens show considerable alteration, with biotite, if present, altering to chlorite, plagioclase altering to sericite, and magnetite altering to limonite with a resultant staining of most of the rock.

The bulk of the ground mass is composed of quartz which is not only concentrated in lenticles and laminae, but is disseminated throughout the rock (Plate XIV). Sericite occurs in bands and as a subordinate component of the quartz-rich laminae. Much of the sericite forms minute elongate plates which parallel the schistosity. The chlorite is mostly clinochlore, and is formed in minute pale-green flakes which also parallel the schistosity. Biotite, when present, is a later constituent, and generally is fine-grained ("sericitiform") and pale-brown in color. However, a few grains of biotite are pale-green and are distinguished from chlorite by a higher birefringence. Some of the biotite replaces earlier chlorite in parallel intergrowth.

Graphite occurs in thin laminae between the quartz-rich and the sericite-rich bands. The graphite laminae apparently were gliding planes. It may be of significance that where graphite is a major constituent of a

PLATE XIV

(Photomicrograph, crossed nicols) Graphitic sericite-quartz phyllite. The quartz-plagioclase (An_{28}) segregation band marginally replaces the finer-grained phyllite. (Spec. E-35, E. side, Beckler River, $1\frac{1}{2}$ miles south of Rapid River).

phyllite or schist, the rock is extremely fine-grained, and lower in metamorphic grade than adjacent, graphite-poor or -free rocks. The writer has remarked this coincidence so many times in the rocks of this area that he wonders if graphite makes a rock resistant to coarse crystallization.

Plagioclase typically forms minute, untwinned anhedra. Usually the plagioclase has indices of refraction less than those of quartz, and apparently is albite. Where the phyllites are in proximity to biotite-quartz schists, and biotite is a major constituent, the plagioclase is twinned and has indices of refraction about equal to those of quartz. These indices, coupled with determinations of composition based on the extinction angles of albite twins, indicate that this unzoned plagioclase is oligoclase with an average composition of An_{28}.

There is an interesting relationship between the quartz-chlorite-sericite phyllites and biotite-quartz schists which occur on the southwest spur of Beckler Peak (plate B, J-2). Here the phyllites have been intruded by mobilized metasomatic granodiorites. Near the contacts of the phyllite with the intruded granitic bodies the phyllite contains biotite. This biotite is later than the main assemblage of the phyllites, and is in part mimetic after the formation of the $\underline{s}_2$ or axial plane cleavage of the phyllite. Most of this biotite is not elongate, and it has only a slight tendency to a preferred orientation.

Intercalated in the phyllites are bands, up to 3 feet thick, of a fine-grained biotite-quartz schist. In this schist there is a later set of shear planes which transects both the $\underline{s}_1$ and $\underline{s}_2$ (cf. p. 43) of the schist. Much of the biotite has been converted to fibrolite in this process of shearing. The contacts between phyllite and schist are marked, locally taking place within 1 inch, measured in "c" (i.e., the axis perpendicular to the initial foliation plane, $\underline{s_1}$). Locally, there is a complete gradation between schist and phyllite which takes place within the space of less than one foot.

This repeated rapid transition from phyllite to schist does not seem possible as a result of regional metamorphism. The evidence apparently indicates that the growth of late biotite in the phyllites, and the formation of thin bands of biotite-quartz schist, is the result of a local thermal contact metamorphism which resulted in a differential biotite growth in the phyllite. These contact effects were restricted to the immediate vicinity of intrusive granodioritic dikes. These dikes, which are discussed in a later chapter, are interpreted as mobilized material of metasomatic derivation. The following facts are introduced in support of this conclusion:

1. The biotite is late and mimetic after the $\underline{s_2}$ of the phyllite and schist. This biotite shows no appreciable elongation or preferred orientation except where later shearing has forced the biotite into alignment along shear zones which lie at an angle to both the $\underline{s_1}$ and the $\underline{s_2}$;
2. The biotite-quartz schist bands are either adjacent to or close to sill- or dike-like bodies of intrusive granitoid materials;
3. Biotite is not present in any of the typical phyllites, nor are there any intercalated bands of biotite-quartz schist more than a few hundred feet from the phyllite-granite contact.

Genetic interpretation. The sericite-chlorite phyllites are typical of the low-grade zone (i.e., epizone of Grubenmann, 19, or chlorite zone of Barrow, 2) of orogenic regional metamorphism. The limited distribution of the phyllites, and the gradation into schists of a higher metamorphic grade, suggests that certain areas did not attain as high a temperature as others during orogenic regional metamorphism. The quartz and graphite content of the phyllites suggests that they were derived from highly carbonaceous shales.

Most of the phyllites show an interesting progression of metamorphic events. The first event was a metamorphic differentiation effected during a crystallization under stress. As a result the phyllite became banded, with alternations of quartz-rich with sericite- and chlorite-rich bands. In this phase s_1, the initial foliation, was produced (Knopf and Ingerson, 21, p. 45; Sander, 40, p. 57). No bedding is visible, and it is presumed that the bedding parallels s_1. Some of the banding, therefore, may be primary, with a later exaggeration through metamorphic differentiation and an accumulation in the crests and a thinning along the flanks of folds.

Subsequent to the formation of the s_1, isoclinal folding occurred. As a result, axial plane cleavage, s_2, was produced at an agle to the s_1. Minute wedges of quartz, transverse to s_1, are evidence of this phase. Where the phyllites transitionally pass into biotite-quartz schists, this latter phase of deformation apparently was accompanied by rising temperatures, for biotite, formed partly at the expense of chlorite, has a preferred orientation parallel to the s_2. A still later generation of biotite, formed transverse to both s-planes, apparently indicates that high temperatures continued after the deformation that produced the s_2 had ceased. Thus, the biotite in the phyllite-schist transitional zones is partly late kinematic, and partly postkinematic.

The latest events involve mineralogical changes caused by weathering.

Medium and High Grade Rocks

Biotite-quartz schists of the kyanite and sillimanite zones.

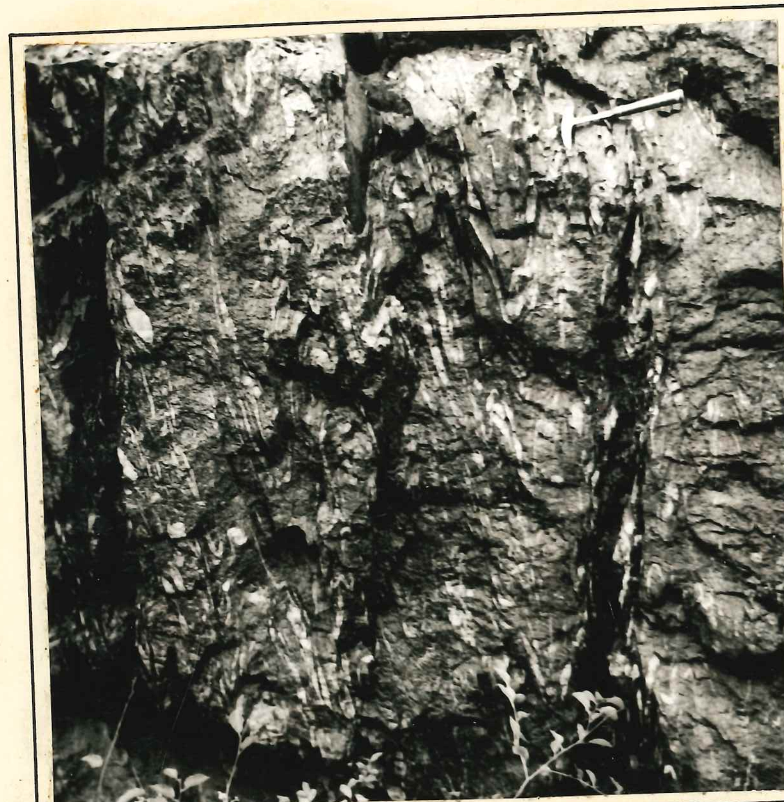
Distribution and structure. The biotite-quartz schists are the most abundant type of schist in the Beckler River-Nason Ridge area. Two of the highest peaks--Mt. Fernow (Plate B, H-8) and Rock Mountain (Plate B, F-10)--are composed of this type of rock. There also are extensive outcrops on the southeastern flank of Evergreen Mountain (Plate B, F-3), on the peak east of Capitan Point (Plate B, H-5), and in the area lying between Grizzly Peak (Plate B, E-5) and Cady Pass (Plate B, B-5).

The schists generally are folded isoclinally and much contorted (Plates XV, XVI). The dips are variable but generally steep to the northeast, and the folds almost invariably are overturned to the southwest.

Many of the biotite-quartz schists are visibly banded, with alternations of light- and dark-colored layers which emphasize even the smallest details of structure (Plate XVII). The biotite-quartz schists have three types of bands. The widest and most prominent bands are composed of medium-grained quartz, and they exhibit a pronounced pinching and swelling across the strike. There also are numerous crescentic quartz lenticles which occupy the crests of the folds. Alternating with these quartz-rich bands are much thinner, fine-grained quartz bands, and thin, dark, fine-grained biotite-rich bands.

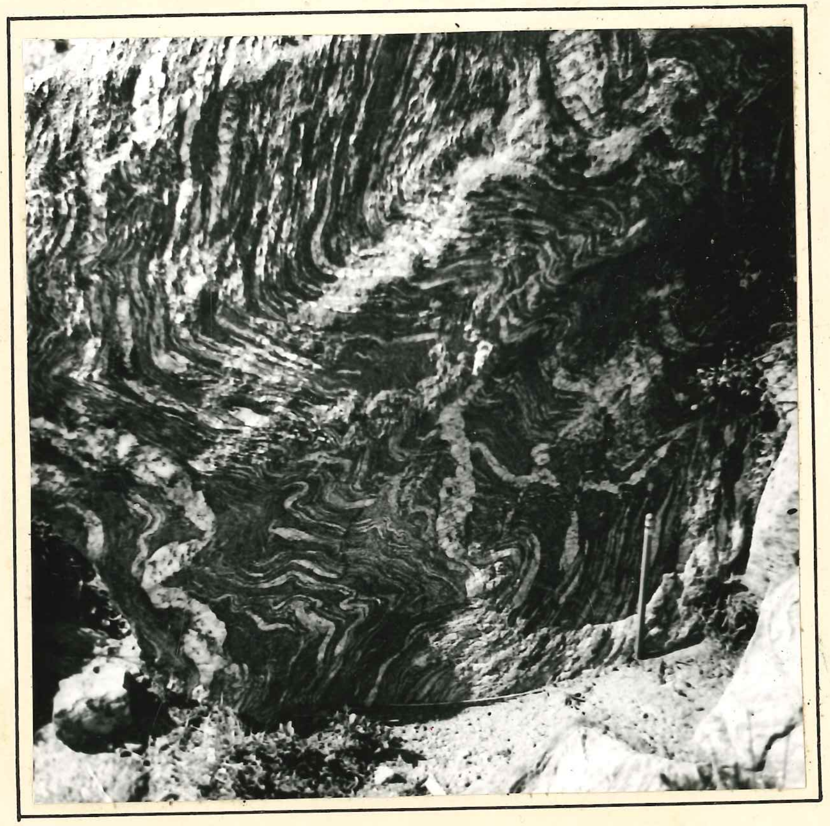
Some of the fine-grained schists have as many as 15 different bands within one inch, while others have thicker bands. Locally there are boudin-shaped quartz aggregates which are up to 18 inches thick perpendicular to the foliation of the schist; i.e., in <u>c</u>, the axis perpendicular to the initial foliation plane, $\underline{s}_1$. These massive segregations of coarser-grained quartz locally extend for a score or more feet in the direction of their longest axis. This long axis parallels the <u>b</u>-lineation of the rocks. The intermediate axis of these aggregates parallels the <u>a</u>-axis in the schist. The usage of the terms <u>a</u>, <u>b</u>, and <u>c</u> <u>axes</u> follows that of Sander (40). In his definitions, the <u>a</u> and <u>b</u> axes lie at right angles to each other in the plane of the foliation,

PLATE XV



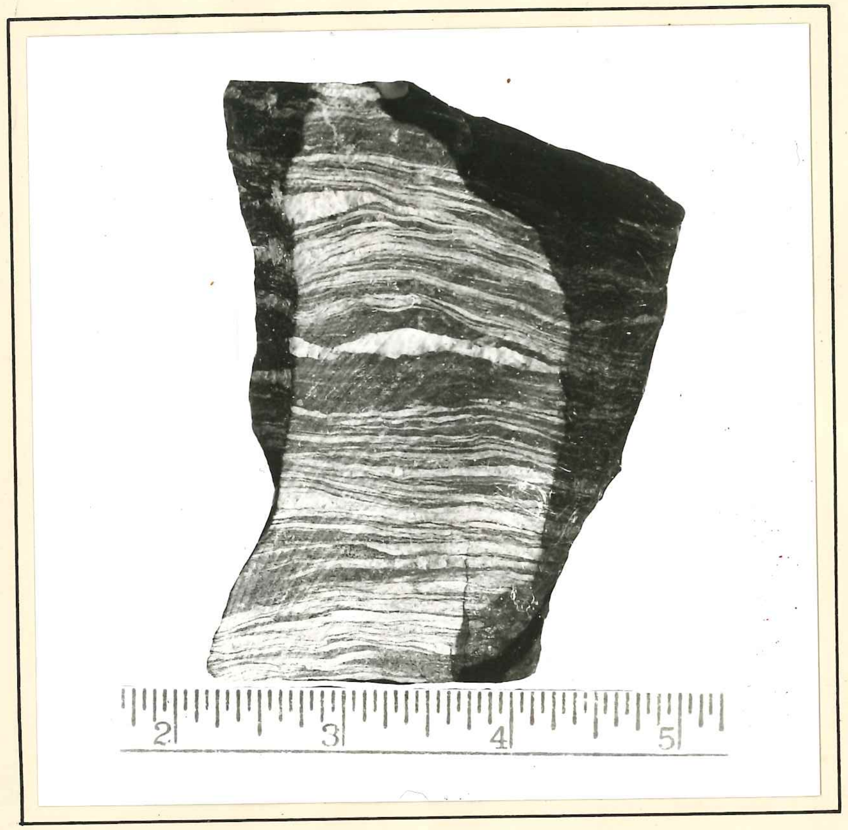
Banded biotite-quartz schist. White exudation bands and lenticles of quartz mark the isoclinal folding and steep dips characteristic of these schists. Immediately west of Schilling Creek on U. S. 2.

PLATE XVI



Banded biotite-quartz schist with intricate minor folding. Later cross-cutting quartz-feldspar replacement veins. East slope of Mt. Fernow.

PLATE XVII



Banded biotite-quartz schist with wider quartz exudation bands, thin bands of quartz-plagioclase mosaic, and dark biotite-rich bands. Small, light-colored spots in the biotitic bands are almandite. Spec. A-24, west flank, Jim Hill Mtn.

with the a axis parallel to the direction of tectonic transport.

A microscopic examination of the biotite-quartz schists shows that many have an abundance of the aluminum silicate minerals kyanite, staurolite, or sillimanite. These minerals are of chemical significance in that they indicate an excess of alumina and strongly suggest that the original materials were rather pure argillaceous sediments. Moreover, these aluminum silicates furnish a convenient method for zoning the schists into metamorphic grades. Following the classical divisions of Barrow (2) and of Grubenmann (19), the presence of kyanite or staurolite indicates that the rock has attained the mesozonal grade of regional orogenic metamorphism. In addition, the presence of kyanite is considered to be conclusive evidence that the rock was subjected to temperatures equivalent to the hotter part of the mesozone. The disappearance of kyanite, and the formation of sillimanite in its place, is considered to be an indication that the highest grade of normal progressive regional metamorphism (i.e., the katazone) has been reached.

Most of the biotite-quartz schists of the Beckler River-Nason Ridge area are of mesozonal grade, and kyanite and staurolite, index minerals of the mesozone, are the most prevalent aluminum silicates in the biotite-quartz schists. However, in the north central part of the mapped area there is a U-shaped zone (Plate B), up to 2 miles wide across the strike, in which there are schists which contain sillimanite as the only aluminum silicate index mineral. Along the borders of these katazonal schists there are narrow transition zones in which kyanite and sillimanite occur together in varying proportions. These border zones are never more than several hundred feet wide across the strike.

The location of the sillimanite-biotite-quartz schists is approximately delineated on Plate B. They crop out within the area which is south of

Top Lake (Plate B, D-6), north of Grizzly Peak (Plate B, E-5), and west of Lake Janus (Plate B, F-7). The northwest extent of the sillimanite-bearing schists had not been determined at the time of the field work. However, in 1954-55, Dr. H. Zwart of the University of Leiden, while participating in the Northern Cascades Project, mapped an area to the northwest and found the northern continuation of this sillimanite belt (personal communication).

The shape of the sillimanite-biotite-quartz schist zone is of interest. Inasmuch as both the sillimanite-bearing and the kyanite-staurolite-bearing schists show the same degree of folding and contortion, it is assumed that both the mesozonal and the katazonal schists were subjected to identical stresses. Thus, variation in stress apparently is eliminated as a factor in this zoning.

The question then arises as to whether variations in depth of burial and hydrostatic pressure were the controlling factors in this development of most of the schists as mesozonal and part of the schists as katazonal in grade. However, this thesis is discarded on the grounds that the isograds are dipping and intersect the horizontal.

Therefore, a thermal control must have determined this zonation. This control would have caused a progressive zoning during regional metamorphism in a manner similar to that described in the Nanga Parbat area of the Himalayas by Misch (24).

Barrow (2), as well as some other petrographers, has assigned kyanite and staurolite to separate zones of regional metamorphism. However, a study of many thin sections demonstrates that these classical zones do not apply to the schists of the Beckler River-Nason Ridge area. On the contrary, kyanite and staurolite are found as contemporaneous and stable constituents in the same schist. Moreover, rocks which separately contain kyanite or staurolite are closely associated with rocks containing both minerals in oriented intergrowth, and the irregular distribution of these two types of rocks shows no zonal pattern whatsoever.

In view of this and the fact that kyanite and staurolite are clearly contemporaneous in many schists of this area, the mesozonal biotite-quartz schists are assigned to a single <u>kyanite-staurolite zone</u>. This zone corresponds to the hotter part of the medium grade or mesozone of regional metamorphism (Grubenmann, 19). It is of interest that other petrographers, including Read and Misch, have previously questioned this concept of separate zones for kyanite- and staurolite-bearing rocks.

In those rocks which are transitional between the mesozone and the katazone, and contain kyanite and sillimanite as stable and contemporaneous constituents, staurolite is absent. This absence of staurolite presumably indicates that kyanite has a somewhat wider range of stability and can exist at higher temperatures. No

The occurrence of sillimanite--a high temperature aluminum silicate--as a stable constituent of some of the schists is indicative of the high grade or katazone of normal progressive, synkinematic regional metamorphism. Where kyanite and sillimanite occur together, it is suggested that the rock is in a transitional zone which corresponds to the coolest part of the katazone.

Many of the schists contain that variety of sillimanite known as fibrolite. These fibrolite aggregates usually can be seen to have formed in connection with a later shearing and squeezing of biotite, and no zonal significance is attached to this late and fibrous variety of sillimanite.

The examination of the biotite-quartz schists impresses one not only with the distinct banding but also with the high content of quartz. An average biotite-quartz schist contains about 50% quartz, though the content ranges from a low of 20% of the rock to a high of about 60%. The wider quartz bands (Plate XVII), lenticles, and boudin-like aggregates are composed of anhedral crystalloblasts averaging 1 mm. in size. These bands contain small amounts of elongate biotite and accessory graphite which occupy positions of random orientation in the intergranular spaces. Locally, there are small anhedral individuals or irregular aggregates of plagioclase lying between the larger quartz grains. Usually the plagioclase is untwinned, but albite and pericline twins do occur, and the composition of the plagioclase has a range from An_{30} to An_{25}. It is noteworthy that this plagioclase has the same composition as that occurring in the other two types of bands which make up the rock.

The quartz bands have participated in the deformation of the schists, and are a part of the isochemical metamorphism of the rock. This is indicated by the undulatory extinction of the crystalloblasts, the sheared marginal areas which subsequently have been recrystallized, and the inclusions of elongate biotite. Moreover, the pinching and swelling of the bands along the strike and the accumulation of quartz in the crests of folds, indicates that the thicker bands are the result of a metamorphic differentiation under conditions of active stress. Thus, they may be termed <u>exudation</u> or <u>segregation bands</u> which separate zones of intense shearing.

These quartz exudation bands usually are adjacent to thin, greyish, quartz-rich, biotite schist bands (Plate XVIII). These bands consist of a very fine-grained mosaic of strained, irregularly-shaped, usually equidimensional quartz, with subordinate biotite and plagioclase. The structure of these bands is best described as granulose, or, after Misch, as a "xenoblastic polygonal mosaic". Elongate biotite and very subordinate magnetite, graphite, and garnet are aligned to form a well-marked but discontinuous foliation.

PLATE XVIII

1.0 mm.

(Photomicrograph, crossed nicols) Banded biotite-quartz schist. Above: quartz-rich band with large grains of strained quartz and subordinate plagioclase. Middle: finer-grained mosaic of quartz and plagioclase. Below: biotite-rich band. Spec. B-10, southeast flank of Union Peak.

The third type of band is dark-colored, rich in biotite, and forms a pronounced foliation (Plate XIX). In this type of band a fine-grained, irregularly-shaped mosaic of quartz is associated with large quantities of elongate biotite which forms layers up to several millimeters thick. These biotite-rich layers vary in longitudinal extent, exceptionally being continuous for several feet. The biotite generally is marked by a pleochroism of X: colorless to pale yellow-green; Y: reddish-brown; and Z: reddish-brown. The biotite flakes generally contain well-developed pleochroic haloes around zircon nuclei (Plate XXII). The biotite generally forms about 30% of the rock, and has a range from 20% to 35%. Graphite is frequently aligned along the cleavage planes of the biotite, and grains and irregular aggregates of magnetite are common inclusions within the biotite.

Generally there are two generations of biotite. The older generation consists of parallel flakes lying in the plane of foliation. These individuals are elongate, average 0.5 mm. in length, are 5 to 7 times as long as they are thick, and have irregular terminations. At the apices of the minute isoclinal and sub-isoclinal folds the biotite is bent and, locally, has recrystallized in polygonal arcs. This first generation of biotite is synkinematic, and has resulted from a crystallization contemporaneous with deformation (Plates XVIII, XX).

The younger generation of biotite generally is subordinate in quantity. It consists of irregularly-shaped plates (Plate XIX), up to 1 mm. wide, which show no appreciable elongation. These plates either approximately follow the foliation marked by the synkinematic biotite, or grow across it with random orientation. Helicitic textures are common, and the foliation, marked by lines of graphite and magnetite, is inherited by the second generation biotite without disturbance. This generation of biotite

PLATE XIX

1.0 mm

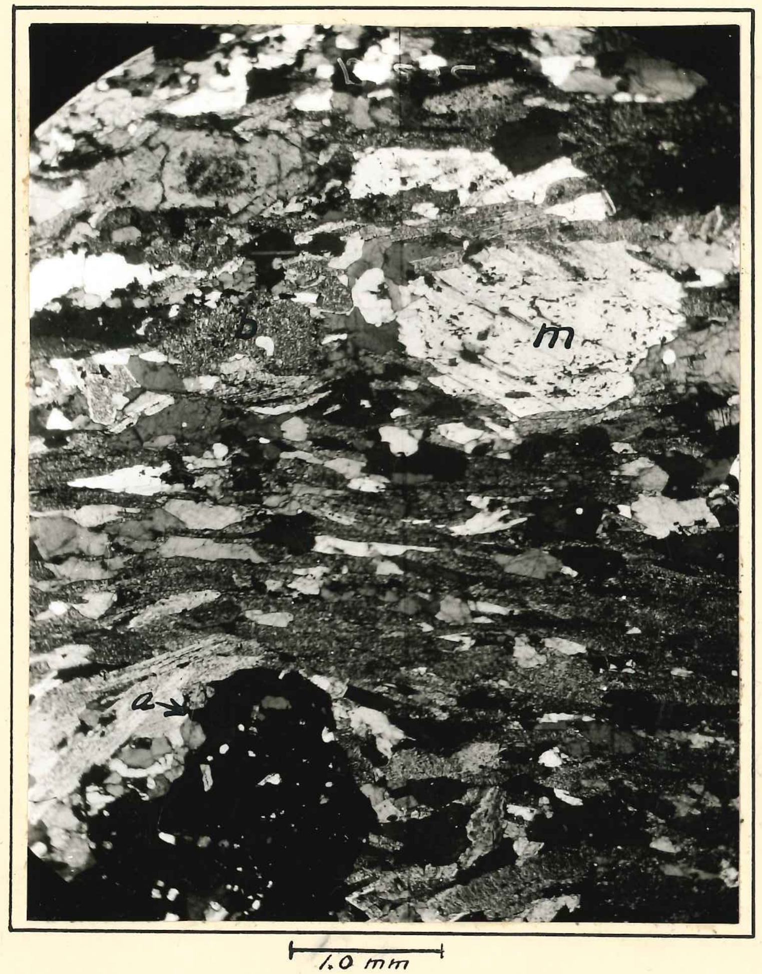
(Photomicrograph, plane polarized light) Contorted biotite-quartz schist. Post-kinematic crystallization of biotite both along and across the foliation. Graphite bands, marking the foliation, are included in the biotite. Spec. A-2, main peak, Mt. Fernow.

apparently represents a period of dying deformation and the static phase of crystallization following it.

Plagioclase is a common constituent of the biotite-quartz schists. In approximately half of the schists plagioclase is a minor constituent, averaging less than 5% of the rock. But in other schists the plagioclase averages about 15% of the rock, and, exceptionally, 45%. The composition of most of the plagioclase is within the range An_{30} to An_{25}. Locally, the plagioclase is a calcic as An_{40}. It is significant that the few specimens having the more calcic plagioclase are poor in quartz and rich in biotite. One typical sample has the following approximate mineral composition: quartz, 27%; biotite, 35%; and plagioclase (An_{36}), 35%. This probably indicates a control by the composition of the original sediments, with the inference that this sediment was relatively rich in sodium and calcium. Such a sedimentary rock might have been a shaly greaywacke, containing andesitic or basaltic detrital material, or a shale containing a tuffaceous admixture of similar (i.e., andesitic or basaltic) material. It is possible that the high plagioclase content is indicative of a moderate amount of "concealed" sodium introduction. However, this is unlikely inasmuch as the minerals appear to be contemporaneous and the rocks seem definitely isochemical in texture.

Where the plagioclase is a contemporaneous constituent of the schists, and apparently has formed during the isochemical metamorphism of the schists, it usually occurs in minute anhedra which form an intricate interlocking pattern with quartz grains. The individual crystals of plagioclase rarely exceed 0.3 mm. in greatest dimension. Most are untwinned, and unzoned, but locally there are albite, Carlsbad, or pericline twins, the last being most prevalent. Bent and ruptured crystals, marginal shearing, irregular extinction, and minute inclusions of graphite and elongate biotite indicate that the plagioclase participated in the deformation of the rock.

PLATE XX



(Photomicrograph, crossed nicols) Mica-quartz schist with synkinematic biotite marking the foliation, and randomly oriented postkinematic biotite (b) and muscovite (m). Almandine garnet (a) at lower left. Spec. B-23c, summit of Nason Ridge east of Lake Merritt.

In summary, the typical biotite-quartz schist is composed of three distinct types of bands, with quartz, biotite, and plagioclase the dominant minerals. If Tyrrell's definition (47, p. 274) is followed, this type of rock, with its alternation of bands and lenticles, would be called "gneissose". However, most metamorphic petrographers do not follow this usage and would unquestionably classify these rocks as banded schists. In the present paper the term "gneiss" is restricted to those fine- to coarse-grained foliated rocks which possess a high feldspar content and approach a granitoid composition.

This main type of schist is the basis for a number of special varieties which are characterized by the presence of additional constituents such as one or all of the following minerals: almandine garnet, kyanite, staurolite, sillimanite, and fibrolite.

Almandine garnet has a patchy distribution in rock types which otherwise have identical compositions (Plates XX, XXI). The garnet generally occurs in small crystalloblasts about 1 mm. in diameter. Locally, the garnet forms porphyroblasts up to 6.5 mm. in diameter. The garnet shows differing times of crystallization with regard to phases of deformation. Some garnet porphyroblasts have a well-defined, S-shaped internal s (Sander, 40, p. 57) consisting of graphite and quartz inclusions. This indicates that there was rotation during the growth of the garnet. Others exhibit a straight internal s which has been rotated 90° or less. This indicates that there was a static garnet growth followed by renewed deformation (Plate XXII). In either case, the garnet is later than the primary deformation which has formed the s_1 of the schist. The garnet, through crystallization force, invariably has bowed-out the biotite on both sides across the foliation, and there has been a random growth of biotite in the "stress shadow areas" resulting from the garnet growth (Plate XXII).

In the biotite-quartz schists which have undergone retrogression, some of the garnet porphyroblasts are altered in part to chlorite. This "retrogression", however, may be the result of weathering.

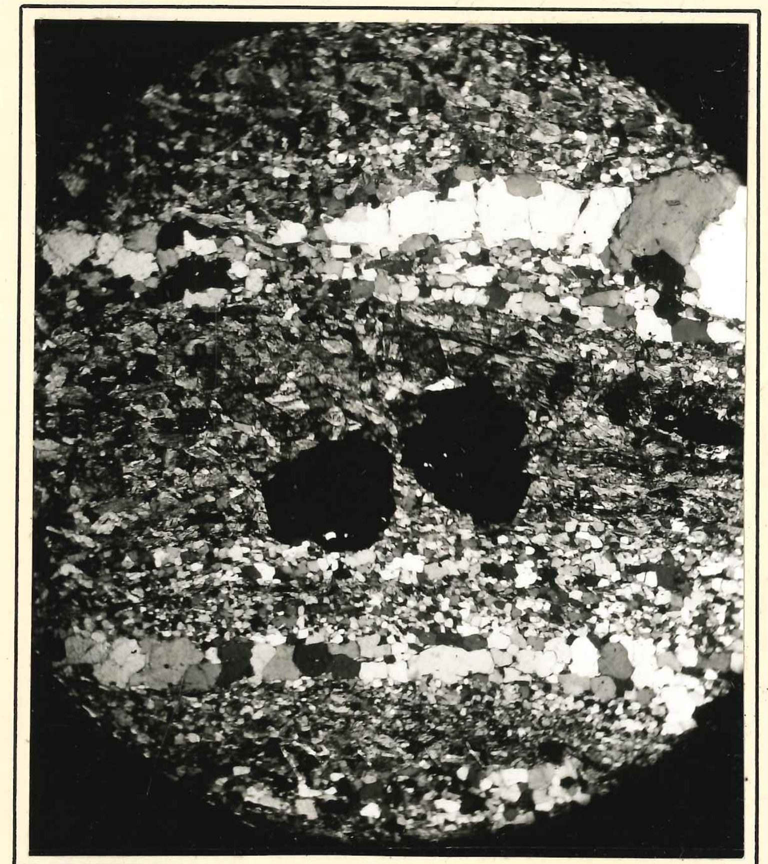
Kyanite and staurolite, index minerals of the hotter part of the mesozone of regional metamorphism, are common constituents of the schists and occur together or separately (Plate XXV). Locally, they form up to 10% of the rock.

Kyanite generally is confined to the darker, biotite-rich bands of the schist, and forms broad, elongate, tabular plates with the c-axes lying in the plane of schistosity. The general occurrence of the kyanite (and staurolite) in the biotite-rich bands, and not in the intervening quartz-rich bands, may be indicative of compositional variations in the original sediments. The kyanite probably developed in aluminum-rich bands which originally were highly argillaceous; the quartz in aluminum-poor, sandy layers.

In many specimens the kyanite is bent, particularly at or near the axes of folds. Then the kyanite commonly contains an internal s of graphite. In a few cases the kyanite has grown across the plane of foliation (Plate XXIII). This phase of kyanite growth is unusual, and is later than the deformation. It apparently was the result of high temperatures which persisted under static conditions.

Staurolite forms rounded, irregular grains or, locally, six-sided idioblastic cross sections which are elongated in the plane of foliation. Irregularly-shaped inclusions of quartz and graphite, and a helicitic texture, marked by the inclusion of lines of graphite and magnetite, are common. Generally the staurolite idioblasts bow-out the biotite on either side across the foliation, indicating that crystallization of the crystals was somewhat later than the primary deformation which formed the s_1. A very subordinate

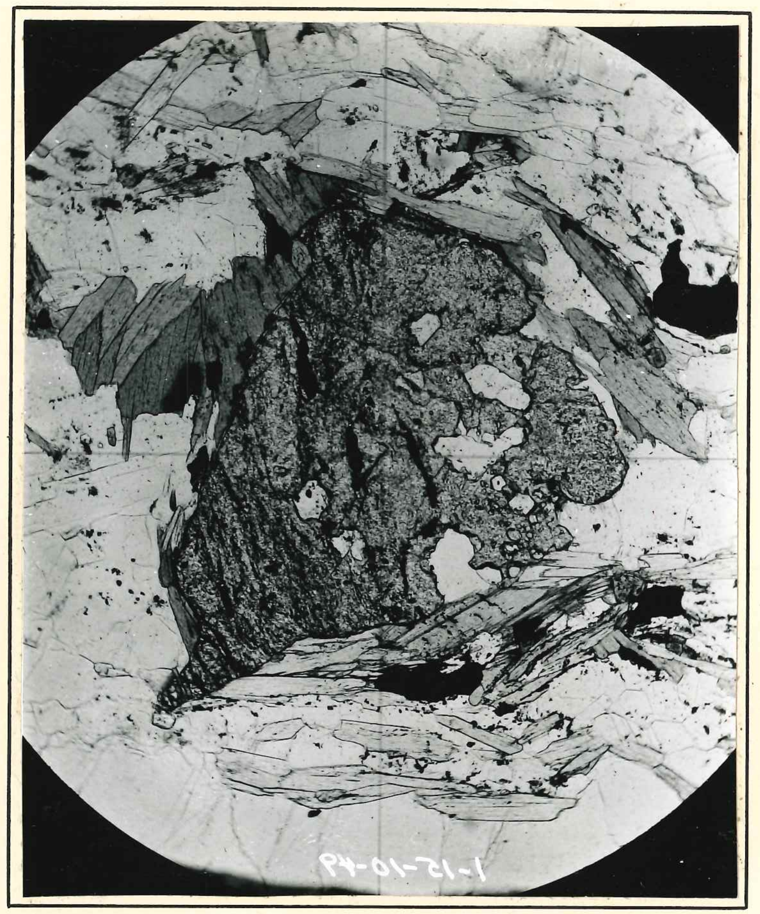
PLATE XXI



1.0 mm

(Photomicrograph, crossed nicols) Almandite porphyroblasts (dark) in biotite-rich layer of banded biotite-quartz schist. Spec. A-24, west flank, Jim Hill Mt.

PLATE XXII



0.5 mm

(Photomicrograph, plane polarized light) Almandite with an internal s of graphite and magnetite displaying post-crystalline rotation. Plane of foliation of biotite-quartz schist from left to right. Randomly oriented biotite has formed in the "stress shadow" areas left and right of the garnet. Biotite plate at upper left contains a dark pleochroic halo (h) around a small zircon grain. Spec. A-44, just west of Schilling Creek on U. S. 2.

part of the staurolite grows with a random orientation across the foliation. Thus, the staurolite is in part synkinematic, and is in part postkinematic (Plate XXIV).

On the southwest flank of Rock Mountain (Plate B, G-10) and on the north spur of Beckler Peak (Plate B, H-2), there are fine-grained, highly carbonaceous biotite-quartz schists which appear to contain large (up to 20 mm. in length) porphyroblasts of chiastolite with well-developed graphite crosses (Plate XXV). A microscopic examination shows that these porphyroblasts are no longer chiastolite, but are an intergrowth of kyanite and staurolite or, locally, a fine-grained aggregate of muscovite. It is noteworthy that in this process of one mineral becoming pseudomorphous after another, the graphite crosses of the chiastolite were inherited without any apparent rearrangement being caused by the growth of the kyanite and staurolite. These rocks record a significant progression of metamorphic events. The chiastolite apparently formed during a static period with temperatures probably in the warmer part of the mesozone. Subsequent to this static phase, dynamothermal metamorphism in the warmer mesozone produced the kyanite and staurolite, and recrystallized under lower temperature the muscovite. The chiastolite is interpreted on the basis of its preference for an environment without stress.

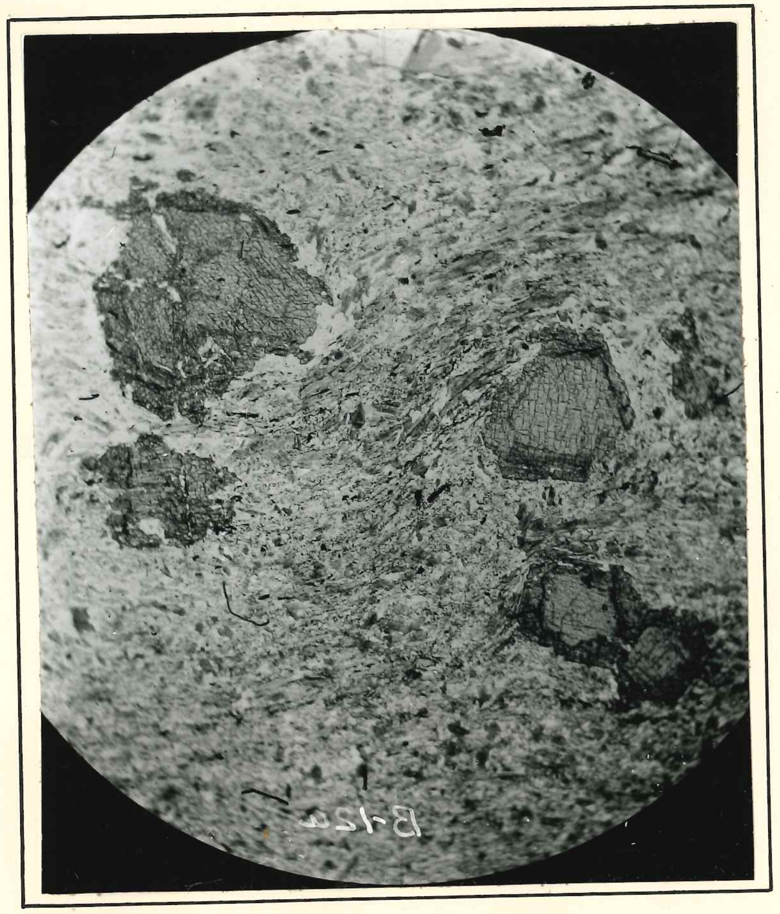
Sillimanite locally forms up to 10% of some of the schists (cf. discussion, p. 47). This aluminum silicate, indicative of the high grade or katazone of regional metamorphism, generally forms columnar aggregates and thin needles which are oriented parallel to the foliation. The sillimanite generally is bent, and is usually restricted to the biotite-rich bands of the rock (Plate XXVI). Garnet is a common associate. In some rocks in the zones lying between the sillimanite-bearing schists and the kyanite-staurolite-

PLATE XXIII

1.0 in.

(Photomicrograph, crossed nicols) Postkinematic kyanite idioblast (dark) transecting foliation of biotite-quartz schist. Growing porphyroblast has bent out the foliation of the groundmass. Some recrystallization of biotite, muscovite, and quartz in the groundmass has produced a very slight superimposed hornfelsic texture. Spec. C-15d, south slope, Mt. Howard.

PLATE XXIV



1.0 mm

(Photomicrograph, plane polarized light) Idioblasts of staurolite in a staurolite-kyanite-biotite-quartz schist. Staurolite has bent out foliation of mica schist matrix. Spec. B-1 2a, southeast flank, Rock Mt.

PLATE XXV

Kyanite and staurolite forming pseudomorphs after chiastolite (light colored areas) in a fine-grained graphite-staurolite-kyanite-biotite-quartz schist. Spec. B-12b, southeast flank, Rock Mt.

bearing schists, kyanite is a stable associate of the sillimanite, and generally forms in parallel intergrowth with the sillimanite. This relationship is interpreted as indicating the rock is in the coolest part of the katazone.

A variety of sillimanite, fibrolite, is a common constituent of the schists. The fibrolite forms fibrous masses which generally are bent and locally occur in swirling, complexly folded "clouds". Most of the fibrolite has formed from squeezed biotite along well-defined, closely-spaced shear planes which commonly are at an angle to the foliation. In a few of the schists the fibrolite occurs in an oriented intergrowth with sillimanite. Associated with the fibrolite is muscovite which forms irregularly-shaped plates with random orientation. The muscovite replaces biotite, and in many examples inherits the aligned graphite and magnetite inclusions of the biotite.

Thus, many of the biotite-quartz schists contain one or more of the aluminum silicates and they can be divided into metamorphic grades. In addition to kyanite, staurolite, and sillimanite, certain other minerals occur in accessory quantities. These include:

a. Muscovite, which locally forms up to 5% of the rock. The muscovite displays the same two generations as biotite. The second generation is most abundant, and forms ill-defined and irregularly-shaped flakes (Plate XX) which lie at various angles to the foliation. Some of this muscovite has grown at the expense of biotite while inheriting the graphite and magnetite inclusions of the biotite. This muscovitization of biotite may indicate a slight postkinematic introduction of potassium;

b. Apatite, which is a common accessory mineral and, exceptionally, forms up to 5% of the rock. The apatite forms irregular to rounded grains in the biotite-rich bands;

c. Magnetite, which forms anhedral grains and clusters, and is concentrated in the vicinity of muscovite-replaced biotite;

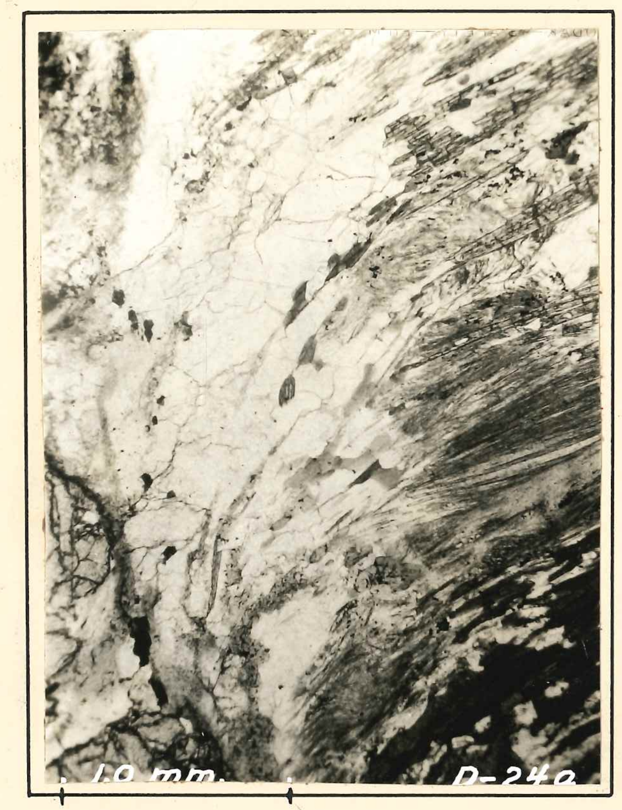
d. Tourmaline, variety schorlite, which has a very patchy distribution in rocks which otherwise are apparently identical in composition.

Other minerals are present in the schists, but collectively they form no more than one or two percent of the rock. These minerals include: zircon, which forms the tiny nuclei of the pleochroic haloes in biotite; graphite, which occurs as minute grains within quartz, biotite, and later muscovite; orthite, which forms the nuclei of some of the pleochroic haloes; chlorite, generally the variety pennine, which is an alteration product of biotite and garnet; and sericite, which forms the cloudy interiors and fuzzy margins of altered plagioclase. Both sericite and chlorite are either retrogressive minerals or are the result of recent weathering.

Hornblende-bearing Schists

Distribution and structure. Schists which contain hornblende as a major constituent or, locally, some other amphibole, are one of the most abundant rock types of the Beckler River-Nason Ridge area. Unlike the biotite-quartz schists which occur in many parts of the mapped area, the hornblende-bearing schists generally are restricted to the region lying northeast of a line drawn between Excelsior Mountain (Plate B, B-2) and Jim Hill Mountain (Plate B, 1-9). The major areas of outcrop occur on West Cady Ridge, in the vicinity of Pear and Heather Lakes, near the hamlet of Berne, and between Rock Mountain and Mt. Howard (Plate B). However, the hornblende-bearing schists

PLATE XXVI



(Photomicrograph, plane polarized light)
A banded garnet-biotite-sillimanite-quartz schist typical of katazonal conditions of regional orogenic metamorphism. Spec. D-24a, near Wenatchee Pass.

are not restricted to the mapped area. Similar schists have been described to the southeast by Page (30) in the vicinity of Chiwaukum Creek.

The hornblende-bearing schists occur as intercalations within belts of biotite-quartz schist or migmatitic gneisses (Plate B). Though the hornblende-bearing schists are not as areally extensive as the biotite-quartz schists, the hornblende present in many of the migmatitic gneisses, in the hornfelsized remnants of schists in migmatite zones, and in the directionless granitoid rocks, indicates that this group of rocks was far more extensive prior to granitization.

These rocks have participated in the same deformation that produced the biotite-quartz schists, and the structures of the two types are identical in nature and degree. The hornblende-bearing schists have steep dips which are generally to the northeast, and have isoclinal folds which typically are overturned to the southwest.

Petrography. It generally is difficult to differentiate the hornblende-bearing schists from the biotite-quartz schists in the field. Most of the hornblende is so fine-grained as to make megascopic determination impossible. Biotite, which locally is present, aids in making these hornblendic rocks very similar in appearance to the biotite-quartz schists. In both types of schist weathering produces the same rusty-brown color. However, some hornblende-bearing schists have a dark-greenish hue which aids in differentiating them from adjacent biotite-quartz schists. Both types of schist are banded, but generally the hornblende-bearing varieties have thinner and less conspicuous bands. Moreover, the wide, prominent quartz exudation bands typical of the biotite-quartz schists are absent in the hornblende-bearing schists.

A microscopic examination of the hornblende-bearing schists shows a notable structural difference from the biotite-quartz schists. This is caused by either a partial or complete postkinematic recrystallization of the mineral assemblage in the hornblendic schists, with the result that crystals lying transverse to the foliation are common. In such rocks the schistosity is no longer delineated by a preferred orientation of the minerals, but is marked by a compositional banding.

Hornblende is the most common mafic mineral present, and the amount ranges from a low of about 5% to a high of 30% of the mineral assemblage. Rocks exist in which the amphibole content is as high as 70%, but these have been assigned to another group, the amphibolites.

The hornblende shows a wide range in composition. Some of the hornblende is of the common green variety, and has a pleochroism marked by X: pale olive brown; Y: olive green; and Z: dark bluish green. The maximum extinction angle (z:c on 010) is about 21°, and the 2V is about 65°. Other examples, apparently magnesium-rich and iron-poor, have the very pale green colors indicative of a high admixture of the actinolite molecule. This pale green hornblende, which quantitatively is the most important variety, has a pleochroism marked by X: almost colorless to very pale olive brown; Y: pale yellow green; and Z: olive- to bluish-green. The maximum extinction angle generally is less than that of the common green hornblende, and ranges from 12° to 18°. The 2V is large, approximating 80°.

The hornblende individuals generally are elongate prisms with ragged terminations. These are most prevalent in bands up to 3 or 4 mm. thick in which individual crystals, rarely exceeding 0.8 mm. in length, form a discontinuous foliation with an imperfect subparallel arrangement (Plate XXVII). Some of the larger crystals, up to 1.5 mm. long, have been recrystallized subsequent to deformation, and they lie transverse to the schistosity. Where a considerable amount of this postkinematic recrystallization has occurred, the crystals lie with random orientation, and the schistosity is delineated solely by compositional banding. Generally, however, synkinematic hornblende is present and aids in defining the schistosity. In hornfelsized zones adjacent to granitoid rocks, recrystallization has destroyed the schistosity insofar as a preferred orientation of the minerals is concerned. However, even under these circumstances the banding has survived.

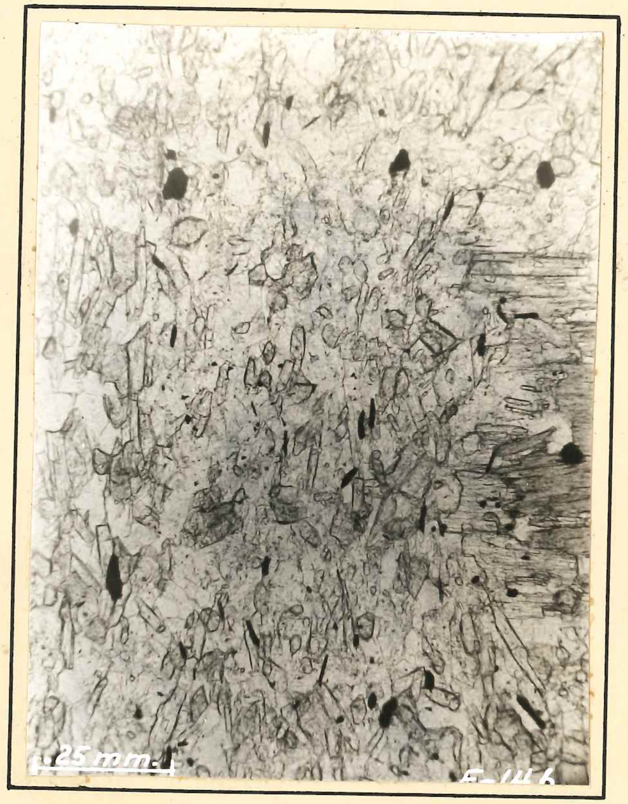
Many of the hornblende individuals have a sieve texture, and the most common inclusions are plagioclase, apatite, and magnetite. Pleochroic haloes about zircon or orthite nuclei are locally abundant. Twinning is relatively common.

Locally, tremolite is the dominant mafic mineral. The tremolite occurs in short prismatic to bladed crystals, and generally is far more fine-grained than the hornblende, averaging less than 0.2 mm. in length (Plate XXVII). The extinction angle (z:c on 010) averages about 12°. Magnetite is a common associate, and commonly there has been a recrystallization, transverse to the schistosity, of later phlogopitic biotite. Plagioclase is the dominant constituent of the tremolite-bearing schists, and quartz generally is very subordinate.

In addition to hornblende, tremolite, or, in one example, actinolite, plagioclase is a major constituent of these schists. The plagioclase generally forms from 35% to 50% of the rock. Some of the plagioclase is found within the amphibole-rich bands, but most of it occurs in narrow bands which alternate with the hornblende-rich bands. This alternation gives the rock its banded appearance. The plagioclase commonly is elongated parallel to the schistosity, and needles of hornblende are frequent inclusions.

The composition of the plagioclase of the hornblende-bearing schists is generally more calcic than that occurring in the biotite-quartz schists.

PLATE XXVII



(Photomicrograph, plane polarized light)
A tremolite-plagioclase schist with large grain of later phlogopitic biotite (right) statically recrystallized transverse to the schistosity. Spec. E-14b, E. slope, Windy Mt.

The general range in composition is from An_{54} to An_{34}. The most calcic composition was determined in tremolite-bearing schists; the least calcic in quartz-rich, pale green hornblende-bearing schists. The average composition of the plagioclase is about An_{40}.

The plagioclase generally occurs in small, untwinned anhedra. Exceptionally there are larger individuals, up to 2.0 mm. long, which are twinned after the Carlsbad, pericline, and albite laws. Some of the twinning is rather complicated.

Most of the plagioclase is a stable member of the mineral assemblage, apparently forming an integral part of the isochemically metamorphosed schist. The prevalence of plagioclase in some bands, and of hornblende in others, is presumably the result of a metamorphic differentiation under shearing stress. The plagioclase crystals often are formed in a xenoblastic polygonal mosaic which is characteristic of zones which have been crushed through shearing and subsequently recrystallized.

Quartz is a common constituent, though locally it is absent. The quartz averages 5% to 10% of the rocks, and in one exceptional specimen it forms 40% of the rock. The quartz occurs as individual grains within the plagioclase-rich bands, and as inclusions within hornblende crystals. The quartz usually forms minute anhedra, most of which are strained and display undulatory extinction. Some individuals show a marginal granulation with a subsequent recrystallization.

Biotite, locally, is an accessory mineral. Where present, the biotite occurs in three separate generations. The first is represented by crystals in parallel intergrowth with hornblende, or by individuals in biotite-rich bands which alternate with hornblende-rich bands. Such an alternation of biotite-rich with hornblende-rich bands is probably a relic of original sedimentary differences. The second generation of biotite is contemporaneous with the folding of the schists and the production of the $\underline{s}_2$ which lies transverse to the $\underline{s}_1$. Much of this biotite has formed from hornblende along closely-spaced shear planes. The third, and most abundant generation of biotite is postkinematic. This biotite forms the largest grains. They are irregular in outline, show no elongation, commonly lie at angles to both s-planes, and have formed from hornblende. Locally, this biotitization process has practically eliminated hornblende. The biotitization process is accompanied by an accumulation of aggregates of magnetite.

The pre-biotitization composition of many of the hornblende-bearing schists is notable for a lack of potassium. Yet the process of biotitization of hornblende requires potassium. It is suggested that a certain amount of potassium metasomatism may have been responsible for the biotitization.

Thus, the typical hornblende-bearing schists are composed of an amphibole (usually a variety of hornblende), plagioclase, quartz, and, locally, biotite. In addition, there are accessory minerals. These include:

Garnet; zircon and orthite, as nuclei of pleochroic haloes; apatite, which is especially prevalent in the quartz-plagioclase bands; muscovite, which is absent in the biotite-free varieties; sericite, which generally has formed from plagioclase; sphene; and chlorite which has formed from hornblende and/or biotite. Locally there are very subordinate quantities of the epidote-group minerals.

Regional retrogressive alteration has strongly affected many of the hornblende-bearing schists. This retrogression has resulted in much of the biotite and hornblende being altered to chlorite (variety penninite). The pleochroic haloes which are characteristic of the hornblende and biotite are inherited intact by the chlorite. Epidote, zoisite, and clinozoisite are local alteration products of both plagioclase and hornblende. Sericite has formed from plagioclase and to such an extent locally that the twinning is obscured and the composition of the plagioclase is no longer determinable. Some bent and ruptured plagioclase crystals are evidence of deformation during this period of retrogression. The latest alteration is caused by weathering, and in deeply-weathered specimens the magnetite has changed to limonite with a resultant staining of the entire rock fabric.

Amphibolites

Distribution and Structure. Amphibolites are very minor in the Beckler River-Nason Ridge area, and they have been found cropping out at only three localities. The most extensive outcrops are southeast of Pear Lake in the vicinity of Wenatchee Pass (Plate B, D-6). Here there are bands of amphibolites up to 6 feet wide intercalated with hornblende and biotite-quartz schists. The zone in which the amphibolites occur is about 500 feet wide across the strike. These amphibolitic bands are in a zone of transition between biotite-quartz schists to the east and migmatitic gneisses and granitic gneisses to the west.

Extensive outcrops also occur near Butcher Creek (Plate B, G-15). The width and occurrence of the amphibolite bands at this locality are similar to those of the amphibolites near Wenatchee Pass, and future field work may disclose the fact that these two areas of outcrop represent the same unit at different places along the strike (see Plate B). The major difference between the two localities of outcrop lies in the fact that the amphibolites near Butcher Creek occur as intercalations within a sequence of migmatitic gneisses.

The third locality at which amphibolites occur is on the east side of Windy Mountain (Plate B, 1-6) where several bands, up to two feet wide, are found in a migmatite zone in a section which is predominantly granitic rock.

The amphibolites at Butcher Creek grade along the strike, both to east and to west, into hornblende-bearing schists. At the other localities the amphibolites grade into granites, gneisses, or biotite-quartz schists along the strike.

The differentiation of hornblende-bearing schists from amphibolites has been made on the basis of the amount of amphibole present. From an examination of many specimens, it was possible to distinguish two main groups of schistose hornblende (or other amphibole) -bearing rocks. One group contains up to 30% of amphibole, generally hornblende. Rocks of this group are designated as hornblende-bearing schists. The other group, of subordinate importance, has an amphibole content generally ranging between 60% and 70% of the rock. Rocks in this group are designated as amphibolites. Only rarely do the hornblende-bearing rocks in this area have an intermediate hornblende content.

The amphibolites commonly have steep dips to the northeast or north, and are generally minutely and isoclinally folded. The minor folds generally are overturned to the southwest or south. Thus, the structure of the amphibolites is a rather faithful copy of that found in the schists.

Unlike the hornblende-bearing schists, which generally weather to the same hues of color as the biotite-quartz schists, the amphibolites are readily distinguished from other schistose rocks. Though a rusty-red weathering color is prevalent, fresher specimens have a dark-greenish color which distinguishes them from the darker-colored schists or the lighter-colored gneisses in which the amphibolites are intercalated. Most of the amphibolites are extremely fine-grained, and a megascopic determination of the mineral assemblage is usually impossible. Many of the amphibolites are banded, with thicker dark-green bands alternating with very thin, light-grey bands.

Petrography. A microscopic examination shows that the banding is the result of an alternation of amphibole-rich bands, up to 10 mm. thick, with plagioclase-rich bands up to 4 mm. thick. This banding gives the rock an over-all schistose structure. In some of the amphibolites there is a preferred orientation of the minerals, but locally there has been a postkinematic recrystallization with a partial to complete destruction of the preferred orientation of the minerals (Plates XXIX, XXX). Where the preferred orientation has been obliterated, only the banding survives to mark the foliation.

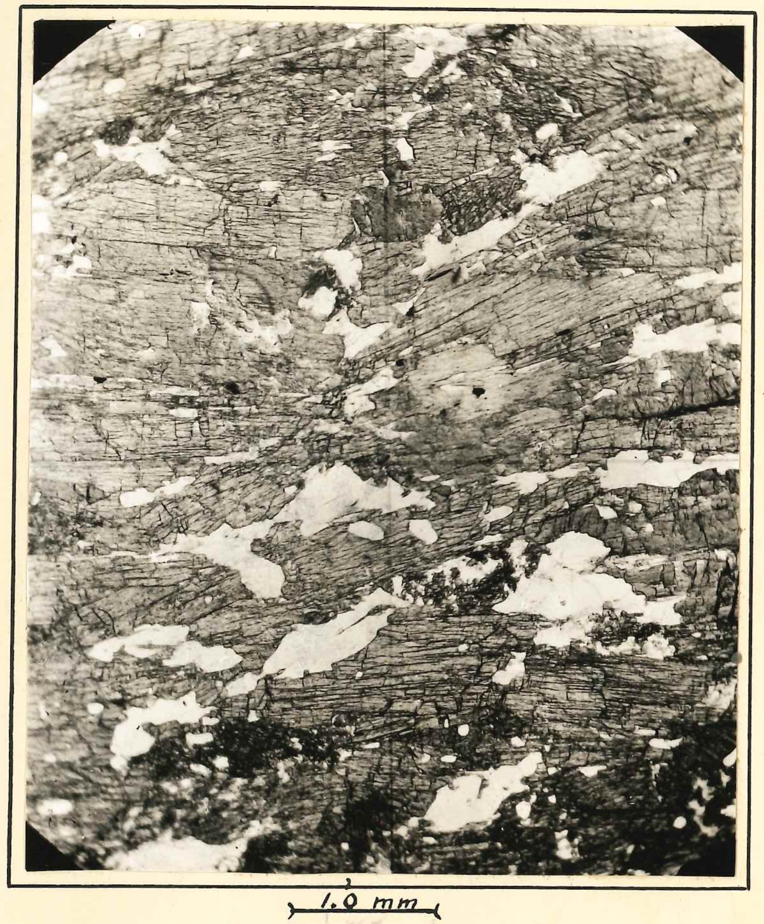
The most common amphibole present is some variety of hornblende, although tremolite and actinolite are locally important. The hornblende generally is a pale-colored variety, and it has a pleochroism marked by X: almost colorless to very pale green; Y: pale green or pale olive-green; and Z: medium olive-green. The maximum extinction angle (z:c on 010) is about 15°, and the 2V is high, approximating 80°. Elongate sections display middle second order interference colors.

This pale green hornblende (probably actinolitic) is the most common amphibole. In a few examples common green hornblende, identical to that of the hornblende-bearing schists (cf. p. 66), occurs.

The hornblende forms minute elongate crystals which locally have a tendency toward euhedralism. Most of the grains range from 0.1 to 0.3 mm. in length (Plates XXIX, XXX), but exceptionally there are individuals up to 3.0 mm. long (Plate XXVIII). These larger crystals generally occur where common green hornblende is the dominant mafic mineral.

The hornblende flakes are in a subparallel arrangement and generally form continuous layers which extend for considerable distances through the rock. Many of the hornblende individuals—especially the larger ones--have a

PLATE XXVIII



(Photomicrograph, plane polarized light) Amphibolite: common green hornblende in subparallel arrangement; subordinate plagioclase and quartz. Spec. B-36, divide between Butcher and Kahler Creeks.

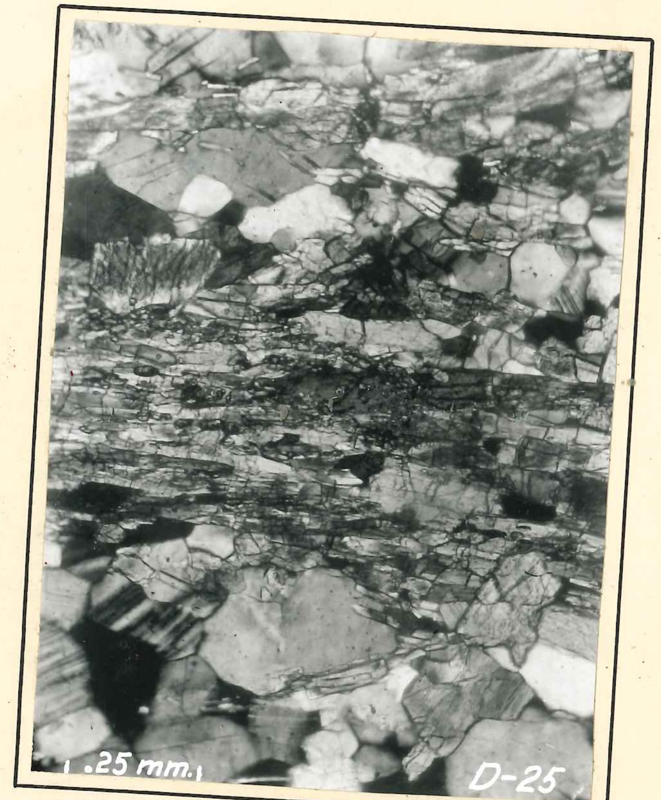
PLATE XXIX

(Photomicrograph, crossed nicols) Fine-grained ortho-amphibolite with local felspathization. Sieve-textured plagioclase (AN 38) porphyroblasts (lower part) include green hornblende and plagioclase of schistose amphibolite. Spec. D-22a, west side, Grizzly Mt.

PLATE XXIX

(Photomicrograph, crossed nicols) Fine-grained ortho-amphibolite with local felspathization. Sieve-textured plagioclase (AN 38) porphyroblasts (lower part) include green hornblende and plagioclase of schistose amphibolite. Spec. D-22a, west side, Grizzly Mt.

PLATE XXX



(Photomicrograph, crossed nicols) Ortho-amphibolite probably derived, through regional orogenic metamorphism, from a basic andesite. The plagioclase averages AN 40 in composition. Transverse pale-green hornblende anhedra show a slight postkinematic recrystallization. Spec. D-25, Lower Pear Lake.

sieve texture, with inclusions of apatite, quartz, magnetite, and plagioclase. Zircon, forming the nuclei of pleochroic haloes, is a common inclusion.

Where tremolite is dominant the rock is extremely fine-grained, and only a very few elongate crystals exceed 0.25 mm. in length (Plate XXVII).

Most of the amphibolites have been partially or completely recrystallized under static conditions. During this phase of metamorphic history many of the larger crystals were formed. Some of these individuals are parallel to the schistosity, but most lie with random orientation at acute angles to the foliation. Some of the amphibolites near Pear Lake (Plate B, D-5) show a postkinematic formation of actinolite. The actinolite partly replaces hornblende along the rims, and partly grows in parallel intergrowth with the hornblende. The actinolite probably represents a postkinematic recrystallization of some of the hornblende during a time of falling temperatures.

Plagioclase invariably is present, and exceptionally forms 50% of the rock. The average plagioclase content is about 30%. The plagioclase individuals are anhedra up to 1.5 mm. in length, many of which are elongated parallel to the schistosity. Most of the plagioclase occurs in the thin plagioclase-rich bands, but individuals and aggregates also occur between the amphibole grains in the more mafic bands (Plates XXVII, XXVIII). The plagioclase generally is untwinned, but locally there are crystals twinned after the Carlsbad, pericline, or albite laws. There are a few complicated twins, and some individuals show weak zoning. It is noteworthy that these complications in twinning, and the weak zoning, occur in a schistose rock which is undeniably non-igneous.

The composition of the plagioclase is variable. In the tremolite-bearing rocks the range is between An_{54} and An_{46}. This is a more calcic plagioclase than that found in the hornblende-bearing schists. The plagioclase of the latter averages An_{40}.

Quartz is a minor constituent of the tremolite amphibolites, and forms up to 10% of the rock. However, quartz generally is absent in the hornblende amphibolites, and where present rarely exceeds 2-3% of the rock. The quartz occurs in anhedra which generally are confined to the plagioclase-rich bands. Locally, the quartz combines with plagioclase to form a xenoblastic polygonal mosaic, the individuals of which average less than 0.1 mm. in diameter.

Biotite generally is present in the tremolite amphibolites and absent in the hornblende amphibolites. The calcic plagioclase of the tremolite rocks indicates a high calcium content, and a high magnesium content is indicated not only by the tremolite but by the fact that the biotite is very pale in color and approaches phlogopite in composition (Plate XXVII).

Magnetite and apatite grains are always present. Locally, clinozoisite, epidote, orthite, and zoisite are accessory minerals. With the exception of the orthite, these minerals apparently are retrogressive alterations of the amphiboles.

These rocks are probably ortho-amphibolites. The considerable plagioclase content, the absence or very minor content of micas and of quartz, the absence of quartz-rich bands and lenticules, and the rather uniform mineral composition of the rocks militate against a sedimentary origin. A volcanic source is considered more probable. In the case of the magnesium- and calcium-rich tremolite-bearing rocks, a dolomitic tuff may have been the source. Such a tuff would have furnished the sodium necessary for plagioclase formation. In the case of the hornblende-amphibolites, a basic andesite ortholeitic basalt may have been the source. In either case, the rock was made schistose through processes of regional orogenic metamorphism, and the banding apparently is the result of a simple metamorphic differentiation under shearing stress.

Lime-silicate Rocks

Distribution and Structure. Lime-silicate rocks are the rarest rock type of the Beckler River-Nason Ridge area. This rock has been found in place only on the summit ridge of Robin Mountain (Plate B, B-5). Here it is exposed imperfectly in a band estimated to be about 3 feet thick. This band is apparently a concordant intercalation in a sequence of migmatitic gneisses and felspathized and hornfelsized biotite-quartz schists. The actual contact of the lime-silicate granulite with the enclosing rocks was not observed. The rock units on Robin Mountain dip at a moderate angle (about 30°) to the northeast, and folding, so common in the foliated rocks of this area, was not observed.

This rock type is very fine-grained, light-grey, and prominently banded, with very thin dark-colored bands alternating with equally thin light-colored bands.

Petrography. A microscopic examination of the rock shows that the light-colored bands are mostly plagioclase and quartz. The plagioclase forms about 40% of the mineral assemblage, and displays two generations. Most of the plagioclase occurs in small, equidimensional, untwinned anhedra averaging 0.1 to 0.2 mm. A common associate is quartz which forms about 30% of the rock. The structure of these plagioclase-quartz bands is granulose. In addition to the fine-grained granulitic plagioclase, there are larger plagioclase individuals up to 2.0 mm. long. These larger plagioclase anhedra are crystalloblastic, and growth into and inclusion of the groundmass is common. Moreover, these porphyroblasts marginally invade the minerals of the darker bands, and grow around some of the mafics present there. The composition of the larger plagioclase porphyroblasts, many of which are twinned, ranges from An_{47} to An_{38}. Associated with these plagioclase porphyroblasts are larger quartz grains displaying strain and undulatory extinction.

The darker bands are mostly composed of fine-grained granulitic plagioclase and quartz, with abundant poikiloblasts of diopside. These diopside individuals are up to 0.25 mm. long, and form about 25% of the rock. The diopside commonly contains inclusions of granulitic quartz and plagioclase. The diopside is light-green in color, and the extinction angle, z : c, averages 40°. Some diopside individuals are altered along their margins to pale-green hornblende which is formed in parallel intergrowth. Orthite, locally with epidote rims, is a constituent of both the plagioclase-rich and diopside-rich bands.

There is no pronounced preferred orientation to any of the minerals, and a true schistose structure is lacking. The structure is that of a banded granulite. The bands vary in width, exceptionally being 1 cm. thick, and they pinch and swell along the strike. These bands possibly represent original compositional differences in a thinly-layered or laminated sedimentary rock. Moreover, the growth of plagioclase and quartz porphyroblasts in the granulitic ground mass suggests either a partial static recrystallization of the rock or an introduction of sodium.

The composition of the original sediment is purely conjectural, but a dolomitic sandy shale is indicated. The calcium content, as evidenced by the diopside and plagioclase, and the magnesium content, as evidenced by the diopside, suggest that the sediment was dolomitic. The rather high quartz content, coupled with the alumina present in the plagioclase, suggests a shale or sandy shale. The presence of epidote suggests that this rock is mesozonal in metamorphic grade--an inference supported by the mesozonal character of the adjacent gneisses and kyanite-bearing schists. No zonal significance is attached to the pale-green hornblende inasmuch as it is a later alteration from diopside, and may be an indication of recrystallization during a period of falling temperatures.

Genetic Interpretation of the Isochemically Metamorphosed Rocks

The petrographic characteristics of the isochemically metamorphosed rocks have been described above. A genetic evaluation of these features suggests the following history for these rocks.

(1) A thick sequence of sedimentary rocks probably formed the source materials from which the isochemically metamorphosed rocks were made. Most of these sedimentary rocks were argillaceous. The sedimentary and argillaceous character of the source materials is suggested by the alumina excess from which there developed the aluminum silicate mineral suite of kyanite, staurolite, sillimanite, and, very locally, chiastolite. The phyllites and the biotite-quartz schists probably were derived from these argillaceous sedimentary rocks, and it is probable that the bulk were rather pure shales. The relatively high graphite content of the phyllites and of some of the schists indicates that some of the shales were carbonaceous.

The prevalence of the aluminum silicates and biotite in certain bands, of quartz and plagioclase in other bands, and of quartz in a third type of band may indicate that this banding represents original sedimentary differences which have been exaggerated by metamorphic differentiation under active stress.

The hornblende-bearing schists show a derivation from a material originally rich in calcium, magnesium, and sodium. Moreover, the occurrence of plagioclase and quartz as important constituents is indicate of a reasonably high silica content. If the hornblende-bearing schists are wholly isochemical in their metamorphism, it is suggested that tuffaceous shales, or greywackes with an admixture of volcanic debris would furnish the calcium, magnesium, silica, and sodium necessary for the metamorphic mineral assemblage.

The very subordinate lime-silicate granulites contain an excess of calcium over magnesium, as evidenced by the plagioclase, diopside, orthite, and epidote content. These granulites may have been formed from a calcareous, dolomitic, sandy shale.

If these suggested source beds are correct, the majority of the isochemically metamorphosed rocks would have been derived from a thick sequence of rather pure shales in which there were subordinate intercalations of tuffaceous shales, greywackes, and calcareous, dolomitic, sandy shales.

On the other hand, neither a pure shale nor a dolomitic tuff of an intermediate composition could be metamorphosed isochemically to produce the amphibolites. Moreover, certain evidence suggests that the amphibolites were not derived from a sedimentary rock. This evidence includes: a., the notably simple and rather uniform mineral assemblage of the amphibolites; b., the absence, or extremely subordinate amount of micas and quartz; and, c., the almost complete absence of quartz-rich bands and lenticles.

Therefore, some type of igneous rock is postulated as having been the source for the amphibolites. The parallelism of the amphibolite layers to the enclosing schists and gneisses indicates that this igneous rock, if such it was, was concordant with the underlying and overlying sediments. Therefore, flows or tuffs interbedded in the sedimentary sequence seem probable. Where tremolite is the dominant amphibole, a dolomitic tuff intercalated in the sedimentary sequence could have furnished the required calcium and magnesium. Where hornblende is the dominant amphibole, an andesitic to basaltic tuff or flow might have been the source bed.

(2) This sequence of sedimentary rocks, with its postulated igneous intercalations, then was subjected to regional orogenic metamorphism. The rocks--whether they be phyllites, mesozonal schists, or katazonal schists--display identical structural details of shearing and folding. In effect, the mechanical yielding was the same in all three metamorphic zones.

Though the phyllites are zonally restricted in the sense that they crop out only in the westernmost part of the mapped area, they are actually distributed in a random fashion within a dominantly schistose terrane. Elsewhere, changes from mesozonal to katazonal schists are gradational both along and across the strike, and the katazonal schists are more or less centrally located (Plate B) in respect to the flanking mesozonal schists.

Variations in intensity of mechanical deformation do not explain this metamorphic zoning. It is probable that temperature was the controlling factor, and there must have been a local "hot spot" in which katazonal rocks were formed, and marginal "cold spots" in which epizonal rocks were formed.

During the first phase of regional orogenic metamorphism, the initial foliation, $\underline{s}_1$, was formed, and a schistose structure was superimposed upon all of the rocks except the lime-silicate granulites. Inasmuch as bedding and $\underline{s}_1$ apparently are parallel in the phyllites, and relict bedding is postulated as forming the banding of the lime-silicate granulites, it is assumed that the $\underline{s}_1$ and the bedding probably are parallel in most of the isochemically metamorphosed rocks. If so, then the banding so typical of the biotite-quartz schists may be relict bedding which has been exaggerated by metamorphic differentiation under active stress.

As temperatures increased, most of the schists attained the kyanite-staurolite zone of regional metamorphism. In at least part of the area there was a static phase with moderately high temperatures during which chiastolite developed. With a resumption of active stress, kyanite and staurolite replaced the chiastolite, forming porphyroblasts which postdate the main phase of deformation during which the $\underline{s}_1$ was produced. The latter is suggested by the pronounced bowing-out of the foliation by kyanite, staurolite, and their common associate, almandite, and by the common inclusion of aligned grains of graphite and magnetite (Plates XX, XXI, XXII, XXIV). Recurrent deformation is indicated by rotated almandite individuals. Some minor folding, which deformed the $\underline{s}_1$ foliation, also belongs in a post-schistosity phase of deformation.

(3) Subsequent to the formation of the $\underline{s}_1$, intense isoclinal folding occurred (Plates XV, XVI, XIX). As a result, the rocks have a complex pattern of minor isoclinal folds, and it is probable that there are larger, not readily recognizable isoclinal folds. During this phase of synkinematic metamorphism an $\underline{s}_2$ was formed which generally lies at an angle to the $\underline{s}_1$.

(4) Following these phases of synkinematic metamorphism, but continuous with them, there was a static phase of recrystallization. Mesozonal and/or katazonal temperatures persisted. In the biotite-quartz schists, local kyanite, more widespread staurolite, very generally biotite, and some muscovite grew across the schistosity with a random orientation (Plates XIX, XX, XXIII). In the hornblende-bearing rocks part of the amphiboles were recrystallized transverse to the foliation. Exceptionally, the entire mineral assemblage was recrystallized with compositional banding the only survivor of the original schistosity.

(5) Temperatures then decreased, and retrogressive minerals formed. Actinolite rims formed on some of the hornblende,

pale green hornblende rims formed on some of the diopside, and muscovite, sericite, chlorite, and epidote came into existence. However, some of the sericite and chlorite probably belongs to the most recent event--weathering.

(6) The last major event was tectonic, and large open folds were superimposed upon the foliated rocks and their complex tight folds. Most obvious of these folds are the northwest-plunging open synclines on Evergreen Mountain and on Nason Ridge (Plate B).

Migmatitic and Granitic Rocks

Introduction

The isochemically-metamorphosed phyllites, schists, and very subordinate lime-silicate granulites have been described above. However, most of the rocks of the Beckler River-Nason Ridge area are granitic in composition. In this paper rocks are frequently described as either "granitic" or "granitoid". These terms are used in the very broad sense that the rocks so labeled have a composition ranging from diorite to granodiorite.

The granitic rocks are divided into two large groups based on the presence or absence of directional elements. Most of the southwestern half of the mapped area (Plate B) contains rocks of a granitic composition in which there is no preferred orientation of minerals and parallel structures are either very subordinate or absent. Thus, this area contains most of the directionless granitic rocks.

The second large group of rocks of dominantly granitic composition is characterized by a gneissose structure. On West Cady Ridge, along the northern half of the Cascade Crest, and along Nason Ridge (Plate B), a preferred orientation of minerals and/or a parallel arrangement of bands of differing composition give the rocks a gneissose structure.

For convenience these gneissose granitic rocks are divided into two main groups. Most of these gneisses are here termed heterogeneous migmatitic gneisses. These rocks are characterized by a wide range in composition and texture; i.e., they are heterogeneous. In these rocks there are all possible transitions between bands of isochemically metamorphosed schist and concordant bands of granitoid rock. This alternation of more-schistose with more-granitic layers gives the rocks a banded, gneissose structure, even where a preferred orientation of the minerals has been lost through processes of recrystallization. These "heterogeneous migmatitic gneisses" are invariably gradational with adjacent schists, and it cannot be doubted that a selective felspathization of the schists has produced this varied group of gneisses.

The heterogeneous migmatitic gneisses are most abundant in the northern and eastern parts of the mapped area (Plate B). They are the major rock type in the area between Grizzly Peak (Plate B, E-5) and Cady Pass (Plate B, B-5), and they form the bulk of Nason Ridge east of Rock Mountain (Plate B, G-10). In addition, these migmatitic gneisses crop out locally within the main granitic mass in the southwestern half of the mapped area (Plate B).

Subordinate in quantity to the migmatitic gneisses are the granitic gneisses of migmatitic derivation. This group of gneisses generally forms a transition zone between the migmatitic gneisses and the directionless granitic rocks. Most of these rocks differ but little in composition from the directionless granitic rocks, but a slight compositional banding and a local preferred orientation of minerals give these rocks a gneissose structure. The parallelism of the structures of these gneisses with those of the adjoining migmatitic gneisses and schists, coupled with local included bands of migmatitic gneiss and schist in parallel arrangement, indicate that these granitic gneisses have been derived from the schists and migmatitic gneisses.

The granitic gneisses are the dominant rock type in the vicinity of Pear Lake (Plate B, C-, D-5) and on Barrier Peak (Plate B, I-7), and they are abundant locally in other localities (Plate B). However, these rocks apparently do not croup out east of Rock Mountain (Plate B, G-10) or west of Mt. Fernon (Plate B, H-3).

Heterogeneous Migmatitic Gneisses of Medium and High Grade

Distribution and Associations

The migmatitic gneisses are one of the most extensive groups of rocks in the Beckler River-Nason Ridge area. From the standpoint of the metamorphic history of this region, they probably are the most interesting, inasmuch as they represent the bridge between the isochemically metamorphosed schists and the directionless granitic rocks.

This group is characterized by banded rocks which are extremely variable in composition and texture. There are all possible transitions between bands of definitely recognizable, isochemically metamorphosed schist, and bands of fine- to coarse-grained (in part "pegmatitic") granitic gneiss. As previously mentioned, the terms "granitic" and "granitoid" are used in the broad sense of any grained rocks of a composition ranging from diorite to granodiorite.

Though these rocks are exceedingly heterogeneous, two main groups may be recognized. In the outcrop areas between Rock Mountain (Plate B, G-10) and West Cady Ridge (Plate B, B-2), the migmatitic gneisses are characterized by layers of leucocratic, generally fine-grained granitic material intercalated in darker schists, forming a lit-par-lit structure (Plate XXXI). Alternations of these layers generally occur within a distance of two or three inches. Locally, there are schistose and gneissose layers several feet thick. Many of the schistose bands have been hornfelsized and felspathized.

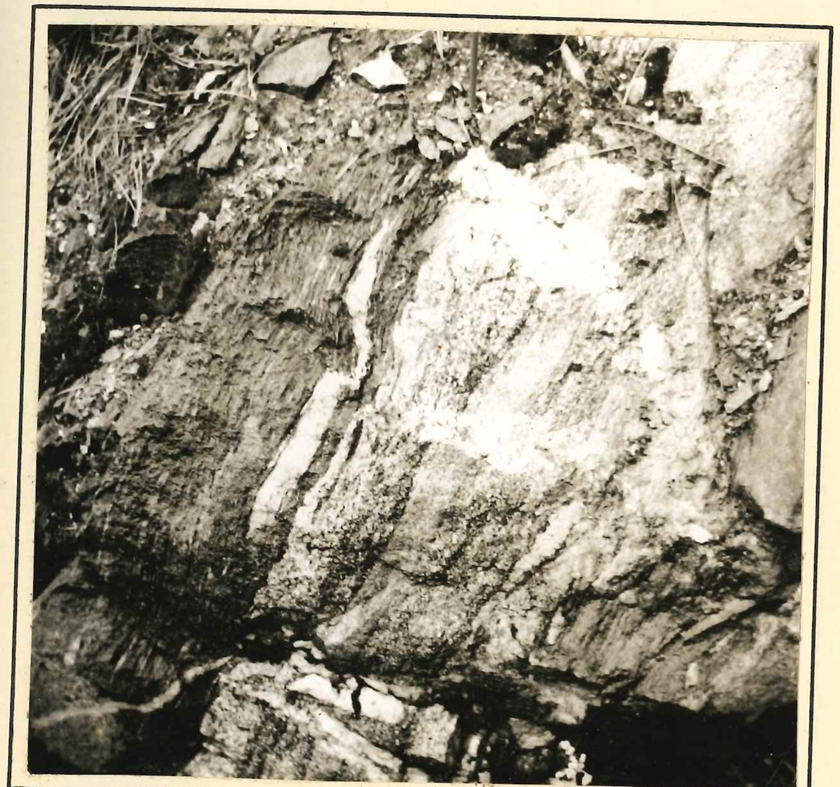
In the outcrops along Nason Ridge between Mt. Howard (Plate B, F-11) and the Leavenworth fault (Plate B, G-15), the mineral assemblages of adjacent bands become very similar, and the banding is delineated more by differences in texture and amounts of dark minerals than it is by an alternation of schistose and granitoid layers. Schistose layers do occur, but they are very subordinate.

The contacts of the migmatitic gneisses with other rock types are generally indistinct. Gradation into other rock types, both along and across the strike, is the rule. In some places the migmatitic gneisses grade into hornblende schists, biotite-quartz schists, or amphibolites; in other places they grade into coarser-grained gneisses of a predominantly granitic composition (Plate B). Locally the gradation is rapid, and takes place within a few feet (Plates XXXIII, XXXIV); in other places the gradation is almost imperceptible, and a distance of several hundred feet is traversed before a recognizably different rock type is reached.

There are two main areas in which the migmatitic gneisses are dominant. The largest lies east of the Cascade Crest and comprises most of Nason Ridge with the exception of Rock Mountain (Plate B, G-10) and the southwest flank of Nason Ridge above Smith Brook (Plate B, G-9). The other area extends northwest from Lake Janus (Plate B, E-7) to West Cady Ridge (Plate B). Migmatite zones along the western part of Nason Ridge, in the vicinity of Lake Janus, connect these two main areas, and future field work probably will demonstrate that the two areas are linked to form a single broad, northwest-southeast trending belt of migmatitic gneisses.

A narrow belt of these gneisses lies between the south flank of Mt. Daniel? (Plate B, J-8) and Silica Mountain (Plate B, D-3), a distance along the strike of over 13 miles.

PLATE XXXI



Migmatite zone. Relict foliation preserved in granitoid rocks by layers differing in content of mafic minerals. Later cross-cutting replacement veins and dikes contain microcline, plagioclase, and quartz. Cirque wall, Lake Valhalla.

PLATE XXXII

Migmatite zone. Relict folds preserved in granitoid rocks by alternations of darker and lighter bands. Layer of hornfelsized and felspathized schist material (s). Post-granitic quartz and feldspar pegmatite (p). North slope, Mt. Fernow.

PLATE XXXIII, A and B

Migmatite zone. A fine-grained, banded, hornfelsized and felspathized garnet-biotite-quartz schist is in gradational contact with a tronjhemitic gneiss. The structure of the schist is preserved within the gneiss. Photo. D-2-7,-8. One half mile north of Fortune Ponds.

PLATE XXXIV

Contract between biotite-hornblende schist and quartz-dioritic gneiss. The structure of the schist has been preserved within the gneiss. Later fine-grained, aplitic, replacement dikes transect both rock types. Photo. D-3-5, summit of ridge NNW of Lake Janus.

Subordinate areas of gneiss crop out near Berne (Plate B, H-10), on the north spur of Mt. Fernow (Plate B, H-8), and south of Lake Valhalla (Plate B, G-6, G-7).

The easternmost extension of the migmatitic gneisses in the mapped area is to the Leavenworth fault (Plate B, G-15). However, a reconnaissance to the north shore of Lake Wenatchee (Plate B, E, F, -14, -15) shows that similar migmatitic gneisses crop out on the flank of Dirty Face Peak (Plate B, D-14). Willis (52) has mapped these gneisses in the Entiat Mountains which lie east of the graben containing Lake Wenatchee and the Swauk (Paleocene) sediments. Waters (49) has found "biotite gneisses", apparently of similar composition, grading into the coarser-grained granodioritic gneisses on the "borders" of the "Chelan batholith".

Petrography

The most characteristic feature of the migmatitic gneisses is the banding. This is emphasized by alternations of dark-colored, generally schistose bands, and light-colored granitoid bands (Plate XXXV). The bands have a wide range in thickness. Some are less than $\frac{1}{4}$ inch thick; others are up to 6 feet thick. The average is about 6 inches. In addition, the proportion of dark-colored bands to light-colored is variable. In zones adjacent to schists, the dark-colored bands are prevalent; in other areas, light-colored bands are dominant. In either case, the foliation of the schistose bands is parallel to that of the gneissose bands. Even where leucocratic granitic bands are transitional into coarser-grained gneisses of granitic composition, the parallelism of the foliation is maintained.

Details of structure are less distinct in the migmatitic gneisses than in the schists. The coarser textures of the gneissic layers and of the hornfelsized and felspathized schist layers obscure the more intricate details. However, folds exist, and locally are well-defined by an alternation of light-

PLATE XXXV

Banded gneiss. Fine-grained highly felspathic layers and medium-grained hornfelsic schist material. Spec. C-18, one-quarter mile west of Merritt.

and dark-colored bands (Plates XXXII, XXXVII). Moreover, reversals in direction of dip suggest that larger folds, not easily recognized, are present (Plate B, F-11).

A study of the structure shows that there is invariably a concordance and parallelism of structure between differing rock types, regardless of whether migmatitic gneisses are adjacent to schists, or are adjacent to coarser-grained granitic gneisses.

The migmatitic gneisses generally are fine-grained, and the leucocratic bands have a granitoid composition. Locally, where hornblende-bearing schists or amphibolites are intercalated (Plate B, C-4, F-6, H-10, G-14), the granitic rock is dioritic. In other areas the composition of the granitic rock is that of a trondhjemite (Plate B, E-6). Most commonly, the composition is quartz dioritic.

From Lake Janus (Plate B, F-7) northwest to West Cady Ridge (Plate B), the migmatitic gneisses are dominantly alternations of leucocratic quartz dioritic layers and darker-colored schistose layers. Feldspar and quartz are the main constituents of the lighter bands, with subordinate biotite, hornblende, or muscovite (rare), in parallel arrangement, defining the foliation. These quartz dioritic layers grade into the schistose layers. Most of the schists west of the Cascade Crest (Plate B) are biotite-quartz schists, but subordinate hornblende-bearing schists and amphibolites occur. The distribution of these amphibolites is shown on Plate B. Most of the hornblende-bearing schists crop out between Lake Janus (Plate B, F-7) and Pear Lake (Plate B, D-5). Some of the darker layers in this lit-par-lit structure are definitely recognizable schist, with a well-defined foliation marked by a preferred orientation of elongate biotite or hornblende. Other layers are hornfelsized, but recrystallization generally has not destoryed the quartz-rich bands and boudin-like aggregates so typical of the biotite-quartz schists. In many cases hornfelsing has been accompanied by felspathization, and thin, feldspar-rich bands occupy positions along the planes of schistosity (Plate XXXVI).

Within the migmatite zone west of Merritt (Plate B, G-13), and especially at the railway overpass near the confluence of Whitepine and Nason Creeks (Plate B., G-12), there exist all possible gradations between hornblende-bearing schists and fine- to coarse-grained dioritic and quartz dioritic gneisses. The schists have been partially recrystallized, and they have a hornfelsic appearance. Along the planes of relict schistosity, augen and lenticular aggregates of feldspar occur (Plate XXXVI). These hornfelsized schists grade into more gneissic rocks containing skialiths (Goodspeed, 17) which are shadowy relics of incompletely transformed schist. The relict schistosity of these skialiths is generally parallel to that of both the enclosing gneiss and the adjacent schist. This skialith-bearing gneiss grades into gneisses free of relict inclusions. It is important to emphasize the parallelism of the foliation in the schists, skialiths, and gneisses.

North and east of Merritt, along Nason Ridge (Plate B), the migmatitic gneisses are much more leucocratic and less distinctly banded than the lit-par-lit migmatitic gneisses of the areas to the west and northwest. This more leucocratic gneiss ranges from quartz dioritic to trondhjemitic in composition. Though the lit-par-lit arrangement generally is lacking, narrow micaceous layers, up to 1 inch thick, remain as relics of the schist bands (Plate XXXVIII A). Locally, there are bands of hornfelsized and felspathized schist up to one foot thick.

Where the gneiss is coarse-grained, the foliation is defined by minute differences in mafic mineral content; i.e., by a compositional banding

(Plate XXXVIII B). Plagioclase is the chief constituent, quartz is subordinate, and muscovite and biotite mark the foliation. In a few spots of limited areal extent, these gneisses grade into almost directionless granitoid rocks (Plate B). However, even in the semi-directionless granitic rocks there generally are very thin micaceous layers with attitudes parallel to those of the adjacent, more clearly foliated rocks.

In the gneisses near the confluence of Nason and Whitepine Creeks (Plate B, H-11) and near Merritt (Plate B, G-13), there are fine- to coarse-grained, in part pegmatitic, relatively structureless granitoid rocks which occur in steep-sided, irregularly-shaped bodies which transect the gneissic structure. Generally, the contacts between these granitic rocks and the gneisses are gradational. The rock generally consists mainly of plagioclase, with subordinate quartz, and a few dark minerals. Locally, there are cross-cutting dike-like masses composed mainly of quartz with subordinate "books" of muscovite mica. Relics of schist and gneiss occur within these granitic and pegmatitic zones. Generally these inclusions have a relict schistosity which is parallel to that of adjacent gneissic and schistose rocks.

A microscopic examination of the migmatitic gneisses shows a wide range in composition and texture. This is especially marked in the migmatitic zones at the contacts of the migmatitic gneisses with the schists. However, away from the contact zones, most of the leucocratic granitic material has a fairly uniform composition. This average type of gneiss is generally fine-grained, has a well-defined foliation marked by a preferred orientation of the micas or hornblende, and is composed of plagioclase, quartz, muscovite, biotite, or hornblende (rare), with subordinate quantities of potassium feldspar, magnetite, almandite, zircon, and apatite. Many specimens contain retrogressive minerals such as chlorite, clinozoisite, epidote, muscovite, and sericite.

Plagioclase is the most abundant mineral. It usually forms about 50% of the rock, with a range from 35% to 55%. The plagioclase occurs as anhedral, irregularly-shaped, crenulated crystals, with a tendency to be elongated in the plane of foliation. The individuals interlock, one with another and with other minerals, in an intricate fashion. The average size of the plagioclase is about 1 mm., though some porphyroblasts are as much as 8 mm. in longest dimension. Twinning after the albite, Carlsbad, and pericline laws is common, and locally the twinning is complicated.

The larger plagioclase porphyroblasts are filled with inclusions of quartz, muscovite, and irregular grains of secondary clinozoisite and epidote (Plate XXXXVI). The plagioclase usually is bent, and locally is ruptured.

The composition of the plagioclase ranges from An_{40} to An_{23}. Where biotite or muscovite are major constituents, the plagioclase averages An_{30}. Where hornblende is locally abundant, or where biotite has formed from hornblende, the plagioclase is more calcic, and averages An_{40} (Plate XXXXII). Some of the plagioclase individuals have anhedral zoning, with up to 5 bands showing a progression from a more calcic core, averaging about An_{40}, to a more sodic rim, averaging about An_{30}.

Quartz commonly forms about 30% of the rock, with a range from 20% to an exceptional 60%. The quartz occurs in anhedral crystals averaging about 1 mm. Most of the quartz grains are strained and display undulatory extinction. The quartz is intimately intergrown with plagioclase, and locally is enclosed in plagioclase (Plate XXXXVI). A vermicular intergrowth of quartz and plagioclase is common.

East of Mt. Howard (Plate B, F-11) the most common mica is muscovite, and it forms up to 10% of the rock. Two generations are recognizable. The first is clear in appearance, is elongated in the plane of foliation, and has

PLATE XXXVI

Banded gneiss. Granitoid bands parallel the relict foliation of a hornfelsized and felspathized hornblende-quartz schist. Spec. B-29a, one-quarter mile west of Alpine Lookout, Nason Ridge.

PLATE XXXVII

Banded gneiss. Felspathization along planes of relict foliation in a hornblende-quartz schist. Later, cross-cutting, fracture-controlled replacement veins contain microcline, plagioclase, and quartz. Spec. C-15c, south flank of Mt. Howard.

PLATE XXXVIII

A. Banded gneiss. Mafic minerals mark the relict foliation. Spec. B-25, one-quarter mile west of Alpine Lookout, Nason Ridge.

1.0 inch

B. Medium-grained, banded, quartz dioritic gneiss. Foliation marked by alternations of lighter and darker bands varying in mafic mineral content. Spec. B-25, summit of Nason Ridge north of Lake Merritt.

ragged terminations. This earliest muscovite commonly lies in parallel orientation, and forms a well-marked, though discontinuous foliation. Much of this muscovite has formed from the alteration of biotite. The second generation of muscovite occurs in large, irregularly-shaped plates which lie transverse to the foliation. This later muscovite is generally turbid in appearance, and has ill-defined margins. Some of the later muscovite is a marginal alteration from plagioclase.

West of Mt. Howard, biotite is the most common mica. It is noteworthy that the biotite displays the same two generations as the muscovite. The biotite generally forms about 5% of the rock, with a range from 4% to an exceptional 10%. Some of this biotite is obviously derived from hornblende. In some zones biotite and muscovite are stable and contemporaneous constituents, and form up to 10% of the rock.

Thus, the average gneiss is composed of plagioclase, quartz, and either muscovite or biotite or both. This mineral assemblage lacks zonal significance. Therefore, it is noteworthy that certain gneisses, especially those cropping out west of Mt. Howard, have minerals which are indices of metamorphic grade. In particular this is true of the gneisses west and south of Rock Mountain (Plate B, F-10) which are in a lit-par-lit arrangement with kyanite- and staurolite-bearing schists. Here the gneisses have inherited the aluminum silicates, and exceptionally the kyanite and staurolite form up to 10% of the gneiss. Moreover, certain of the gneisses near Top Lake (Plate B, C-6) and on Grizzly Peak (Plate B, E-6) contain sillimanite (Plates XXXIX, XXXX, XXXXI). Thus, the gneisses are rather faithful copies of the schists in that there is a conformity in zone between schist and adjacent migmatitic gneiss. Where nearby schists contain sillimanite, the gneisses also contain sillimanite. The same is true for kyanite and staurolite. Moreover, the presence of these three aluminum silicates is proof that the gneisses are of a migmatitic origin.

Many of the gneisses show a post-crystalline deformation, and fibrolite has been produced from squeezed biotite along well-defined shear planes which lie transverse to the primary foliation. In addition, almandite, a common constituent of many of the intercalated schists, is inherited by the gneisses.

Clinozoisite, epidote, and zoisite (rare) form as much as 10% of the rock. They occur as irregular grains in the plagioclase, and also as individuals and aggregates in the intergranular spaces. In some cases these minerals are closely associated with biotite, and it is presumed that they formed as a result of biotitization of earlier hornblende. This interpretation is supported by the occurrence of hornblende in adjacent layers of schist, and by local, partially biotitized remnants of hornblende within the gneiss. It is noteworthy that hornblende only rarely survives to be a constituent of the gneisses. Plate XXXXIII shows a felspathized amphibolite which occurs in a lit-par-lit arrangement with more leucocratic gneissic bands.

In some specimens the minerals of the epidote group are alteration products of plagioclase, indicating a retrogressive phase of metamorphism.

In the migmatitic contact areas the gneiss is transitional with the schists. Within a few inches the gneiss grades across the strike into biotite-quartz schists or into hornblende-bearing schists. The schist bands adjacent to the gneiss bands generally have undergone a phase of static recrystallization. As a result, the schists have acquired a superimposed hornfelsic texture, and they have partially lost their schistosity (Plates XXXV, XXXVI). The biotite, muscovite, and hornblende of these hornfelsized bands have recrystallized with random orientation. Small porphyroblasts of plagioclase, generally similar to that in the gneiss, form thin bands and augen parallel to the schistosity. As the gneiss is approached, these feldspar bands become wider, and the porphyroblasts become larger (Plate XXXVI).

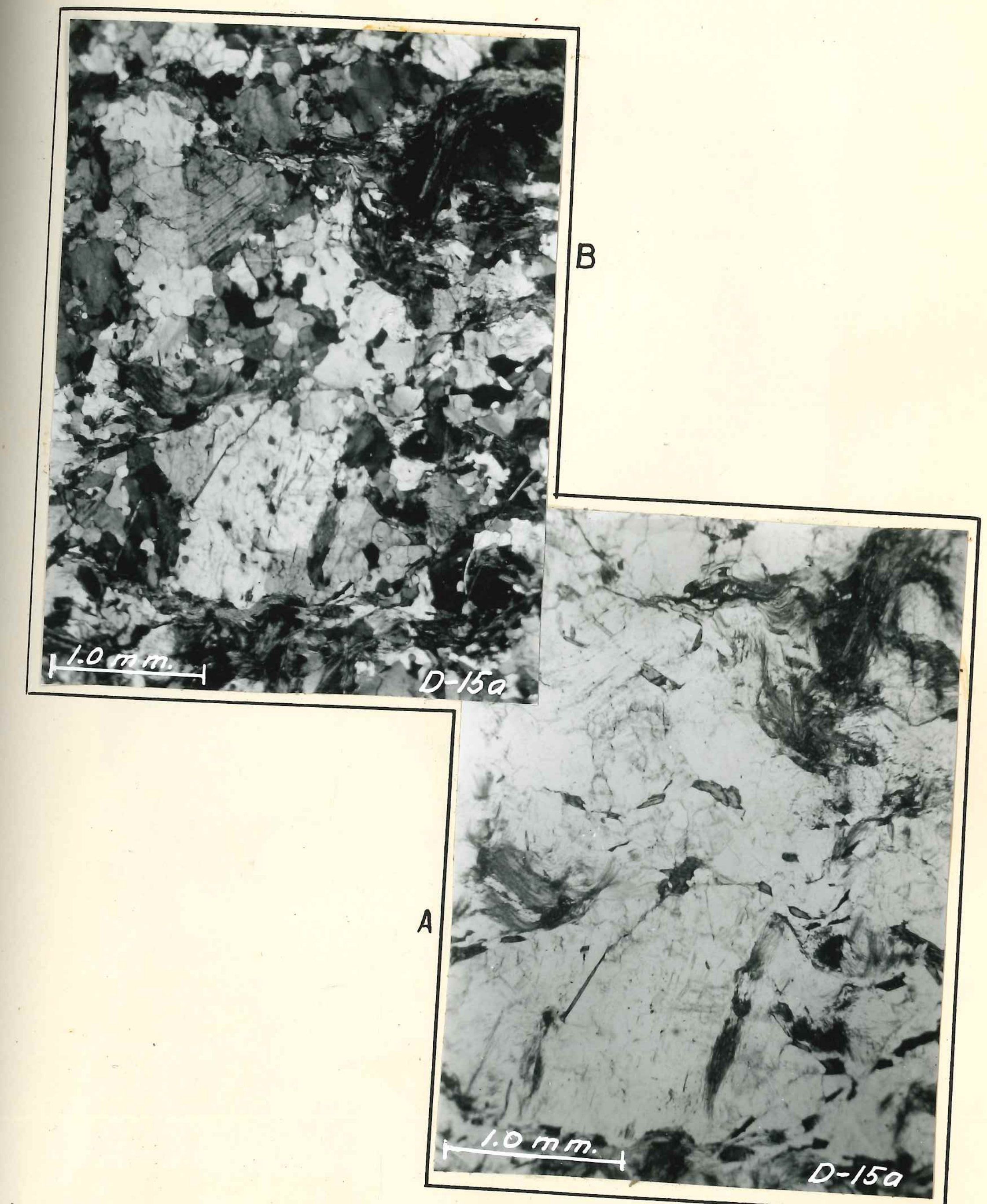
PLATE XXXIX A and B

(Photomicrographs: A, plane polarized light; B, crossed nicols) lit-par-lit replacement of a banded staurolite-sillimanite-biotite-quartz schist. Note foliation marked by bands (top and bottom) of elongate biotite. The felspathized bands are of quartz dioritic composition. Minerals in center are: plagioclase and quartz (colorless); staurolite (high relief); sillimanite (fibrous aggregates and tabular crystals). Spec. D-17b, Grizzly Meadows.

PLATE XXXX

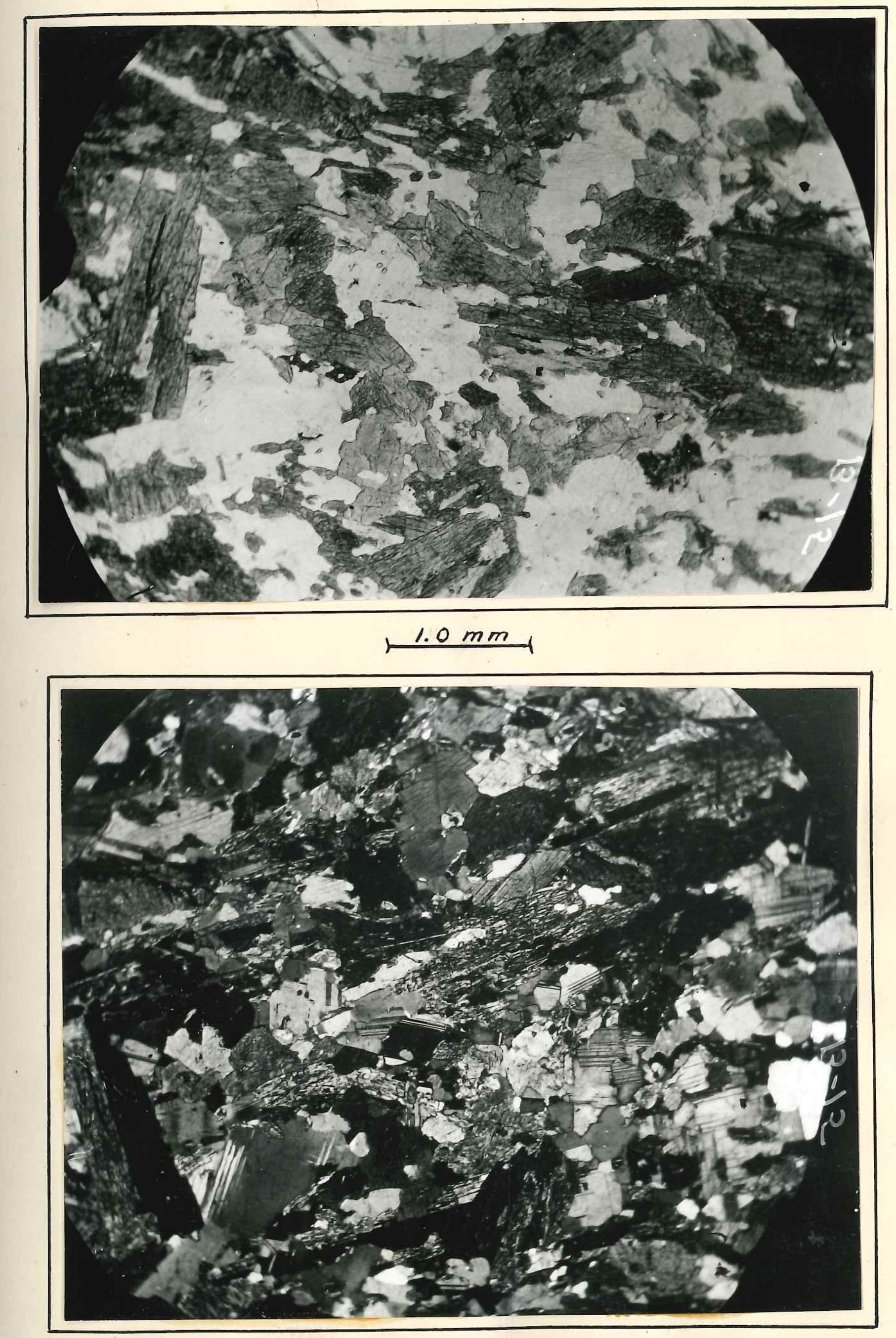
(Photomicrographs, crossed nicols) Felspathized kyanite-biotite-sillimanite-plagioclase schist. Elongate sillimanite and compositional banding (left) mark the schistosity. Plagioclase porphyroblasts (right) enclose sillimanite and groundmass. Later untwinned plagioclase and quartz partially replace the felspathized bands. Spec. D-22b, west side, Grizzly Mt.

PLATE XXXXI A and B



(Photomicrographs: A, plane polarized light; B, crossed nicols) Biotite-sillimanite gneiss. Large plagioclase (AN 30-25) porphyroblasts include the quartz and sillimanite of the original schist. Some sillimanite displays incipient diaphthoresis, with the formation of iron oxide rims about partially sericitized and biotitized sillimanite. Spec. D-15a, south peak, Grizzly Mt.

PLATE XXXXII A and B



(Photomicrographs: A, plane polarized light; B, crossed nicols) Felspathized amphibolite. Andesine almost equals common green hornblende. Quartz very minor. Foliation weakened by partial static recrystallization of hornblende. Spec. B-15, summit of Nason Ridge east of Lake Merritt.

In the average gneiss described above, and also in many of its varieties, there is microcline. Almost invariably the microcline is confined to rather narrow zones transecting the gneissic structure, and forms porphyroblasts which average 2 mm., but exceptionally are 8 mm. in size. The microcline is associated with a noticeable vermicular growth of quartz and plagioclase. Several specimens show plagioclase being eaten into and engulfed by microcline.

A comparison of adjoining layers of schist and gneiss shows the two do not differ radically in texture or mineral composition. Whereas quartz is usually the dominant constituent of the schists, plagioclase assumes that role in the gneisses. Most of the biotite of the schists becomes muscovite in the gneisses. Where hornblende was a major constituent of the schists, biotite, muscovite, clinozoisite, and epidote are present in the adjoining gneiss. In both cases the total amount of mica is reduced. Aside from these differences, the other mineral constituents of the gneisses and schists are identical in type and, usually, in quantity.

A very clear demonstration of the migmatitization process is observed in the lit-par-lit migmatitic gneisses on the southeast flank of Evergreen Mountain (Plate B, E-3). Here there are much contorted, banded biotite-quartz schists with intercalations of leucocratic trondhjemitic gneiss. The gneissose bands range in thickness from 1 inch to 5 feet.

There are three main types of bands in this Evergreen Mountain zone of migmatitization. The first and most prevalent type of band represents the host rock. This is a fine- to medium-grained, garnet-bearing, plagioclase-rich, biotite-quartz schist. The composition of this schist is: plagioclase--An_{32}, 37%; biotite, forming both a continuous and discontinuous foliation, 35%; quartz, 22%; and accessories. The minerals, other than minor retrogressive chlorite, form a stable and contemporaneous assemblage, and they indicate that this rock is an isochemically metamorphosed schist formed through the processes of regional orogenic metamorphism.

This type of band grades into a hornfelsized schist. As the contact between hornfelsized schist and gneissic layer is approached, the schist is increasingly felspathized. The biotite has been recrystallized into irregular plates with random orientation. A microscopic examination shows a marked increase in the amount of plagioclase as the gneissic layers are approached. An average composition for the hornfelsized schist bands is: plagioclase, An_{30}, 45%; biotite, 35%, and quartz, 20%.

Transitional with the hornfelsized and felspathized schist bands are gneissic layers. These contain a fine-grained, inequigranular, completely crystalloblastic mineral assemblage. Thin stringers of biotite and lenticles of fine-grained quartz-plagioclase mosaic occur as relics of the schist. These gneissic layers show a patchy distribution of minerals. Some areas are quartz-rich, while others are plagioclase-rich. However, the gneissic structure is absolutely parallel with the compositional banding of the hornfelsized schist bands and the foliation of the schists.

The composition of the gneissic layers in the Evergreen Mountain migmatite zone is that of a leucocratic trondhjemite. The minerals are: plagioclase--An_{27} to An_{23}, 55%; quartz, 35%; muscovite, 6%; and biotite, 4%. The plagioclase forms twins up to 2 mm. in size, and contains numerous inclusions of quartz, plagioclase, and muscovite. Many of the twins are bent and ruptured, and many have been replaced marginally, or along minute cross-cutting fractures, by quartz and untwinned plagioclase of albitic composition. Some of the larger plagioclase twins also contain bundles of squeezed and contorted biotite. Part of the biotite is altered to muscovite, and part to fibrolite.

This zone on Evergreen Mountain shows a progressive, differential metasomatism of a biotite-quartz schist. Certain layers have been hornfelsized and felspathized, and it is noteworthy that the plagioclase becomes more sodic as the rock acquires more granitic characteristics. The fibrolite inclusions within the plagioclase twins suggest that a differential shearing opened avenues of approach for the sodium-bearing solutions. This first introduction of sodium apparently was followed by a later sodium and silica introduction. The latter is suggested by the late albite and quartz replacement of the large plagioclase twins. The muscovitization of the biotite may indicate a minor potassium introduction.

Plates XXXIX, XXXX, and XXXXI show a similar differential metasomatism from the vicinity of Grizzly Peak (Plate B, E-6).

Genetic Interpretation

Structural field evidence and microscopic studies indicate that the migmatitic gneisses have been derived from schists through processes of synkinematic and postkinematic metasomatism.

In the field, the contacts between schists and gneisses are invariably gradational. Moreover, the foliation of gneisses and adjacent schists is generally parallel. This parallelism exists both where thin, lenticular bands of schist are completely enclosed in gneiss, and where smaller relics of schist occur in the gneiss.

A genetic evaluation of the structural and petrographic features of the migmatitic gneisses indicates the following probable sequence of events.

(1) During and after the isochemical metamorphism which formed the schists, there was an introduction of sodium and silica in the areas now occupied by the migmatitic gneisses. This assumption is required to explain the presence of plagioclase as the dominant constituent of the gneisses. At the

same time, the hornblende of the hornblende-bearing schists was biotitized, suggesting the introduction of some potassium in addition to sodium and silica. At a later stage, biotite was extensively converted to muscovite.

The biotitization of hornblende released mainly calcium, whereas the transformation of biotite into muscovite set free magnesium and iron. In addition to these mineral transformations, the total amount of mica decreased during the felspathization. This led to a further release of iron and magnesium, as well as some aluminum which was utilized to form metasomatic feldspar. It is of interest that kyanite, staurolite, and sillimanite remained as stable constituents of those migmatitic gneisses having a lit-par-lit structure. The absence of these aluminum silicates in the more homogeneous and less obviously banded gneisses north and east of Merritt may be the result of two factors: (1) The schists may have been dominantly hornblende-bearing varieties, thus never having had the aluminum silicates; of, (2) the aluminum silicates were broken down during the more advanced felspathization of this area.

The genesis of the metasomatic plagioclase may be outlined as follows. Aluminum, set free by the breaking up of mica, and, possibly, by the breaking up of aluminum silicates; quartz, from the schists; and calcium, set free as a result of the biotitization of hornblende: all combined with metasomatically introduced sodium to form the plagioclase.

This plagioclase ranges from oligoclase to andesine. Where hornblende was a major constituent of the schists, the relatively large amount of calcium released by biotitization made a more calcic plagioclase which approximates An_{40} in composition. Where biotite was the dominant mafic in the schist, and hornblende was either minor or absent, a more sodic plagioclase formed in the gneisses, approximating An_{30} in composition. This variation in composition can be correlated with the composition of adjacent schists.

(2) The processes described in (1) continued after the end of deformation. High temperatures and sodium introduction evidently continued. Large porphyroblasts of plagioclase, with random orientation, developed during this static phase of felspathization, both in the gneisses and the adjacent schists. Transverse grains of biotite and muscovite grew across the foliation of the schists, and to a certain extent a hornfelsic texture was superimposed on the schistosity. Hornfelsing is especially marked where schists are immediately adjacent to gneisses (Plate XXXV).

(3) Following the production of the gneisses, widespread fracturing occurred. A system of cross-cutting fractures was formed along which dike-like and other more irregular bodies of fine- to coarse-grained granitic rock were produced. These granitic bodies transect both schists and gneisses. Generally one contact of these bodies is well-defined, suggesting a pre-granitic cross-cutting fracture as a marginal control. The other contact of these bodies is generally irregular in detail and gradational with the country rock. In some of these granitic bodies there are haphazardly oriented inclusions of schist and gneiss. These suggest a fault breccia which has been replaced by granitizing materials, or an incipient mobilization and local intrusion by granitic materials (Plates LII-LIV). In other places, the inclusions have attitudes parallel to those of the surrounding schists or gneisses, and obviously have not been displaced (Plates LVII, LVIII). Flow structures parallel to the long axes of the granitic bodies are rare, and the parallel structure of the enclosing gneiss or schist generally can be traced across the dike-like bodies as a relict structure. However, some of the coarser-grained, "pegmatitic" dike- and vein-like bodies lie with marked discordance to the country rock, and some display dilation effects. It is probable that these locally became mobilized and intrusive.

The cross-cutting dike-like bodies generally consist of a fine-grained, "salt and pepper"-like granitic rock. A microscopic examination shows that this granitic material generally grades into the country rock at one or both contacts. The average size of the mineral constituents is 0.2 to 0.5 mm. Locally there are pegmatitic varieties which have crystals up to 20 mm. Plagioclase, ranging from An_{35} to An_{25} is the main constituent, and averages 60% of the rock. Most of the plagioclase crystals commonly approximate An_{35} in composition. The smallest (generally less than 0.2 mm.) and apparently latest crystals are more sodic and average An_{25}. Moreover, some of the largest individuals (up to 20 mm. long) are relatively sodic and also approximate An_{25}. In all cases the plagioclase is anhedral, and shows the irregular margins characteristic of crystalloblastic growth. The smaller, more sodic plagioclase grains grow at the expense of the larger and more calcic plagioclase, as well as of the quartz and biotite.

Quartz averages 25% of these granitic rocks, and forms anhedra ranging in size from large irregular crystalloblasts, up to 8 mm. long, to small rounded grains which occupy the intergranular spaces.

Biotite is the only important mafic constituent, and forms about 10% of the rock. The biotite is haphazardly oriented in irregular plates that possess ragged and fuzzy margins. The size of the biotite ranges from 0.1 to 0.5 mm., with a very few individuals forming "book-like" aggregates up to 10 mm. long. These are restricted to the quartz- or plagioclase-rich "pegmatitic" bodies.

Thus, the granitic rock of these cross-cutting bodies approximates the composition of a quartz diorite.

An examination of these dike-like bodies suggests that the majority have formed by replacement in situ. Locally, however, there are flow structures developed parallel to the dike walls, or there are sharp and discordant contacts and dilation effects, and the dike is then interpreted as being a mobilized migmatite which locally has become intrusive.

Locally, there are porphyroblasts of microcline which invade and engulf plagioclase and quartz. These microcline porphyroblasts are restricted to narrow, often microscopic, vein-like elongate zones which transect the pre-existing granitic rock and the adjacent gneisses and schists. Invariably this microcline is associated with a vermicular growth of later quartz and untwinned plagioclase. The microcline suggests a potassium introduction along minute fractures during a postkinematic phase of recrystallization.

(4) The last event was the formation of epidote and sericite from plagioclase, and of chlorite from biotite. Apparently these low-temperature minerals formed during a phase of retrogression at the end of metamorphism, when temperatures were falling. However, part of the sericite and chlorite is the result of recent weathering.

Granitic Gneisses of Migmatitic Derivation

Distribution and Associations

Coarser-grained gneisses of granitic* composition are subordinate in areal extent to the migmatitic gneisses. They form narrow bands or zones between migmatitic gneisses and schists, and directionless granitic rocks. In the southern part of the mapped area on Barrier Peak (Plate B, I-7), and in the northern part of the mapped area around Pear Lake (Plate B, C-5), these granitic gneisses are the dominant rock type. Other narrow zones occur wherever there is a transition from schist or migmatitic gneiss into directionless granitic rock. Some specific localities where the granitic gneisses crop out are:

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*Granitic is again used in the broad sense of any grained rock ranging in composition from diorite to granodiorite.

on West Cady Ridge (Plate B, B-3, -4); on the south spur of Fortune Mountain (Plate B, G-5, -6); and in an elongate zone between Meadow Creek (Plate B, E-4) and Barrier Peak (Plate B, I-7).

The parallel structure of the granitic gneisses and their intercalated beds of schist and migmatitic gneiss invariably parallels that of the adjacent, more sharply-foliated rocks. Moreover, the granitic gneisses are completely gradational with all adjacent rock types. Thus, these rocks form the transition zones between the directionless granitic rocks and the more obviously metamorphic foliated rocks.

The granitic gneisses grade both along and across the strike into migmatitic gneisses and schists. One of the most important facts brought out by a study of this gradation is that of the absolute correlation between the mineral assemblages of the gneisses and the assemblages in the migmatitic gneisses and schists. This is especially marked by the ferro-magnesian mineral content of the contrasted rocks. Where biotite-quartz schists grade along the strike into migmatitic gneisses and then into granitic gneisses, biotite carries through as a principal constituent. Where hornblende-bearing schists or amphibolites grade along the strike into gneisses, hornblended, or biotitized hornblende, carries through as a major constituent. This absolute correlation holds true also where diopside-bearing granulites and actinolite-bearing schists grade into the gneisses. This coincidence of mineral composition, coupled with the parallelism of structures, strongly suggests that the granitic gneisses are derivatives of the schists.

<u>Petrography</u>

The granitic gneisses vary in texture and composition. Most are medium-grained, with the major constituents averaging 3 mm. in size. A few are fine-grained, and the individuals rarely exceed 1 mm. in size. At Pear Lake (Plate B, C-5), the gneisses are coarse-grained, with some individuals up to 15 mm. long (Plate XXXXIII A).

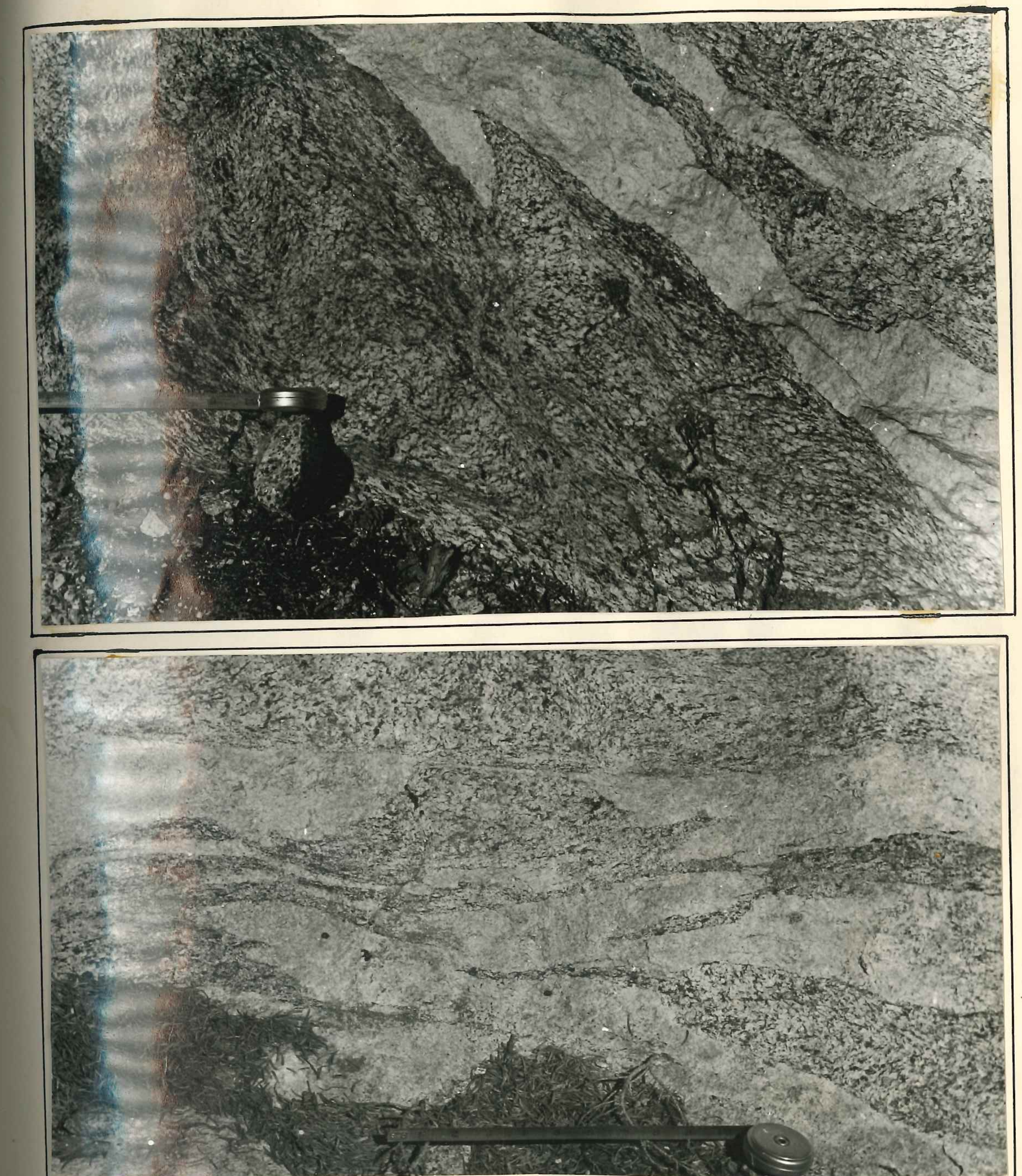
In some of the gneisses the foliation is closely-spaced and well-defined by elongate minerals (Plate XXXXIII A). In other cases the foliation is less distinct (Plates XXXXV, XXXXIX B, L B). Locally, the rock becomes almost directionless, and thin relict stringers or lenticles of schistose material, or thin bands rich in biotite or hornblende, mark the foliation (Plates L A, LVII, LVIII).

The composition of the granitic gneisses is variable, but generally any one specimen can be correlated with one of three groups of granitic rocks. Some of the gneisses are alaskitic; some are trondhjemitic; most are quartz dioritic in composition. However, there are all possible gradations between these three groups. Thus, there actually is no one typical granitic gneiss. One method of differentiating the gneisses is based on the biotite, hornblende, or diopside content.

All of the granitic gneisses in this area have biotite as a major constituent. In most, biotite is the only ferro-magnesian mineral of importance. However, some of the gneisses have hornblende or actinolite (rare) as an important associate of the biotite. In a very few specimens diopside is an associate of biotite.

A microscopic examination of the granitic gneisses shows that plagioclase is the principal constituent, and forms from 50% to 65% of the rock. Generally there are three generations of plagioclase. The first generation is represented by minute, rounded, untwinned grains which, in shape and composition, are reminiscent of similar individuals within the adjacent schists. These small anhedra rarely exceed 0.25 mm. in size, and they generally occur as inclusions within larger plagioclase and quartz crystalloblasts.

PLATE XXXXIII A and B



Quartz-dioritic gneiss with inclusions of hornfelsized, partly felspathized hornblende (in some zones, actinolite)-biotite-quartz schist, with later fine-grained alaskitic replacement dikes. Photo. D-1-10,-11; west wall of Pear Lake cirque.

PLATE XXXXIV

Migmatite zone showing contact between a medium-grained, biotite-rich trondjhemite and a hornfelsized, partially felspathized, banded sillimanite-biotite-quartz schist. Felty aggregates of muscovite and sericite are pseudomorphous after andalusite. Photo D-3-3, E. flank, Deobrah Peak.

PLATE XXXXV

Knots and individual crystals of muscovite pseudomorphous after andalusite occur as inclusions within a weakly genissose trondhjemite. Photo. D-3-1, E. flank, Deborah Peak.

The second generation of plagioclase consists of large crystalloblasts which average 3 mm. in length, and are, exceptionally, 6 mm. long. These have a tendency to be elongated parallel to the foliation. These individuals have crenulated borders and interlock, one with another and with other minerals, in an intricate fashion. They contain numerous inclusions of one or more of the following minerals: small plagioclase grains, a few of which are twinned; quartz; biotite; and muscovite (Plate XXXXVI).

Twinning after the albite, Carlsbad, and pericline laws is common, and much of the twinning is complicated. Many of the plagioclase porphyroblasts are zoned. This zoning is anhedral, and there is very little correlation between the zonal boundaries and the margins of the crystals. Most of the zoning is progressive, the cores generally being more calcic, and the rims more sodic in composition.

The composition of these larger porphyroblasts ranges from An_{46} to An_{23}. This compositional range is a function of two factors. First, there is a range in the zoned plagioclase, from a more calcic core generally averaging An_{40} to a rim exceptionally as sodic as An_{23}. Second, the average composition of the plagioclase is determined by the total composition of the rock which is reflected in the type or types of ferro-magnesian minerals present. Moreover, the type of mafic minerals are directly correlative to the types of mafic minerals occurring in the adjacent migmatitic gneisses and schists. Where hornblende, diopside, or actinolite is a major constituent, the average composition of the plagioclase ranges between An_{46} and An_{35}. Where these minerals are absent, and biotite or muscovite are principal constituents, the average composition ranges from An_{30} to An_{25}.

Many of the porphyroblasts of this second generation of plagioclase are bent or ruptured (Plate XXXXVI); others are traversed by minute fractures.

PLATE XXXXVI

(Photomicrograph, crossed nicols) Oligoclase porphyroblast (upper left) containing inclusions of quartz, biotite, and muscovite. Deformed plagioclase (lower right). Quartz dioritic gneiss. Spec. B-24, Lake Merritt.

PLATE XXXXVII

(Photomicrograph, crossed nicols) Typically granoblastic metasomatic trondjhemitic gneiss. The synkinematic phase is marked by bands (top and bottom) of elongate biotite. Static Felspathization has occurred with plagioclase anhedra growing between the schistose bands. Spec. D-37a, N. Peak, Grizzly Mt.

PLATE XXXXVIII

(Photomicrograph, crossed nicols) Diopside-biotite-quartz dioritic gneiss. Diopside (bottom) is partly replaced by biotite. Ruptured plagioclases are marginally replaced by later quarta. This is a typical granoblastic granitized rock. Spec. E-24, near junction of Meadow Creek and Rapid River.

Filling these fractures and invading the margins of the plagioclase are anhedra of the third generation of plagioclase.

The individuals of this third generation generally are untwinned. But twins after the albite, Carlsbad, and pericline laws locally occur. Regardless of which mafic constituents are present, this last generation of plagioclase is quite sodic, and ranges in composition from An_{28} to An_{23}. Moreover, it generally occurs in a vermicular intergrowth with a third generation of quartz.

Quartz is a major constituent of the granitic gneisses, and averages about 25% of the rock. In the rare alaskitic gneisses, the quartz forms up to 35% of the rock. In certain of the hornblende-biotite quartz dioritic gneisses, in which biotite forms about 15% and hornblende almost 10% of the rock, the quartz averages about 17%.

There are three generations of quartz, which, apparently, are contemporaneous with those of the plagioclase. With the exception of the first generation of rounded, minute grains, the quartz is porphyroblastic and grows into and around the earlier constituents.

Biotite is always present. In some of the gneisses it is the only important ferro-magnesian mineral. The amount of biotite ranges from a low of 5% in the alaskitic gneisses to a high of 15% in those quartz dioritic gneisses which contain diopside or hornblende. The average amount is about 10%. Part of the biotite can be seen to have formed from hornblende, and is associated with it in a parallel intergrowth.

Two generations of biotite are recognizable. The first generation consists of elongate plates with ragged terminations. These plates occur in a sub-parallel arrangement and form a well-defined but discontinuous foliation. Locally, the biotite occurs in polygonal arcs which apparently are relics of a schist. Most of the biotite is concentrated in narrow stringers which are widely spaced, the interspaces generally containing almost directionless granitic material. Pleochroic haloes about zircon nuclei are common, and many of the smaller elongate biotite individuals are inclusions in larger plagioclase and quartz crystalloblasts. Some of the biotite has been squeezed and minutely folded, and some has been converted to fibrolite.

The second generation of biotite forms irregular plates with no appreciable elongation. Some of these individuals lie parallel to the foliation; most have a random orientation. Fuzzy margins are common. This later biotite generally is darker reddish-brown than the first generation. Retrogression and/or weathering has caused penninite to form from some of the biotite.

Hornblende or, actinolite (rare), is a common constituent of the quartz dioritic gneisses, but neither is present in the tronhjemitic or alaskitic varieties. Hornblende and biotite, in parallel intergrowth, are common associates, and much of the biotite has formed from the hornblende. Most of the hornblende, though bent, is in a subparallel arrangement, and aids in defining the foliation. The hornblende has very pale colors, and apparently is rich in the actinolite molecule.

Diopside occurs in a few of the gneisses which crop out near Pear Lake (Plate B, C-5), and locally it forms up to 5% of the rock. The diopside occurs in irregular masses which are marginally altered to biotite (Plate XXXVIII). It is noteworthy that these diopsidic quartz dioritic gneisses, when traced along the strike, are transitional with the diopside-bearing lime-silicate granulites of West Cady Ridge (Plate B, B-4).

Isolated clumps of what megascopically appear to be andalusite crystals are locally encountered in the vicinity of Deborah Peak (Plate B, E-7).

PLATE XXXXIX

A. Leucocratic, medium-grained quartz diorite. Patchy arrangement of mafic minerals. Spec. C-5, near confluence of Mill and Nason Creeks.

B. Gneissose quartz diorite. Relict foliation marked by darker and lighter bands varying in mafic content. Spec. B-2, Lake Valhalla.

PLATE L

A. Quartz diorite. Variation between a directionless rock and one with relict foliation marked by layers of mafic minerals. Spec. A-29, east ridge of Barrier Peak.

1.0 inch

B. Quartz-dioritic gneiss. Relict foliation marked by subparallel orientation of biotite and hornblende. Spec. A-22, summit of Barrier Peak.

microscopic examination discloses that they are felty masses of muscovite and sericite, and no vestige of the original mineral remains (Plates XXXXIV, XXXV).

Thus, the granitic gneisses typically contain plagioclase, quartz, and biotite, with hornblende or diopside as locally important constituents. It is important to reiterate the fact that those gneisses which contain biotite as the sole important ferro-magnesian mineral can be traced into biotite-quartz schists, while those which contain hornblende or diopside can be traced into isochemically metamorphosed hornblende- and diopside-bearing rocks.

There are various accessory minerals. Chlorite, generally penninite, is a retrogressive mineral which has formed in parallel intergrowth with biotite. Muscovite has formed from biotite in some specimens, and locally it apparently is pseudomorphous after andalusite. Zircon occurs as the nuclei of pleochroic haloes, as does orthite. Magnetite forms irregular grains and aggregates, and is especially prevalent where hornblende has been biotitized. Apatite forms small grains and is quite common in the biotitic and hornblendic bands. Epidote and clinozoisite, as well as sericite, have formed from plagioclase.

A genetic interpretation of these granitic gneisses is included with that of the directionless granitic rocks.

Directionless Granitic Rocks

Distribution and Associations

Directionless granitic rocks form the most abundant group in the Beckler River-Nason Ridge area. These varied rocks underlie about one-half of the mapped area, and they are the dominant rock type in the area which is bounded by the Tye River on the south, the Beckler River on the west, the Rapid River on the north, and the Cascade Crest on the east. The distribution of these rocks is shown on Plate B, but they probably extend far beyond the confines of the mapped area. When looking south from the higher peaks west of Stevens Pass (Plate VII), it appears that these granitic rocks are continuous with the granodiorites of the Mt. Stuart area (41).

The term granitic is applied to these rocks, though they vary greatly in texture and composition. In this paper, "granitic rocks", "granitic", and "granitoid" are used in the broad sense of any grained rocks varying in composition from diorite to granite. However, there are no rocks of a true granite mineralogical assemblage in this area, and diorites generally are restricted to the migmatite areas previously discussed. The granitic rocks of this area commonly are quartz diorites, with subordinate trondhjemites, granodiorites, and alaskites.

The term directionless is applied to these granitic rocks as a matter of convenience. It serves to differentiate them from the bordering rocks in which foliation is discernible.

Contacts

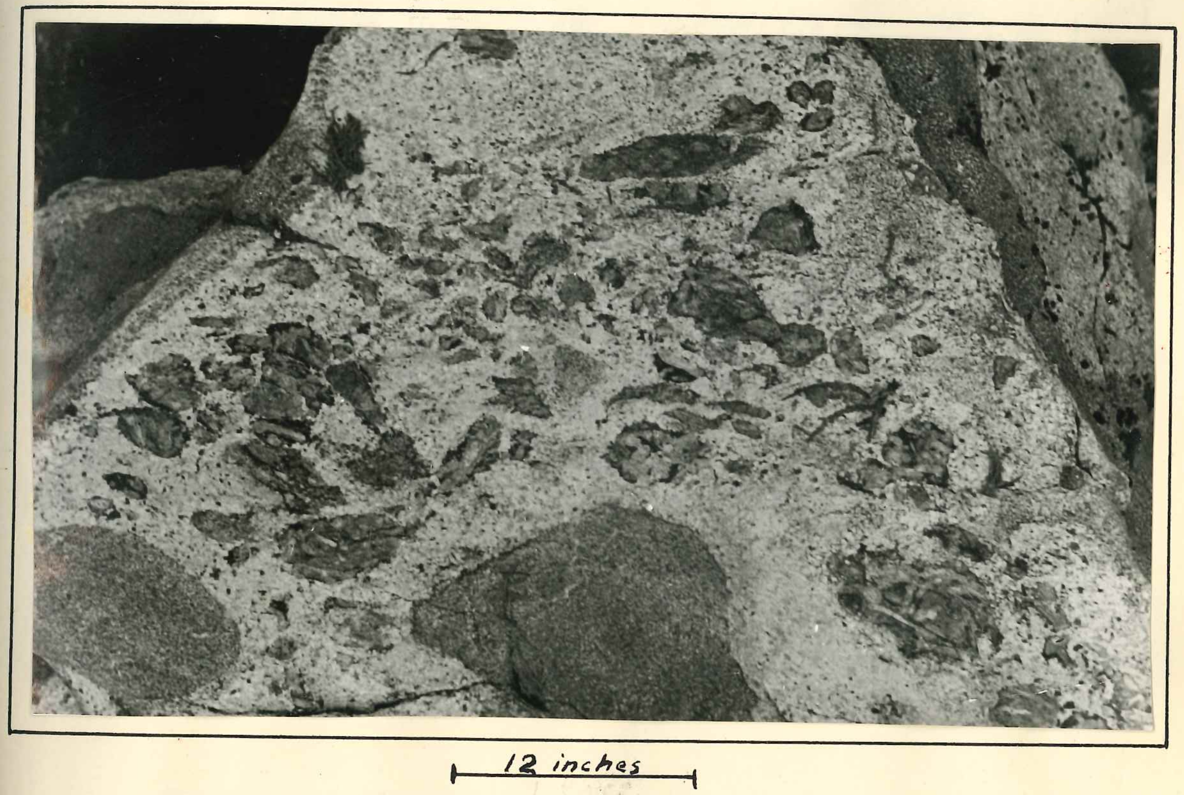
The contacts of the granitic rocks with other rock types are of four types.

Type I: Most commonly the granitic rocks are completely gradational with granitic gneisses (Plate B). All gradations exist between relatively uniform, mostly directionless granitic rocks and partly directional, partly directionless granitic gneisses. These gneisses form narrow zones, up to 1000 feet wide, which are in turn gradational with migmatitic gneisses and schists. The relationship of the granitic gneisses to more clearly foliated rocks has been discussed previously.

Type II: A second type of contact is restricted to the ridge immediately south of the main summit of Mt. Fernow (Plate B, I-7). Here the granitic rocks are in a moderately to absolutely sharp contact with hornfelsized schists (Plate LX). The contact transects the structure of the schists. The marginal several hundred yards of the granitic body are filled with inclusions of schist in varying stages of transformation. Proceeding from the main granitic body toward the discordant contact with the schists, the inclusions, which in the main granitic body form amounts of less than two per cent, become more and more abundant. These inclusions vary considerably in texture and degree of transformation into more granitic rocks. Some of them are composed of schist which is unaltered except for a superimposed hornfelsic texture. Others are mere shadowy relics or skialiths (Goodspeed, 17) which differ only slightly in texture and composition from the enclosing granitic rocks. In most cases the contact between the inclusions and the enclosing granitic rock is gradational. Where the contact is sharp there is generally a 0.5 to 2.0 mm. wide selvage of biotite around the inclusion.

Type III: A third type of contact generally is restricted to the area of the migmatitic gneisses lying east of the Cascade Crest, and the granitic rocks associated with these migmatites have been discussed previously. At these localities, granitic rocks transect schists or migmatitic gneisses in dike-like and more irregular bodies up to 50 feet wide. In these bodies there are numerous irregularly-shaped, haphazardly-oriented fragments of schist which appear to indicate that brecciation of the schists facillitated the emplacement of the granitic materials. The schist inclusions range from remnants of hornfelsized and felspathized schist to skialiths (Plates LI-LVI). Easily accessible examples of this third type of contact occur in the road cuts along U. S. Highway 2, both above and below the confluence of Mill and Nason Creeks (Plate B, H-9). However, these localities, interpreted as replacement breccias, are not restricted to small granitic bodies surrounded

PLATE LI



Metasomatic quartz-bearing biotite diorite with plagioclase-rich inclusions of hornfelsized biotite-hornblende schist. The mineral composition of both granitic rock and inclusions is practically identical; the inclusions differ mainly by being less coarsely crystallized. This outcrop demonstrates incomplete granitization in a replacement breccia. Photo D-1-7, ridge west of Glasses Lake.

PLATE LII

Replacement breccia displaying plagioclase porphyroblasts growing within hornfelsized schist. Beneath the tape is a quartz lenticle bordering a boudin-like relict of the original schist. Quartz diorite. Photo. D-3-2, E. flank, Deborah Peak.

PLATE LIII

Replacement breccia. Medium-grained quartz diorite containing hornfelsized, biotitized, and felspathized inclusions which are relicts of a quartz-biotite-hornblende schist. Photo. D-1-6, meadow south of Camp At Last.

PLATE LIV

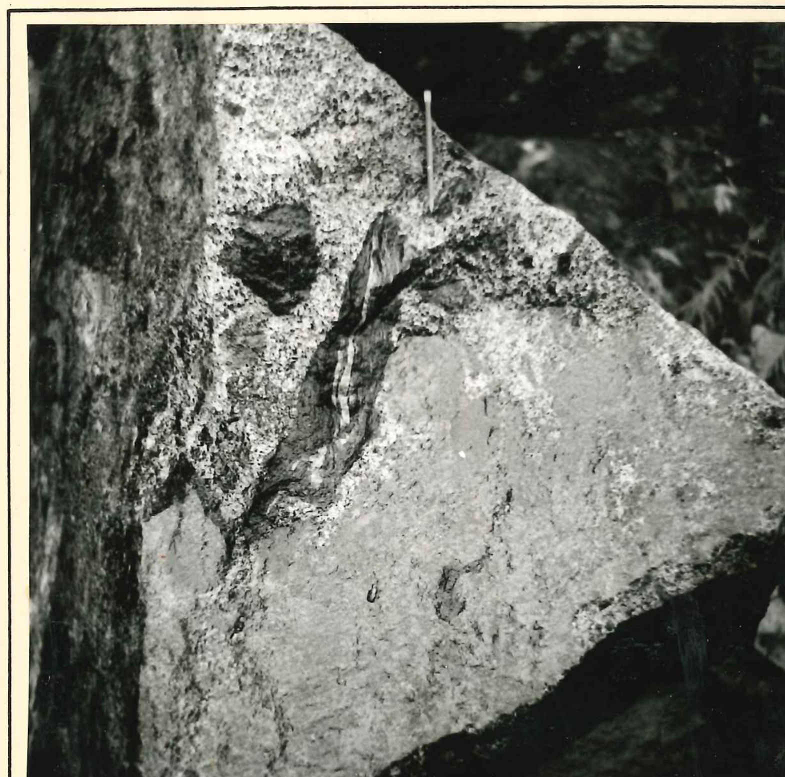
± 12 inches

Replacement breccia showing inclusions and skialiths within a granitic rock with varies from a medium-grained quartz-diorite to a coarse-grained biotite-rich trondjhemite. The inclusions, differentially hornfelsized and felspathized, vary from banded sillimanite-biotite-quartz schist to quartz-plagioclase granulites. Photo D-3-4, east flank, Deborah Peak.

PLATE LV

Migmatite. Quartz diorite with bands, inclusions, and skialiths indicative of an incomplete felspathization of a biotite-hornblende schist. Photo. D-1-4, ridge east of Stuart Basin.

PLATE LVI



Replacement breccia. Inclusions of schist material vary in degree of transformation from hornfelsized biotite-quartz schist to skialiths. Dark inclusion to the left of the biotite-quartz schist is a segregation of mafic minerals. Lower Mill Creek.

by schist and gneiss. There are similar migmatite zones deep within the granitic terrain.

In the Type II and Type III migmatitic contacts just described, there exist all gradations between, and all proportions of granitic and gneissic or schistose materials. Therefore, it is impracticable to single out one specimen as being typical. However, regardless of the position within the migmatite zones, the rocks share certain characteristics:

(1) The contacts between the relatively coarse-grained, leucocratic granitic rocks and the more fine-grained, often darker, migmatitic gneisses and schists, are usually gradational. This applies, regardless of whether the schist or gneiss is a small, blocky, or rounded inclusion surrounded by granitic rocks, a layer intercalated in the granitic material, or whether the schist or gneiss is spatially continuous with its parent body.

(2) Though the schist material in the border zones megascopically resembles the rocks found in the more uniform parent body, it generally displays a superimposed hornfelsic microtexture. This is especially true in schist inclusions which are surrounded by granitic material. Relict schistosity and occasional polygonal arcs generally have been preserved in the schist materials. However, most of the mafic minerals have recrystallized into irregularly-shaped and haphazardly-oriented grains, some of which enclose thin bands of graphite marking the original schistosity. In many cases the schistosity has been destroyed, especially in the more strongly transformed inclusions of skialith-type.

(3) With the hornfelsic texture there always is associated a growth of small plagioclase grains which are usually of a more sodic composition than the larger plagioclase crystals of the adjacent granitic rock. Moreover, the amount of quartz has increased, and this increment is particularly conspicuous

where the schist rock was a quartz-poor hornblende schist or amphibolite. During this plagioclase and quartz growth, elongate biotite and hornblende flakes were not only included along the twinning planes of plagioclase, but were invaded by plagioclase and, locally, quartz.

The superimposed hornfelsic texture, and the increase in plagioclase and quartz content of the schist materials within the migmatite zones, gradually disappear with increasing distance from the contact between migmatite and schist. On Mt. Fernow (Plate B, I-8), a few hundred feet north of the contact, the schists have a well-marked preferred orientation of their mafic constituents.

(4) The granitic rocks of the border zones vary in composition and texture. The specific variety of granitic rock produced is definitely correlative with the variety of schist invaded, as well as with the degree of felspathization and transformation of the schist material. Where biotite-quartz schists have been transformed into granitic rock, as on Mt. Fernow, a leucocratic quartz dioritic rock has resulted. Where a hornblende-rich rock was invaded, a dark dioritic rock has been formed. This latter variety is most common along Nason Creek (Plate B) where schists rich in hornblende have been infiltrated by granitic materials.

(5) One fact concerning these migmatitic zones must be emphasized. With very few exceptions there is no evidence of forcible intrusion of the schists or gneisses by granitic materials. Only exceptionally is there any evidence for intrusive flow structure, regardless of whether granitic material is intercalated in the schists, or transects the schists in vein- and dike-like irregular masses. Moreover, dilation effects are lacking. A static invasion of most of the schists by granitic materials is indicated by the many discontinuous but aligned layers of schist material lying within the granitic

rocks, and the very common folded relict structures within the granitized rock which are marked by alternations of lighter and darker bands (i.e., "nebulite", after Sederholm).

Schist blocks with random orientation are common, but the zones containing these rotated blocks are interpreted as being replacement breccias, and the rotation of their schist blocks is attributed to pre-granitic tectonic brecciation. This interpretation of replacement breccias formed by incomplete static granitization of previously brecciated schists is strongly suggested by the following features:

a. There is no evidence of intrusive flow structures;

b. All textures in schist materials and granitic rocks are crystalloblastic;

c. These migmatite zones contain many large, shadowy blocks with hornfelsized schist centers which show a complete gradation between relatively coarse-grained granitic rock and much finer-grained hornfelsized schist;

d. Stringers of mafic materials extend from partially transformed schist blocks into the granitic rocks. Locally these stringers extend completely across the dike-like and more irregular granitic bodies. This fact alone denies the possibility of forcible intrusion of the granitic materials.

Type IV: The fourth type of contact occurs on the southwest spur of Beckler Peak (Plate B, I- and J-2), and on the east side of the Beckler River about two miles south of its confluence with the Rapid River (Plate B, G-2). At these two localities the granitic rocks lie in sharp and discordant contact with phyllites and subordinate schists.

The best exposed example of this fourth type of contact occurs near the 2500 feet level on Beckler Peak. Here logging road cuts display over 500 feet of nearly continuous exposures of this contact zone.

At this locality the main granitic body lies to the east, with dark phyllites to the west (Plate B). The latter rock is a quartz-chlorite-sericite phyllite with late biotite. This phyllite is much contorted and isoclinally folded. Its average strike is N. 15° W., with a dip averaging 50° to the east. The phyllite is transected by vertical to steeply north and east dipping joints and faults. As a result, the phyllite is deeply weathered and fresh specimens are difficult to obtain.

Between the main mass of phyllites and the main granitic body is a zone about 300 feet wide. Here there is an alternation of near vertical slices of phyllite, commonly from 5 to 10 feet in width, separated by dike-like bodies of granitic rock of similar width. Exceptionally the phyllite and granitic bodies are as much as 30 feet wide. In every case the contact between phyllite and granite is a fault, and both rock types are marginally sheared, slickensided, and brecciated. On the west edge of this 300 feet wide zone, there apparently is a major fault. Here there is a 5 feet wide zone of gouge and breccia which separates sheared phyllite on the west from sheared granitic rock on the east. This fault strikes about N. 15° W., and has a 70° dip to the east.

It must be emphasized that though locally the granite and phyllite are concordant, insofar as faulting permits of such an observation, by and large the granite and phyllite are in a relationship of angular discordance.

Intercalated in the phyllite, or cutting across the phyllite, are sill-like to vein-like bodies of granitic rock up to 1 foot wide. These decrease in width away from the adjacent granitic body, and generally are no more than 5 or 10 feet long. A direct connection of these granitic veins and sills with the wider dike-like granitic bodies is never visible because of separation along the faulted phyllite-granite contacts. However, a microscopic examination shows that the composition of these bodies is similar to that of the larger granitic bodies, and that they differ only by having a finer grain size.

A microscopic examination of the foliated rocks in contact with the granites shows that most are phyllites. This rock consists of about 65% quartz which forms not only a fine-grained mosaic in the ground mass but occurs as "micro-boudins" in the axial regions of the minute isoclinal and subisoclinal folds. Some quartz fills wedge-shaped areas which lie at an angle to the $\underline{s}_1$ of the phyllite.

Graphite forms up to 10% of the rock, and is concentrated in thin gliding planes which delineate the schistosity. The graphite also occurs in minute fault zones and in an $\underline{s}_2$ which has been superimposed across the $\underline{s}_1$ of the phyllite. The $\underline{s}_2$ apparently is an axial plane cleavage associated with the folding.

Chlorite and sericite, in minute elongate flakes, form up to 10% of the rock, and occur not only in the intergranular spaces of the quartz mosaic ground mass, but also as inclusions in the quartz wedges and along the graphite-inhabited gliding planes.

Biotite, forming up to 10% of the rock, is late, and is in part mimetic after the $\underline{s}_2$. This mimetic growth, marked by inclusions within the biotite of the graphite-marked $\underline{s}_2$ planes, is controlled mainly by the $\underline{s}_2$ and only locally by the $\underline{s}_1$. Most of the biotite is not elongate, and it has only a slight tendency to have a preferred orientation.

Intercalated in the dominant phyllite are bands up to 3 feet thick of a fine-grained biotite-quartz schist. In this schist there is a later set of shear planes which transects both the s_1 and s_2 of the schist. In this shearing process much of the biotite was forced into an alignment parallel to this latest system of shears, and most of the biotite was squeezed and partly converted to fibrolite.

The change from phyllite to schist is very rapid, locally taking place within 1 inch, measured in "c" (Sander, 40). Occasionally there is a complete gradation between schist and phyllite, but still within the space of less than 1 foot. Commonly a gliding plane of graphite with subordinate chlorite and biotite separates the two rock types.

Structures and Inclusions

The granitic rocks of this area apparently have been considered as structureless and homogeneous by Smith (43, 45). This is true to the extent that most of them lack any preferred orientation of their mineral components. However, though here termed directionless, the granitic rocks are neither homogeneous nor structureless.

Relict foliation is not only common in the border zones of the granitic rocks, but occurs within the main granitic mass. Generally this relict structure is not associated with any preferred orientation of the minerals, but is compositional, being caused by varying proportions of light and dark minerals in alternating bands and lenticles. Most of this relict foliation occurs in bodies of limited areal extent, and commonly these are near outcrops of granitic gneiss. In all such cases the attitudes of the relict foliation are parallel to those of the more clearly foliated rocks.

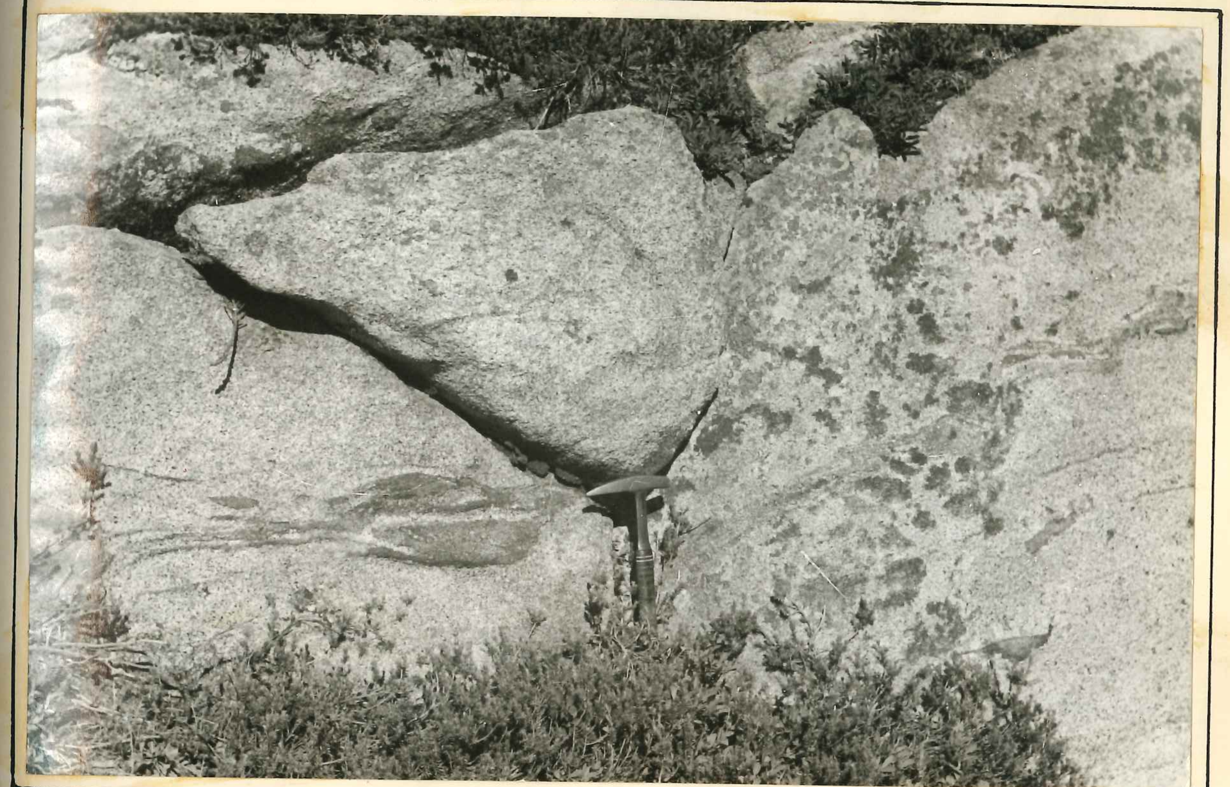
In addition to the relict foliation, dark inclusions in varying stages of transformation are common. Nowhere is there a mass of granitic rock more than a few feet across that lacks these inclusions. The materials forming most of the inclusions range from slightly hornfelsized schists to shadowy remnants or skialiths. Locally, there are lenticles of quartz, up to 6 inches in length, which are identical in shape and composition to the elongate quartz bodies which are common in the biotite-quartz schists (Plate LII). Moreover, these quartz inclusions contain elongate biotite in parallel orientation. Another common type of inclusion consists of lenticular aggregates or attentuated stringers of biotite. These range in length from several inches to a score of feet (Plate LVII).

Most of the various types of elongate inclusions occur in small groups, the members of which are in a striking parallel arrangement (Plate LVIII). It is noteworthy that the orientation of these aligned inclusions is in harmony with the attitudes of the schists and gneisses in the border zones. This is true even where the inclusions are as much as several miles distant from the contact of the granitic rocks with the foliated rocks.

Locally the inclusions are not elongate in shape, and they have a random orientation with indications of rotation. These zones are interpreted as schist or gneiss areas which were brecciated and subsequently invaded by granitic materials (Plates LI-LVI), but the possibility also exists that in some of these zones some later movement may have occurred.

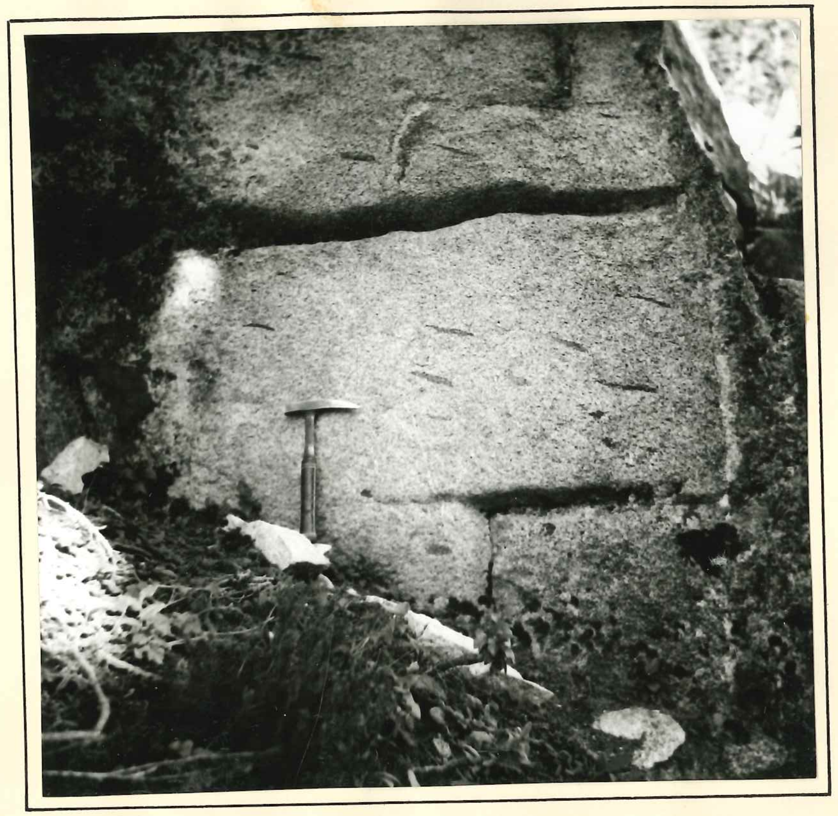
The many inclusions of schist within the granitic rocks vary in texture and degree of transformation. Some of them are composed of schist which is unaltered except for a superimposed hornfelsic texture (Plate LI). More commonly the inclusions are felspathized and hornfelsized and differ mainly from the granitic rock in having a higher content of dark minerals (Plate LIX). Other inclusions are mere shadowy relics or skialiths which differ only slightly in composition from the enclosing granitic rocks, and mainly in having a more fine-grained texture (Plate LV).

PLATE LVII



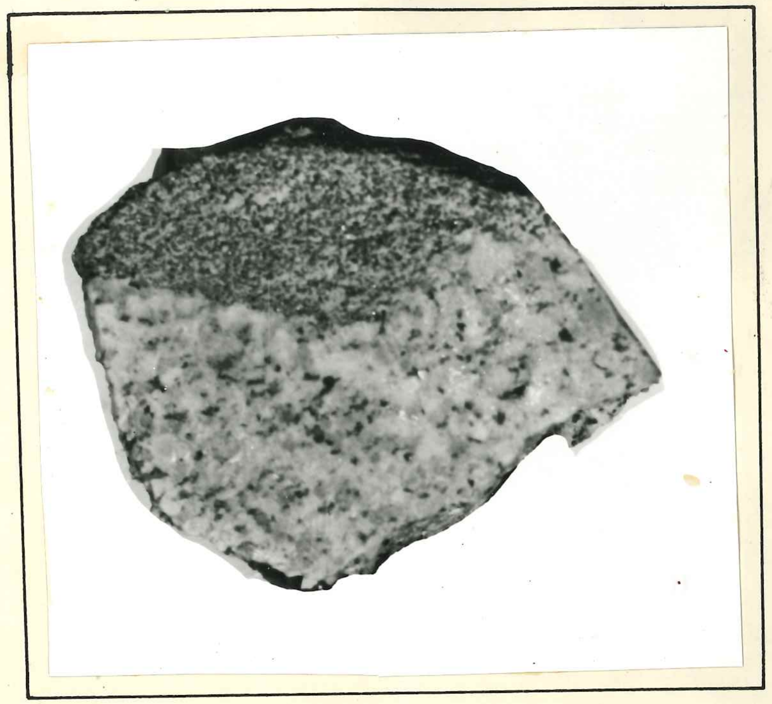
Quartz diorite with relict structure. Bands and inclusions are hornfelsized, felspathized biotite-quartz schist. Photo. D-1-5, ridge east of Stuart Basin.

PLATE LVIII



Quartz diorite containing elongate inclusions of hornfelsized schist material in parallel arrangement. Attitudes identical to those of adjacent schists. Southwest of Lake Valhalla.

PLATE LIX



1.0 inch

Leucocratic quartz diorite with inclusion of hornfelsized and felspathized schist material. Spec. B-3, southwest of Lake Valhalla.

PLATE LX

Sharp and discordant contact of schist and granitoid rock. Schists with a slight superimposed hornfelsic texture. South ridge of Mt. Fernow.

Generally, the contact between the inclusion and the enclosing granitic rock is gradational. Locally, the contact is sharp and there is a thin selvage of biotite, up to 2.0 mm. in width, around the inclusion. This biotite layer may be interpreted as a very local basic front, and probably represents a segregation of the mafic constituents during felspathization (Reynolds, 36).

Many of the moderately altered inclusions of schist have the following approximate mineral composition: biotite, 25%; pale green hornblende, 25%; plagioclase, averaging An_{35}, 25%; quartz, 10%; and accessory minerals such as apatite, magnetite, sphene, garnet, chlorite, muscovite, sericite, and tourmaline. This type of inclusion most commonly is bounded by a thin selvage of biotite. The inclusions generally consist of alternating lighter and darker bands. Thus, they megascopically appear to be schistose. However, a microscopic examination shows that the biotite and hornblende have lost their elongate shape and their parallel orientation due to a superimposed static recrystallization. Commonly the original structure of the schist is preserved as a relic in the form of parallel bands of graphite and magnetite which traverse the mafic crystals. Locally, some of the biotite and hornblende individuals have remained elongate, and some polygonal arcs, similar to those in the schists, persist. However, these are rare.

Usually there is evidence that hornblende was once the dominant mafic mineral, and that most of the biotite has been derived from the hornblende. It is noteworthy that most of the granitic rocks of the Beckler River-Nason Ridge area have hornblende as a constituent, presumably indicating that the granitic rocks occupy an area in which hornblende schists were once a dominant rock type.

Part of the plagioclase of these inclusions has the same composition as the plagioclase of the surrounding granitic rock, and it differs mainly in being smaller in size. Part of the plagioclase of the mafic-rich inclusions is somewhat more sodic than the plagioclase of the adjacent granitic material. Accessory minerals, such as apatite, sphene, magnetite, tourmaline, orthite, zircon, and occasional garnet are the same in the inclusions as in the granitic rock.

In addition to the internal structures described above, regular jointing is very common in the granitic rocks. Commonly there are three sets of joints approximately at right angles to each other. However, these joints apparently do not have a consistent orientation in this area.

Petrography

A microscopic examination of the granitic rocks shows that they can be assigned to four main groups. These are, in decreasing order of abundance, quartz diorites, trondhjemites, granodiorites, and alaskites.

Quartz diorites. The great bulk of the granitic rocks are quartz diorites. These are leucocratic, medium-grained, extremely inequigranular rocks characterized by a very patchy distribution of the mafic minerals. All textures are crystalloblastic, and the mineral constituents are anhedral, very irregular in outline, and interlock, one with another, in an intricate fashion. Penetration of one mineral by another is common. Not only do plagioclase and quartz grow into and enclose other minerals, but they shoulder aside and warp biotite and hornblende. Commonly, a biotite or hornblende crystal, caught between two plagioclase individuals, will be bent in an undulating fashion by the growth of the plagioclase porphyroblasts toward one another. Plagioclase commonly grows along the cleavage of biotite and hornblende, and wedges these crystals apart.

The dominant minerals in the quartz diorites are plagioclase, quartz, biotite, and hornblende. Apatite, magnetite, muscovite, orthite, sphene, and tourmaline are common accessories. Clinozoisite, epidote, chlorite, sericite, and zoisite are local secondary minerals. In some specimens, garnet and diopside are minor constituents.

Plagioclase generally forms about 55% of the rock, with a range from 40% to 65%. The plagioclase individuals range in size from minute, 0.1 to 0.2 mm. rounded grains, to crystals up to 8 mm. long. The average size is about 2 mm. Twinning after the albite, Carlsbad, and pericline laws is common, and locally the twinning is complicated.

Strain shadows are common in the plagioclase, and the crystals are often bent in an undulating fashion. Examples of warping and bending of plagioclase grains, and of rupturing and of healing with plagioclase substance, are common.

Most of the larger plagioclase crystals contain numerous inclusions of biotite, hornblende, and small rounded grains of plagioclase and quartz (Plates LXIII, LXIV). Locally, retrogressive sericite, epidote, and clinozoisite are present. The sericite has clouded many of the plagioclase centers and obliterated the twinning.

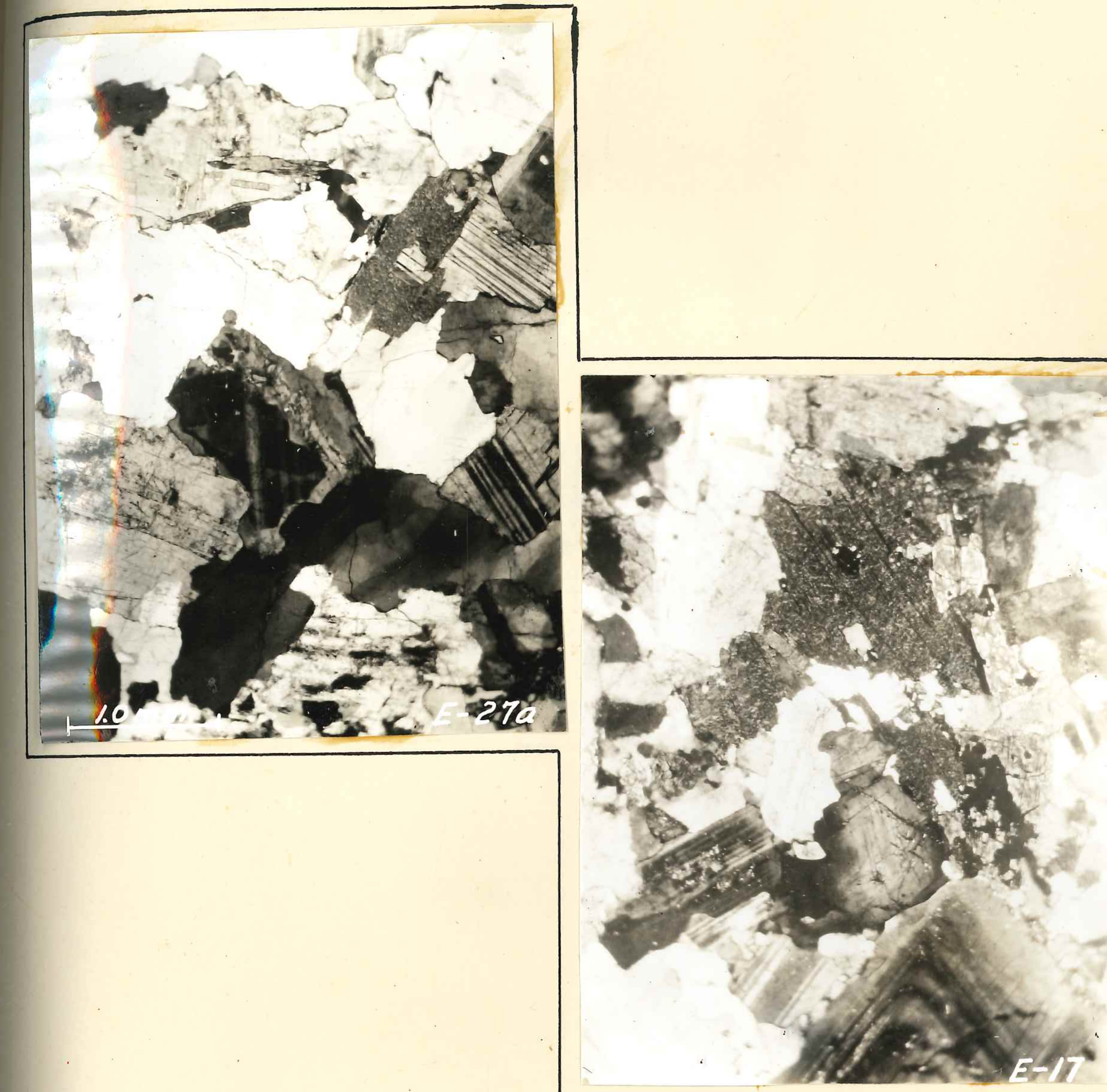
The larger plagioclase individuals are crystalloblastic (Plates LXII-LXIV). With very few exceptions they are anhedral in outline, and they invade or surround smaller grains of the ground mass. The average composition of the plagioclase is about An_{30}, with a range from An_{45} to An_{25}. The more sodic composition generally is associated with the occurrence of biotite as the dominant mafic mineral. Where hornblende or, rarely, diopside, is a constituent, the plagioclase is more calcic, and averages An_{35}. This more calcic plagioclase also occurs in those rocks which originally possessed a high hornblende content and have been biotitized. Where a late stage of plagioclase growth has occurred (Plate LXIV), as on the rims of many of the larger individuals or along minute elongate zones which transect the rock, the plagioclase averages An_{25}, and the composition apparently is not influenced by the type of mafic mineral present.

Some of the larger plagioclase individuals are zoned. Generally the zoning is anhedral, with the zonal boundaries and crystal outlines showing little or no parallelism. Locally, the zoning is euhedral, and is generally associated with a tendency to euhedralism of the plagioclase crystals. However, it must be emphasized that the zoning is largely anhedral and gradational--a type of zoning common to metamorphic rocks.

The zoned crystals commonly have three or four zones or bands (Plates LXI A; LXII A) from core to rim. However, in some examples there are as many as 15 bands to 1 mm. (Plate LXI B). The type of zoning varies. Where biotite is the only mafic mineral, or is the dominant mafic mineral, the zoning generally is progressive. At or near the core the plagioclase averages An_{40} to An_{35}; with a progression to a rim with an average composition of An_{30} to An_{25}. Where hornblende is a major constituent, or biotitization of hornblende has occurred, the zoning commonly is recurrent. In some specimens, adjacent zones differ as much as 5% in their An content. In other examples, a set of three or four bands show progression, followed by a recurrence of a more calcic zone and another sequence of progression. The recurrent zoning is most commonly in the composition range An_{40} to An_{35}, though cores as calcic as An_{45} occur.

Even where there is recurrent zoning, the rims are generally the locus of progressive zoning, and range in composition from An_{30} to An_{25}. The presence of recurrent zoning where hornblende and biotitization of hornblende

PLATE LXI



A. (Photomicrograph, crossed nicols) A typical metasomatic quartz diorite. Granoblastic plagioclase (upper right) invades biotite. A plagioclase porphyroblast (dark, left center) displays anhedral zoning. Later quartz (undulatory extinction, lower center) replaces twinned, sericitized plagioclase anhedra. Spec. E-27a, Meadow Creek Gorge.

B. (Photomicrograph, crossed nicols) Metasomatic hornblende-biotite-quartz diorite displaying biotite (upper part) forming from green hornblende, anhedral oscillatory zoning in plagioclase prophyroblast (lower right), and latest quartz partially replacing the main assemblage. Spec. E-17, south face, Windy Mt.

PLATE LXII

A. (Photomicrograph, crossed nicols) Metasomatic quartz diorite with large plagioclase porphyroblast containing inclusions of quartz and small, twinned plagioclase. The large porphyroblast (upper right) displays anhedral zoning. Biotite, in part formed from green hornblende, is altered to chlorite (left edge). Spec. E-6, Windy Mt.

B. (Photomicrograph, crossed nicols) Medium-grained biotite-rich trondjhemite, showing clumps of anhedral biotite, porphyroblasts of plagioclase, and anhedra of quartz. Spec. D-40c, east side, Deborah Peak.

PLATE LXIII

(Photomicrograph, crossed nicols) Oligoclase porphyroblast in quartz diorite. Inclusions of biotite, epidote, chlorite, and quartz. Spec. B-2, Lake Valhalla.

PLATE LXIV

1.0 mm

(Photomicrograph, crossed nicols) Sodic oligoclase porphyroblast growing in groundmass of biotite, muscovite, and quartz. Inclusion of twinned calcic oligoclase (top). Quartz diorite. Spec. B-2, Lake Valhalla.

The latest generation of quartz fills minute fractures, up to 4 mm. in width, which transect the rocks. In some cases this quartz has grown into and wedge apart larger, earlier crystals of plagioclase and quartz (Plate LXV A). This quartz invariably is associated with a vermicular growth of quartz and plagioclase, and, commonly, with small anhedra of microcline.

This vermicular growth generally occurs in maggot-like patches along narrow, elongate zones. Adjacent to these zones are quartz and plagioclase crystals showing strain shadows, snipped-off ends, and mortar structure. These suggest that the vermicular growth occurred in fractures during a stage of recrystallization which post-dated the formation of the main mineral assemblage.

In these recrystallized minute fracture zones the newly-formed, usually small plagioclase grains are more sodic than the plagioclase of the main rock, and they have an average composition of An_{25}. This third generation of quartz, plagioclase, and subordinate microcline invades the larger and earlier minerals which border these zones.

This growth of microcline, quartz, and plagioclase suggests that potassium and silica were introduced during the recrystallization of these later fracture zones.

The mafic minerals of the quartz diorites average about 25% of the rock, and range from 10% to an exceptional 45%. The higher amounts generally occur in rocks in which there is a relict structure marked either by elongate inclusions in parallel arrangement or bands of a high mafic mineral content.

The mafic minerals are not evenly distributed in the rock but generally form irregularly-shaped and irregularly-distributed clusters which give the rock a patchy appearance. It should be emphasized that none of the quartz diorites have a homogeneous, even-grained appearance.

Biotite generally is the most common mafic mineral, and it forms irregular plates averaging 1.0 to 2.0 mm. in size. The biotite is deeply colored, and it has a marked pleochroism which generally is: X: colorless to pale brown to yellow; Y=Z: emerald green or dark brown.

Most of the biotite has a strong development of pleochroic haloes about zircon nuclei. Locally, a grain of orthite is the nucleus of a pleochroic halo. These haloes are identical to those found in the schists. In addition, small magnetite grains are common inclusions in the biotite. Most of the biotite has formed from hornblende and lies in parallel intergrowth with the hornblende (Plate LXI B). The amount of magnetite is greatest where the biotite obviously has formed from hornblende.

Many of the biotite flakes are bent and warped, and show minute fractures, some of which have only partly been healed. A few of the crystals have thin lines of graphite or magnetite grains in parallel arrangement, which are reminiscent of the same phenomena in the hornfelsized schists. Chloritization of the biotite along the cleavage planes is common (Plate LXII A), especially in the more deeply weathered rock specimens, and muscovite and sericite are additional products of the alteration of biotite. A large part of the chlorite is penninite.

The second mafic mineral of importance is hornblende. Locally, where biotitization has not been intensive, the hornblende exceeds the biotite in quantity. Most of the hornblende has pale colors, and it is suggested that there is a high proportion of the actinolite molecule present. The hornblende is identical with the common type of the hornblende-bearing schists.

The hornblende generally has pale colors. Much of it is marked by a pleochrosim of X: tan; Y: olive brown; and Z: pale olive green.

Some of the hornblende grains are zoned, with the bulk of the grain having Y: olive to brown, and the rim having Y: light greyish-green. The rims commonly have a slightly different extinction angle, and it is probable that these rims have a slightly higher admixture of the actinolite molecule.

Most of the hornblende occurs in irregular flakes which average 2 mm. in size. Exceptionally there are irregular crystals up to 5 mm. long. None of the hornblende shows any perceptible elongation. Most of the hornblende is biotitized, and locally biotitization has almost eliminated the hornblende. Small, rounded grains and aggregates of magnetite which are associated with, and often included in the biotite are interpreted as having formed during the biotitization process to accommodate some surplus iron released. This biotitization of the hornblende suggests an introduction of potassium at an earlier stage than the more local, late introduction which caused microcline to form in minute fracture zones.

Diopside poikiloblasts, in irregular grains and masses, locally form up to 5% of the rock. The occurrence of diopside within the quartz diorites has been noted only from the area near the confluence of Meadow Creek and Rapid River (Plate B, E-4).

Generally the diopside is altered marginally to biotite. The extinction angle (z:c on 010) averages 42°. In thin section pleochroism is lacking, but a certain proportion of the hedenbergite molecule is present inasmuch as the diopside is usually of a pale green color. Part of the diopside is simply twinned.

It has been emphasized that the mafic minerals in the quartz diorite rocks commonly occur in unevenly-distributed, irregular clusters. In most cases these patches lack a preferred orientation of their mineral constituents. However, locally there is a parallel orientation of the mafic minerals, and some quartz diorites, megascopically apparently directionless, contain gently curved polygonal arcs of biotite and hornblende. In addition, there are small, irregularly-shaped zones in which an alternation of lighter and darker bands, varying in mafic mineral content, gives the rock a gneissose appearance. This structure is caused by a compositional variation rather than by a preferred orientation of the individual mineral constituents. These gneissose areas are generally in close proximity to areas of granitic gneiss outcrop, and it is noteworthy that on Barrier Peak (Plate B, I-7), for example, the gneissose structures have attitudes parallel not only to those of closely adjacent aligned inclusions, but also to the trend of farther distant major gneiss and schist bodies.

Accessory minerals in the quartz diorites are orthite, sphene, apatite, and, locally, garnet. Epidote, clinozoisite, muscovite, and sericite are common secondary minerals, and generally have formed in and around plagioclase and biotite. Part of these secondary minerals are retrogressive and probably were formed during a time of falling temperatures. Part are undoubtedly the result of recent weathering. There is a conspicuous similarity between the accessory minerals of the quartz diorites and the accessory minerals of the schists and gneisses.

On Valhalla Mountain (Plate B, G-6) there occurs an interesting variety of the quartz diorites. Here there are extremely fine-grained, leucocratic granitic rocks which occur in dike-like bodies up to several feet thick. These dikes have extremely sharp contacts with the enclosing quartz diorites, and obviously are a later type of granitic rock.

The Valhalla Mountain dike rocks consist of a very fine-grained ground mass in which there are larger (up to 2 mm.) euhedral plagioclase crystals which appear to be phenocrysts. (Plate LXVI B). From the dikes there branch forth tongues and apophyses of dike material which ramify through the adjacent quartz diorites in serpentine, vein-like bodies up to 1 inch thick.

A superficial examination suggests that these rocks are intrusive andesite porphyries (Plate LXVI B). A microscopic examination discloses that the rock is dioritic to quartz-dioritic in composition. Most are quartz-dioritic, and because of the very fine-grained texture these rocks are here termed micro-quartz diorites.

The ground mass is composed of a fine-grained quartz-plagioclase granulite. Through this granulite pass thin stringers of biotite and hornblende, and a suggestion of flow structure is imparted by the approximate parallelism of these stringers to the walls of the dike.

The composition of these rocks varies. Most commonly the rock contains about 50% plagioclase, 20% quartz, and 25% green hornblende and/or biotite. A less common, dioritic variety, contains about 60% plagioclase, 25% green hornblende, and 15% biotite, most of which is obviously derived from the hornblende.

The plagioclase of the ground mass is anhedral, generally untwinned, and has a range in composition from An_{40} to An_{25}. This plagioclase, as are most of the other constituents, is crystalloblastic, and forms an intricate, interlocking pattern with the accompanying quartz anhedra. Minute inclusions of rounded quartz, plagioclase, and magnetite grains are common in the plagioclase crystalloblasts.

The hornblende is common green hornblende, and forms up to 25% of the rock. This hornblende has a marked pleochroism of X: pale olive brown; Y: olive brown to deep olive green; and Z: pale to stronger bluish green. The hornblende occurs in elongate plates up to 2 mm. long, is anhedral, and is shredded in appearance. A few individuals have pseudo-hexagonal cross-sections with a tendency to be euhedral. Inclusions of rounded grains of quartz and plagioclase are common in the hornblende.

Biotite, pleochroic from colorless and pale yellow to chocolate brown, is similarly elongate and shredded in appearance, and also has inclusions of quartz and plagioclase grains. Much of the pale-colored biotite is phlogopitic in appearance. Some of the biotite lies in parallel intergrowth with hornblende, and much obviously is derived from the hornblende.

Apatite, magnetite, orthite, sericite, and epidote are accessory constituents. Zircon forms the nuclei of pleochroic haloes in both biotite and hornblende.

Within the ground mass are larger plagioclase crystals which appear to be phenocrysts (Plate LXVI B). Most have a euhedral outline, and most are twinned, often in a complicated fashion. Moreover, the majority of the plagioclase is zoned, and the zonal boundaries are approximately parallel to the crystal outlines.

The composition of these larger plagioclase individuals is significantly the same as that of the smaller plagioclase of the ground mass, and ranges from An_{40} to An_{26}. This range in composition is generally most conspicuous in the larger crystals where a normal progressive zoning occurs.

Associated with the larger plagioclase individuals are knots or clumps of hornblende and subordinate biotite. These clumps consist of haphazardly-oriented aggregates of partially biotitized hornblende.

The microscopic examination of these dike rocks discloses the fact that the large plagioclase individuals do not "float" as exotics or phenocrysts in a finer-grained ground mass, but actually have grown in the ground mass. Inclusions, identical in type and shape to the individuals of the fine-grained ground mass, are common. Moreover, the appearance of euhedralism is delineated by the outermost zone. Beyond this zonal band the crystals have crenulated borders and the margins of the crystal ramify outward into the intergranular spaces of the ground mass. Moreover, a true igneous porphyry with this mineral assemblage would most probably have andesine plagioclase, not oligoclase, as the phenocrysts.

These features of growth of the larger plagioclase individuals, coupled with the crystalloblastic character of the constituents of the ground mass and the striking anhedral shape of the larger hornblende and biotite crystals, suggest that this rock is metamorphic-derived. However, the sharp and distinct borders of these dikes, and the alignment of the hornblende and biotite stringers parallel to the dike margins, suggest that this rock became mobilized and intrusive into the quartz dioritic host rock. Moreover, the fact that both margins of these dikes are sharp, presumably indicates that the intrusion produced dilation and was not confined to a replacement of the host rock along one well-defined joint or fracture plane.

Trondhjemites. Trondhjemites rank next in abundance to the quartz diorites. These rocks are not restricted to any particular part of the granitic terrane, but they occur as patches or zones of limited extent throughout the area. The trondhjemites generally are more leucocratic than the quartz diorites, but a microscopic examination is necessary for their precise delineation. As a result, it is not practicable to hazard a guess as to how much of the main granitic mass is trondhjemitic in composition. The sole quantitative analysis practicable is based on the more than 100 samples collected from the granitic terrane. Of these, more than 80% were quartz dioritic in composition.

A microscopic examination of the trondhjemites shows that in textures and structures they are very similar to the quartz diorites. Most of what has been said about the quartz diorites equally applies to the trondhjemites. A study of these rocks has convinced the author that the trondhjemites were once quartz diorites, and that they represent a local and later progression from the quartz diorites.

There are two significant differences between the quartz diorites and the trondhjemites. The first concerns the mafic mineral content and causes the more leucocratic appearance of the trondhjemites. Generally, the only mafic mineral present is biotite. The biotite occurs in irregular plates. It averages about 15% of the rock, and ranges from 5% to an exceptional 20%. This biotite is identical to that of the quartz diorites.

Hornblende is locally present, but it never exceeds 5% of the rock. In those rocks with both hornblende and biotite, they collectively never exceed 20% of the rock. Thus, the trondhjemites have a much smaller mafic mineral content than the average quartz diorite.

Where hornblende is present, it forms irregular grains up to 4 mm. long. These are shredded in appearance and patchily converted to biotite. Most of the hornblende occurs as relict cores surrounded by later, fresher-appearing, biotite.

In addition to this decreased mafic mineral content, and the tendency to become mono-mineralic insofar as the mafic minerals are concerned, the trondhjemites have an appreciable microcline content. The microline forms between 2% and 10% of the rock, and is definitely later than the main assemblage of the rock. As in the quartz diorites, the microcline is generally formed in narrow zones which transect the rock. Strained plagioclase and quartz, snipped-off ends, and mortar structure indicate that these narrow zones are microscopic fractures. Accompanying the microcline are quartz and sodic plagioclase (Plate LXV B) which often occur in a vermicular intergrowth.

The microcline forms anhedral crystals up to 2 mm. long, and marginally invades and replaces the quartz and plagioclase transected by the narrow fracture zones. Locally, there are microcline crystals invading the main assemblage away from one of these fracture zones. But in every observed case, such microcline is never more than 1 cm. removed from a fracture zone.

Some of the microcline forms aggregates with plagioclase in a microperthitic growth.

Accompanying the microcline and latest quartz and plagioclase, is an alteration of adjacent biotite flakes to muscovite. Generally the muscovite forms in parallel intergrowth with the biotite. It is significant that hornblende never occurs adjacent to either microcline crystals or to biotite which has been partly converted to muscovite.

In all other ways the trondhjemites resemble the quartz diorites, and it is suggested that the trondhjemites are a local variety of quartz diorite in which multiple fracturing has formed avenues of approach for a late phase of potassium, sodium, and silica introduction.

Granodiorites. Where the microcline content of the rock exceeds 10%, and exceptionally reaches 30%, the rock here is termed a granodiorite. These rocks generally are restricted to small, irregular-shaped zones a few feet wide, which are enclosed by the more prevalent quartz diorites and trondhjemites. However, in the southwesternmost part of the granitic terrane, on Beckler Peak (Plate B, I-2, -3), the granodiorites are the dominant rock type.

The textures and structures of the granodiorites are identical to those of the quartz diorites. A megascopic differentiation of these rocks from the quartz diorites is generally possible. This is based on the sharply

PLATE LXV

A. (Photomicrograph, crossed nicols) Medium-grained granoblastic trondjhemite showing plagioclase porphyroblasts which contain quartz and plagioclase inclusions. The prominent sutured border is that of plagioclase (dark) marginally replaced by later quartz (light). Spec. D-40d, east side, Deborah Peak.

B. (Photomicrograph, crossed nicols) Inequigranular crystalloblastic rock of alaskitic to granodioritic composition. Large plagioclase porphyroblast (left) and microcline (lower right) grow in the finer-grained groundmass of quartz and plagioclase. Spec. E-4, Martin Peak.

PLATE LXVI

A. (Photomicrograph, crossed nicols) Porphyroblastic granodiorite of "Sheku-type" (Misch, 25) with microcline (top) and plagioclase porphyroblasts growing in finer-grained quartz-plagioclase mosaic. Spec. E-5, Windy Mt.

B. (Photomicrograph, crossed nicols) Metamorphic-derived mobilized rock which has approached a neo-magmatic state and acquired igneous characteristics. Euhedral-zoned plagioclase, and anhedral biotite and hornblende grow in a finer-grained quartz-plagioclase granulite. Spec. E°9a, west face, Valhalla Mt.

reduced mafic mineral content and the importance of muscovite in the mineral assemblage. Concomitant with this reduction in mafic minerals and prevalence of muscovite is an extremely leucocratic appearance.

Common minerals present in the granodiorites are biotite and muscovite. Collectively they form a maximum of 15% of the rock. The biotite is generally partly altered to muscovite, and most of the muscovite lies in a parallel intergrowth with the biotite and has obviously formed from it. This muscovite is apparently contemporaneous with microcline, inasmuch as the microcline invades the margins of biotite, as well as plagioclase and quartz, but never invades the muscovite.

Unlike the microcline of either the quartz diorites or trondhjemites, the microcline of the granodiorites is not restricted to narrow and elongate zones. On the contrary, the microcline is widely, if patchily, distributed through the rock. This microcline is definitely later than the main mineral assemblage, inasmuch as it invades and, locally, engulfs preexisting plagioclase, quartz, and biotite (Plates LXV B, LXVI A). Locally, the microcline forms large porphyroblasts, up to 5 mm. in size, which grow between and into the prior mineral assemblage.

From the summit of Beckler Peak west to the faulted contacts with phyllites and schists (Plate B, I-2), the granodiorites are markedly different in texture from those lying farther east. In this zone the granodiorites have a porphyritic appearance.

This variety of the granodiorites is composed mainly of a ground mass of plagioclase laths with "phenocrysts" of twinned, euhedrally zoned plagioclase. Both the plagioclase of the ground mass and that of the "phenocrysts" average An_{27}, and they differ only in size. The plagioclase of the ground mass ranges from 0.1 to 1.0 mm., while the larger crystals average

3 mm., and exceptionally are 5 mm. Accompanying the larger plagioclase individuals are well-formed plates of biotite. The biotite is deeply colored, and has a marked pleochroism of X: nearly colorless; Y=Z: reddish brown to dark brown. Locally there are vivid green colors of pleochroism.

Scattered through the ground mass are knots or patches, up to 3 mm. long, composed of an interlocking mosaic of about 65% quartz and 35% untwinned plagioclase. The individuals of these patches are anhedral and intricate in outline.

Accessory minerals present are chlorite, epidote, zoisite, orthite, sericite, and late muscovite. With the exception of orthite, these minerals are alterations of plagioclase and biotite.

Superimposed upon this mineral assemblage are large microcline and untwinned or Carlsbad twinned plagioclase individuals (Plates LXV B, LXVI A). The microcline and plagioclase occur as porphyroblasts up to 8 mm. long, and the plagioclase laths of the ground mass and, locally, the mosaic patches, are inclusions. There is a noticeable vermicular growth of quartz and plagioclase along the margins of the larger microcline porphyroblasts.

Some of the plagioclase laths of the ground mass show a rude parallelism suggestive of flow structure. This, coupled with the sharp and discordant relationship of this granitic rock with the adjacent phyllites and schists, suggest that this rock became mobilized and intrusive.

A microscopic examination suggests the following sequence of events in the formation of this granodiorite. First, the granoblastic patches of plagioclase and quartz are interpreted as being relics of a previous metamorphic rock. In appearance these patches are not dissimilar to the xenoblastic polygonal mosaics typical of the biotite-quartz schists. The inclusions of this mosaic material within some of the plagioclase laths suggests crystalloblastic growth and a probable sodium introduction.

The euhedral form of the plagioclase laths, some of the biotite, and the larger "phenocrysts" of plagioclase is interpreted as indicating that the rock was subjected to conditions which caused an increase in the amount of intergranular liquid, or even produced an incipient stage of partial liquefaction. It is suggested that contemporaneous with this state the granitoid rocks invaded the phyllites and schists of this area. Subsequent to this phase, and probably aided by complex, multiple fracturing, potassium and sodium were introduced to form anhedral porphyroblasts of microcline and albitic plagioclase which partly replace and partly engulf the earlier mineral assemblage.

A similar type of rock occurs locally on Windy Mountain (Plate B, I-5). Here the large "phenocrysts" of plagioclase are absent, but a granoblastic ground mass of quartz and plagioclase has been the site for a crystalloblastic growth of microcline and sodic plagioclase. This porphyroblastic granodiorite bears a striking resemblance to the "Sheku-type" described by Misch (25).

Alaskites. In many places within the granitic terrane there are cross-cutting dike-like bodies up to 10 feet in width. Generally one contact of these bodies is relatively sharp, while the other is one of gradation between the dike rock and the granitic host rock. This field relationship is suggestive of a fracture control of the emplacement of these bodies.

The rock of these dike-like bodies is generally very fine-grained and extremely leucocratic. However, coarse-grained, pegmatitic varieties occur. Widely distributed dark specks, representing biotite or magnetite, give the rock a "salt and pepper" appearance.

A microscopic examination shows that these rocks are composed almost entirely of plagioclase and quartz, with very subordinate quantities of biotite, muscovite, and magnetite. All textures are crystalloblastic, and the quartz and plagioclase form a mosaic of interlocking anhedra. Generally the individual grains do not exceed 0.2 or 0.3 mm. in size.

The proportions of plagioclase and quartz vary. Commonly the plagioclase forms about 50% of the rock, with quartz forming about 45%, and the accessories the remainder. Exceptionally the rock has 80% plagioclase and about 15% quartz.

The plagioclase is twinned after the albite, Carlsbad, and pericline laws, and has a composition within the range An_{28} to An_{24}.

The high plagioclase and quartz content indicates that these rocks are alaskitic in composition.

A variety of these alaskites occurs within the contact zone between granitic rocks and phyllites on Beckler Peak. Here there are several dike-like bodies which transect the phyllites with angular discordance. One of these dikes is about 15 feet wide, but its exact relationship to the enclosing phyllites and adjacent granodiorites has been obscured by marginal faulting. The dike is much jointed and consequently deeply weathered--so much so that marginal specimens cannot be collected. A microscopic examination of a specimen from the center of the dike shows that the rock is a fine-grained, highly silicic rock of alaskitic composition. The rock is extremely inequigranular, and the texture is characterized by a patchy distribution of clear, clean albite and quartz enclosed in a maze of vermicular plagioclase-quartz intergrowth.

The overall mineral composition of this alaskite is about 80% plagioclase, 15% quartz, with subordinate biotite and muscovite. In addition, zoisite, clinozoisite, epidote, magnetite and limonite occur in accessory quantities.

The plagioclase forms two generations. The first generation is difficult to discern. It apparently consisted of anhedral individuals in which some albite, pericline, and Carlsbad twinning can be seen. Where measurable, this plagioclase has a narrow compositional range of An_{24} to An_{26}. This first generation is now obscured by a vermicular growth of plagioclase and quartz which almost obliterates the details of the earlier mineral assemblage.

The second generation of plagioclase is clear, clean, and untwinned. The low indices of refraction considerably less than quartz, the positive sign, and a 2V approximating 75°, all indicate an albitic composition. This generation is contemporaneous with clear anhedra of quartz.

The quartz, anhedral in shape, mostly displays undulatory extinction. Locally there are muscovite flakes and plagioclase grains as inclusions.

Biotite forms 1 or 2 percent of this rock. The biotite occurs in irregular patches or as thin bands between plagioclase individuals. Most of the biotite is irregular in shape, and shredded and decayed in appearance. Invariably associated with the biotite are cleaner-appearing muscovite flakes, magnetite grains, limonite as an intergranular film, and minerals of the epidote group.

The field relations suggest that these dike-like bodies are intrusive. The dimly discerned anhedral shape of the earlier generation of plagioclase suggests that the original granitic rock may have been metamorphically derived. However, the earlier textures are generally obscured by a superimposed reconstitution of the mineral constituents, and the vermicular structure is interpreted as being due to a static invasion by silica. This silica introduction quite probably is a late phase induced by a shearing and brecciation which offered avenues of approach for the silica.

Genetic Interpretation of the Granitoid Rocks

The field and petrographic evidence presented is interpreted as indicating that the granitoid rocks of the Beckler River-Nason Ridge area have been formed by the metasomatism of pre-existing schists and subordinate amphibolitic rocks. It has been pointed out above that there is evidence for an introduction of sodium and silica which caused the isochemically metamorphsoed rocks, most of which apparently contained hornblende, to be changed in texture, structure, and composition to granitoid rocks of a predominantly quartz dioritic composition. This metasomatism is considered to have been mainly static, and to have followed the synkinematic metamorphism which formed the schists, the amphibolites, and the primary felspathization of the migmatitic gneisses.

Quartz diorites are the most abundant granitoid rock of this area, and they are considered to be the basis upon which the other, more subordinate granitoid rocks were built. This main type of rock apparently was subjected locally to fracturing which facilitated the entry of potassium and silica. During this later phase of metasomatism microcline formed in localized fracture zones, producing the trondhjemitic varieties of granitoid rock. In the rocks designated as granodiorites, the microcline has extensively replaced the quartz dioritic mineral assemblage.

The conclusion that the granitoid rocks of this area are the result of a static metasomatism caused by the introduction of sodium, silica, and potassium applies to all of the granitic rocks without exception. However, in the southeastern and southwestern parts of the granitic area--specifically on Mt. Fernow (Plate B., J-8) and on Beckler Peak (Plate B, G-, I-, and J-2)--there is evidence for a marginal mobilization of the granitoid rocks and an intrusion by these of the country rocks. The use of the term <u>mobilization</u>

follows that of Wegmann, and implies that metasomatized material moved by plastic flowage. Dike-like bodies which show features of metamorphic replacement and characteristics of flowage are here termed mobilized replacement dikes (Goodspeed, 14, 15).

The evidence for a metasomatic origin of the granitoid rocks has been presented above in the descriptions of the granitic gneisses and the directionless granitic rocks. A summary of the evidence applicable to the great majority of these rocks is given first, and is followed by evidence for a local mobilization along some of the borders of the main granitic mass.

1. Field evidence for a metasomatic origin of the granitoid rocks.

   a. The contacts between the granitoid rocks and the schists are generally gradational, and are accompanied by wide migmatite zones in which there are all kinds of transition between schists, migmatitic gneisses, granitic gneisses, and directionless granitic rocks. Similar transitions occur in the interior parts of the main granitic mass where there are inclusions and relict bands of schist which are extremely gradational with the enclosing granitoid rocks. It must be emphasized that most of the granitic rocks can be traced, through infinite gradation, into isochemically-metamorphosed schists (Plate B).

   b. Many of the schist inclusions found in the interior of the directionless granitic body, often miles from the migmatitic border zones, are aligned, and are parallel to bands of hornfelsized schist within the granitic body. Both schist inclusions and bands are parallel to the attitudes of the main schist and migmatitic gneiss bodies. The lack of disturbance of these relict schist inclusions and layers appears to preclude emplacement of the granitoid rocks by forcible injection.

c. Relict foliation occurs, both in the migmatitic border zones and in the interior parts of the granitic body. This foliation is parallel to the strike of the schists and migmatitic gneisses adjacent to the main body of directionless granitic rock.

d. Neither in the migmatitic border zones, nor where schist material occurs in the interior of the main granitic body, are there structures which would indicate either forcible intrustion or dilation.

2. Petrographic evidence for metasomatism of the granitoid rocks.

a. The textures of the various granitoid rock types are entirely crystalloblastic. The growth of plagioclase, quartz, and microcline, at the expense of and around pre-existing minerals, is especially conspicuous and suggests replacement. The fact that a preferred orientation of minerals is absent, and that a compositional banding alone defines the foliation of the granitic gneisses, strongly suggests that the replacement occurred during a static phase following synkinematic metamorphism. The total absence of directional elements in the main granitic body supports this conclusion.

b. The granitoid rocks conspicuously lack uniformity in composition, structure, and texture. Layers and inclusions of schist material, unevenly-distributed patches of mafic minerals, and variations in composition from quartz dioritic to alaskitic, emphasize this heterogeneity.

c. Though most of the rocks are quartz diorites, the type and content of mafic minerals varies. The type of mafic mineral is directly correlative to the type of schist replaced, as evidenced by adjacent schist inclusions and layers. There is a definite association of quartz- and hornblende-bearing dioritic types with hornblende-rich schists, and of biotite-bearing quartz dioritic types with biotite-quartz schists.

d. Relict schistosity and polygonal arcs of biotite and hornblende are common to both hornfelsized schists and granitoid rocks.

e. Both the relict inclusions and the surrounding granitoid rocks have accessory minerals, such as garnet, orthite, tourmaline, and zircon, which are generally identical in quantity and type. It is noteworthy that the pleochroic haloes around zircon nuclei in biotite flakes are found throughout the schists, the migmatitic gneisses, the granitic gneisses, and the directionless granitic rocks.

f. The mafic minerals of the relict schist material and the enclosing granitoid rocks are of identical optic character and composition.

g. The plagioclase of the hornfelsized schists and of the granitoid rocks varies in a similar manner with the original mafic mineral; it is more calcic in the presence of hornblende, and more sodic in the presence of biotite. This correlation has been demonstrated in so many examples that for those granitoid rocks which have biotite as the only mafic mineral, the author feels justified in ascribing the biotite to a biotitization of earlier hornblende if the plagioclase is as calcic as An_{35}.

From a chemical point of view the essential difference between the schist material and the granitoid rock is an addition of sodium, silica, and minor potassium which has led to an increase in plagioclase and quartz, to the biotitization of part or all of the hornblende, and to a more local development of late microcline and biotite-derived muscovite.

Thus, most of the granitoid rocks are interpreted as having formed through processes of metasomatic replacement, essentially in situ. However, at the margins of the main granitic mass on Mt. Fernow and on Beckler Peak, mobilization of the metasomatized material apparently occurred with a resultant intrusion of the country rock. The mechanism of mobilization is ill-defined and subject to question on Mt. Fernow. But the excellent exposures on Beckler Peak, especially on the south flank (Plate B, J-2), are interpreted as proof of mobilization. Most of the evidence summarized below is derived from observations at the Beckler Peak locality.

1. Field evidence for marginal mobilization.

   a. On Mt. Fernow, and on both the main (south) and north peaks of Beckler Peak, the contacts between the granitoid rocks and the schistose rocks are sharp and discordant. There is a complete absence of the customary zone of transition between schistose rocks, various types of gneisses, and directionless granitic rock. Moreover, on Beckler Peak the schistose rocks are not even medium grade schists, but are mainly phyllites. On Beckler Peak the granitoid rocks form dikes which steeply transect the phyllites and subordinate schists. On Mt. Fernow, where the border zone of the main granitic mass is migmatitic and is represented by numerous inclusions of schist material, there is no transition from schist through migmatitic and granitic gneisses to directionless granitic rock. The ultimate contact of this zone is sharp and discordant (Plate LX).

b. Sill-, vein-, and dike-like bodies apparently branch off the larger granitoid dikes of the Beckler Peak and Rapid River contact zones. Though every phyllite-granitoid dike contact is faulted, it cannot be doubted that these apophyses stem from the larger dikes. A mineralogic identity supports this conclusion. These minor, tabular bodies transect transect the phyllites and subordinate schists with generally sharp and discordant contacts. Some offsets of the wall rocks demonstrate dilation, and aberrant attitudes in the phyllites on either side of some of these tabular bodies indicate a wedging apart.

c. The numerous schist inclusions within the granitic materials on Mt. Fernow might be interpreted as a static replacement of a crushed zone in the schists. This is supported to the extent that all textures in the granitic materials are crystalloblastic, and directional elements, suggestive of flowage, are absent. However, the sharp and discordant contact of the granite and schist suggests that the rotation of the schist blocks, and their haphazard orientation, are caused by an incipient marginal mobilization of the granitic mass. This mobilization would, of necessity, be merely local, inasmuch as relict structures occur to the west on Barrier

Peak (Plate B, I-7) and immediately south on the spur of Mt. Fernow (Plate B, J-7). Such undisturbed relict structures preclude forcible intrusion of the main granitic mass.

The field evidence presented above equally applies to the formation of these granitic rocks by magmatic intrusion or by marginal mobilization of metasomatic materials. However, certain factors militate against a magmatic intrusion.

a. The granitic rocks of the contact zones on Mt. Fernow and on Beckler Peak pass with infinite gradation into granitoid rocks which demonstrably are metasomatic in origin (Plate B).

b. The oligoclase composition of the "phenocrysts" in the Beckler Peak contact zone is not that to be expected in an igneous porphyry of similar composition. Andesine plagioclase would be more likely in a similar igneous rock. It is noteworthy that there is a striking similarity in composition between the plagioclase of the ground mass and that of the "phenocrysts".

c. Though the larger granitic dikes on Beckler Peak are in faulted contact with the phyllites, it cannot be doubted that the subordinate dike-, sill-, and vein-like bodies which ramify through the phyllites are apophyses from the larger dikes. These smaller, tabular bodies conspicuously lack the following expectable igneous features:

(1) Glassy or chilled borders;

(2) Any evidence for optalic metamorphism of the invaded rocks;

(3) High temperature minerals, with low temperature minerals obviously caused by deuteric alteration;

(4) A progressive increase in grain size toward the center of the body.

d. It is difficult to reconcile the large, apparently euhedral "phenocrysts" of plagioclase with the completely anhedral and equally large aggregates of hornblende and biotite which also "float" in the ground mass.

2. Petrographic evidence for mobilization of metasomatized materials.

a. Though the granitic rocks of the Beckler Peak contact zone appear to be porphyries, a microscopic study discloses that the plagioclase "phenocrysts" are actually porphyroblasts. A misleading impression of phenocryst development is imparted by the euhedral zoning of these crystals. However, the "phenocrysts" do not "float" in a finer-grained ground mass, but external to the outermost zone of the crystal, the plagioclase material extends into and between the components of the ground mass in an intricate fashion. Thus, the actual outline of these "phenocrysts" is one of crenulation and growth into the ground mass.

b. The textures of the granitic rocks and schist inclusions of the Mt. Fernow contact are totally crystalloblastic, and the hornfelsized schist inclusions contain plagioclase porphyroblasts of a composition almost identical with that of the granitic materials.

c. Granoblastic patches of plagioclase and quartz, apparently identical to the xenoblastic polygonal mosaics common to the biotite-quartz schists, are abundant in the granodiorites on Beckler Peak, and suggest that these dikes are derived from metasomatized schist materials.

d. Stringers and layers of hornblende and biotite are aligned parallel to the walls of the dikes and the smaller granitic bodies. Moreover, there is a tendency for the plagioclase laths of the ground mass to be elongated and aligned parallel to the walls. These factors suggest flowage.

e. The "medium grade contact action" which produced biotite along the margins and in zones of the phyllite.

Thus, the granodiorites of Beckler Peak and, possibly the quartz diorites of Mt. Fernow, are interpreted as being metamorphic-derived and mobilized to the extent that they intruded the country rock.

In addition to the intrusive relationship, the rocks of the Beckler Peak locality are significantly different from the main body of granitoid rock. This difference lies in the fact that microcline, later than the main assemblage, is a prominent constituent, and the rocks have been changed mineralogically from quartz diorites to granodiorites.

In other areas the quartz diorites and trondhjemites, as well as local zones in the migmatitic gneisses, have microcline which invariably is associated with minor fractures. These fractures apparently formed avenues of approach for potassium introduction. The sheared contacts between the granodioritic dikes of Beckler Peak and the phyllites, coupled with the noteworthy granodioritic composition of this part of the granitic terrain, suggest that the Beckler Peak contact area has been the site of recurrent faulting. Such faulting may have provided the avenues of approach for a potassium introduction which superimposed microcline on a pre-existing quartz dioritic rock.

The evidence may be interpreted as supporting a conclusion of recurrent faulting. At least three pulsations of faulting may be envisaged. The first would have been contemporaneous with the intrusion of the country rock by mobilized metasomatic materials. The second would have been that which, with intricate fracturing, permitted an introduction of potassium and a widespread growth of statically-formed, haphazardly-oriented microcline. The third, and latest phase of faulting, would have been that which produced the sheared contacts between the granitic dikes and the phyllites. This phase would also have caused the severance of the minor granitic bodies from their parent larger dikes.

Cenozoic Volcanic Rocks

Andesites

Distribution

Porphyritic hypersthene andesites are the only true igneous rocks cropping out in the Beckler-River-Nason Ridge area. The andesites occur at two separate but closely adjacent localities in the northernmost part of the mapped area.

The first mode of occurrence is that of a large dike which is imperfectly exposed on the heather slopes of Robin Mountain (Plate IX; Plate B, B-5). Though much of this dike is obscured by talus and vegetation, observations on either side of the ridge of Robin Mountain suggest that the dike has a rather uniform width of about 50 feet.

This large dike strikes approximately north-south, and dips to the east at about 45°. The dike cuts across the mesozonal migmatitic gneisses and biotite-quartz schists which form the bulk of this ridge. Because of the poor quality of the exposures, and a marginal shearing, the precise contact relationships of the dike with the country rock is not known. However, field observations suggest that the contacts are sharp.

The dike is intricately jointed, and the master joints form rude columns of polygonal cross section which lie approximately at right angles to the walls of the dike. These columns range from 6 inches to 12 inches in the walls of the dike. These columns range from 6 inches to 12 inches in diameter.

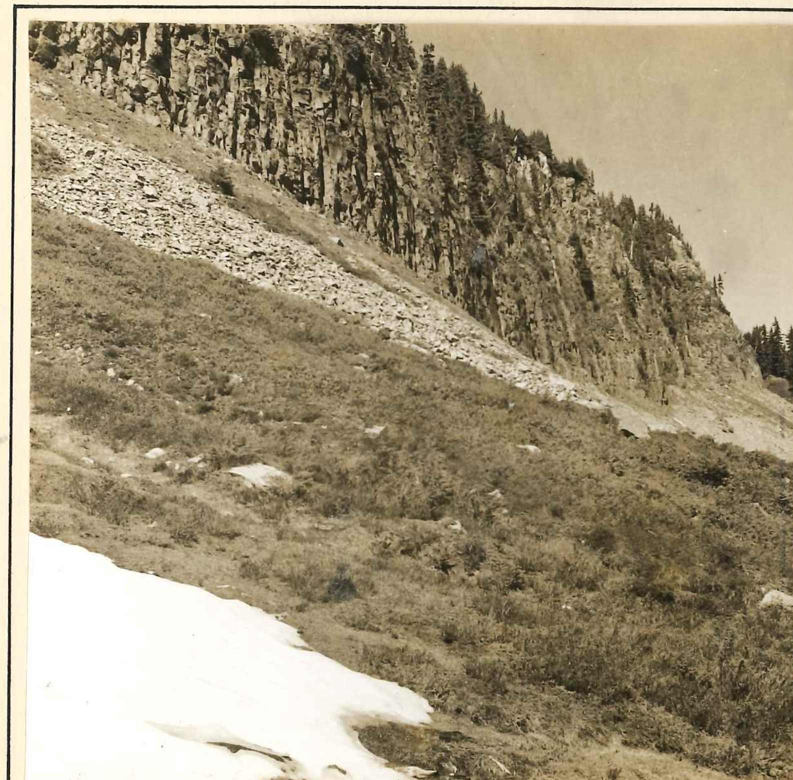
Marginal alternations of lighter and darker colored bands, with a "toffee"-like appearance, suggest flow structures. This compositional banding rudely parallels the walls of the dike. The rock composing the dike is extremely fine-grained, and the only megascopically visible minerals are euhedral phenocrysts of plagioclase. There is no appreciable increase in grain size from the borders of the dike toward the interior.

The second and most extensive outcrop of the andesite is a thick flow which forms the cap of Bench Mark Mountain (Plate B, B-4), the highest peak in this part of the mapped area. This flow covers about one-half square mile of the summit ridge. A near vertical escarpment on the west, north, and east sides of Bench Mark Mountain is formed by these lavas (Plate LXVII). The rock is much jointed, and one prominent set of joints, inclined about 15° to the north from the vertical, forms rude columns with polygonal cross sections. Some of these columns are up to 75 feet long. At right angles to these master joints, with a prevailing east to west strike and a 10°-15° dip to the north, is a closely-spaced set of joints which separate the columns into "leaves" ranging in thickness from 1 to 3 inches.

The thickness of the flow is not known. Approximately 150 feet of columnar lavas are exposed in the summit escarpment, but a cap of fine talus, and steep talus slopes at the base of the escarpment obscure the true thickness. At no place was andesite observed resting on the bed rock.

The rocks of this flow megascopically resemble those of the Robin Mountain dike. They are extremely fine-grained, and the only megascopically identifiable minerals are phenocrysts of plagioclase and limonitized hypersthene and magnetite.

PLATE LXVII



Columnar andesites forming escarpment on east side of Bench Mark Mountain.

Petrography

A microscopic examination of both the Robin Mountain dike rocks and the Bench Mark Mountain flow rocks shows that they are extremely fine-grained porphyritic hypersthene adesites.

The identifiable minerals, in order of decreasing abundance, are andesine, hypersthene, magnetite, and quartz.

Plagioclase is the most abundant mineral, and generally forms in excess of 60% of the rock. Two types of plagioclase are present. The most abundant forms the bulk of the ground mass and consists of a mesh of elongate laths which have a euhedral tendency. Most of these laths are aligned in a subparallel orientation which suggests flow structure. These individuals average 0.3 mm. in length, with a range from 0.1 to 0.5 mm. Some very finely-divided material in the intergranular spaces may also be plagioclase. Most of these laths are untwinned, but a few individuals have simple Carlsbad twinning. Most are clear, but inclusions of magnetite and an amber to red amorphous material occur.

The remainder of the ground mass is composed of small anhedral and subhedral grains of hypersthene, small blebs of magnetite, and amber, red, and brown amorphous material which fills the intergranular spaces. The high lustre of this amorphous material, and the color, suggest that this material is glass.

Enclosed in this ground mass of plagioclase laths and accessory minerals are phenocrysts of plagioclase, hypersthene, and magnetite. These average 2.0 mm. in size, with a range from 1.0 mm. to 3.0 mm. Both the plagioclase and the hypersthene are elongate, and they rudely parallel the flow structure delineated by the aligned, smaller plagioclase laths.

The most abundant phenocrysts are plagioclase. They are twinned after the albite, Carlsbad, and pericline laws, and often in a complicated fashion. The average composition of the plagioclases constitutes the main difference between the Robin Mountain dike rock and the Bench Mark Mountain flow rock. The dike rock phenocrysts average An_{50}, with a range from An_{40} to An_{55}. The flow rock phenocrysts average An_{38}, with a range from An_{30} to An_{40}.

This range in composition is best shown in the larger phenocrysts in which zoning is common. Up to 8 different zones or bands have been observed in a single phenocryst, and generally the overall zoning is normally progressive from a more calcic core to a more sodic rim.

Inclusions are common in the plagioclase phenocrysts. Most of these consist of magnetite grains and irregular blebs of the amorphous, glass-like material. Sericite commonly obscures the cores of the phenocrysts, especially in the more deeply weathered rock samples.

Coombs (3; p. 1503) has studied lavas similar to these on Mt. Baker, and he believes that the largest plagioclase phenocrysts were formed by a cumulophyric clustering of smaller individuals. He remarks that "Evidence for this is the glassy inclusions which mark out possible individual crystals, comparable in size with the intermediate-sized plagioclase crystals, and the extremely complex twinning, probably resulting from the heterogeneous grouping of partially resorbed phenocrysts".

Hypersthene forms the next most abundant type of phenocryst. The hypersthene occurs in prismatic individuals up to 2.5 mm. long. Some of these phenocrysts consist of hypersthene rims encircling an amorphous interior in which magnetite grains are common. The hypersthene generally is pale-colored, and the pleochroism is marked by X: pale red; Y: pale orange or amber; and Z: pale bluish green. The 2V is rather uniform, and approximates 60°.

Magnetite forms the third type of phenocryst. There are anhedral individuals and irregular aggregates, but commonly the magnetite forms euhedral crystals up to 2 mm. long. Most of the euhedral cross sections apparently are slices across octahedrons inasmuch as triangular and square cross sections are common.

Quartz is not abundant, but occurs as small grains in the intergranular spaces of the ground mass.

Most of the andesites are deeply weathered, and much of the plagioclase consequently is sericitized. Zoisite and clinozoisite also occur within and marginal to the plagioclase. Much of the magnetite has been converted marginally to limonite, and there is a limonitic intergranular film which stains the rock fabric.

Andesites similar to these have been described by Coombs (3) from Mt. Baker and Mt. Rainier. It may be significant that the porphyritic andesites of the Beckler River-Nason Ridge area are restricted to the northernmost part of the mapped area, and thus are closest to the prominent andesitic cone of Glacier Peak (Plate VIII).

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Plate B: Distribution of the crystalline rocks between the Beckler River and Nason Ridge, Washington.
(Only areas traversed depicted)
epizonal phyllites
mesozonal migmatitic gneisses
non-granitized biotite-quartz schists, chiefly mesozonal
sillimanite zone
migmatitic granitic gneisses
directionless granitic rocks
hornblende-bearing schists
andesite lavas
amphibolites
metamorphosed pyroxenite
SCALE
5 4 3 2 1 0
(feet in thousands)
1 2 3 4 5
miles
N
Keith F. Oles
121°00' 1956
120°50'
Snohomish Co.
King Co.

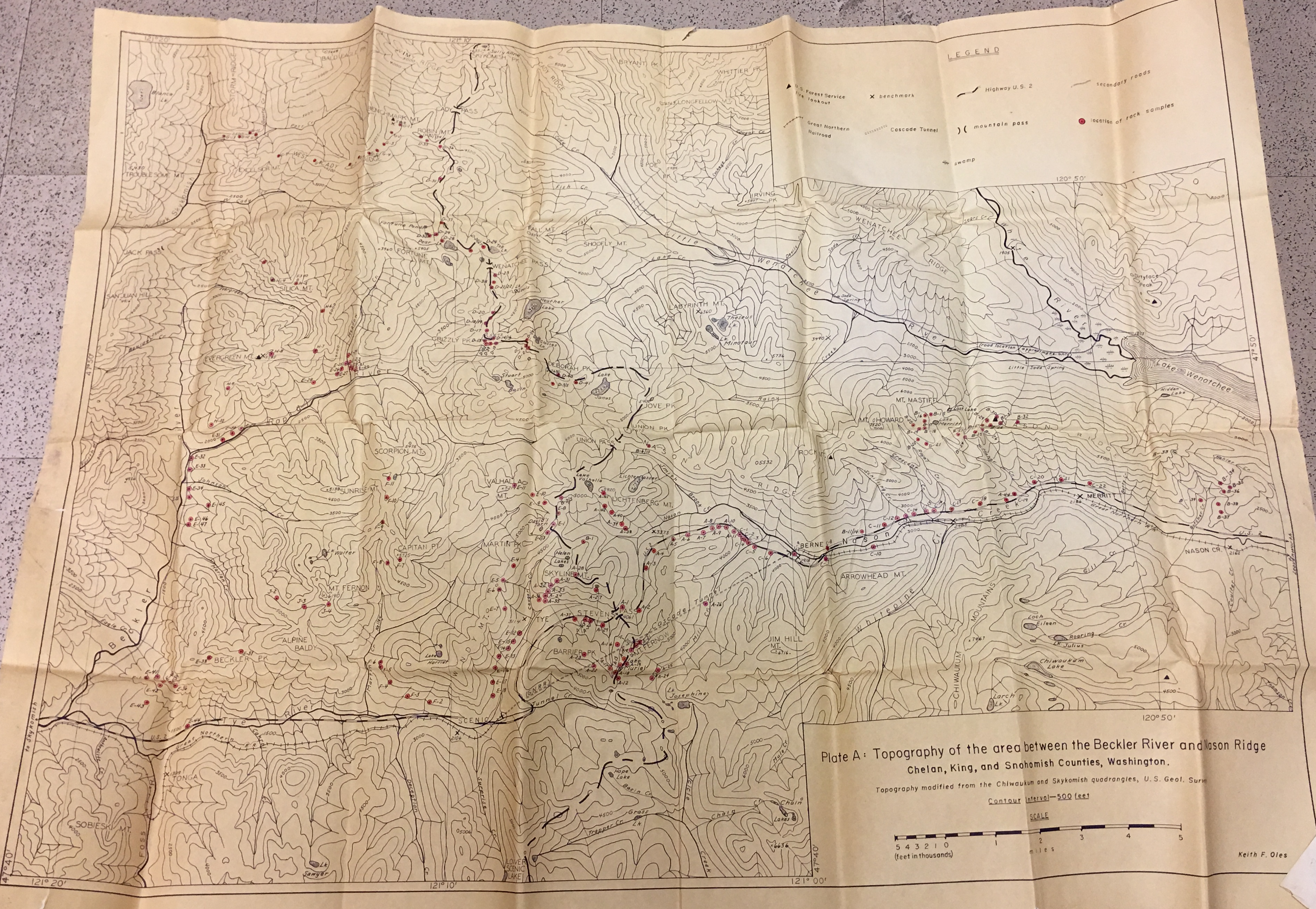


Plate A: Topography of the area between the Beckler River and Nason Ridge

Chelan, King, and Snohomish Counties, Washington.

Topography modified from the Chiwaukum and Skykomish quadrangles, U. S. Geol. Surv[e]

Contour Interval—500 feet

SCALE

5 4 3 2 1 0 (feet in thousands) — 1 2 3 4 5 miles

Keith F. Oles

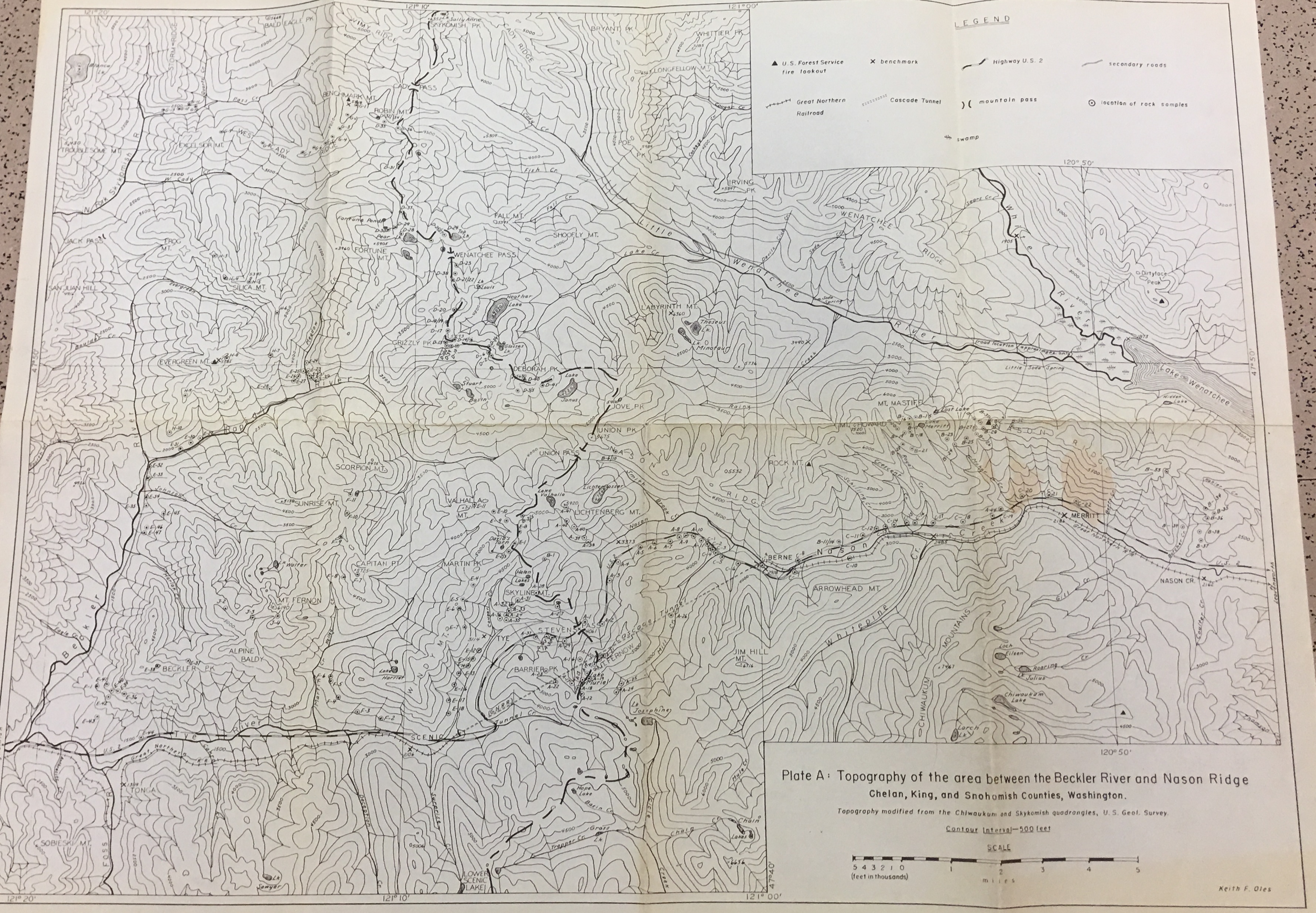


Plate A: Topography of the area between the Beckler River and Nason Ridge
Chelan, King, and Snohomish Counties, Washington.
Topography modified from the Chiwaukum and Skykomish quadrangles, U. S. Geol. Survey.

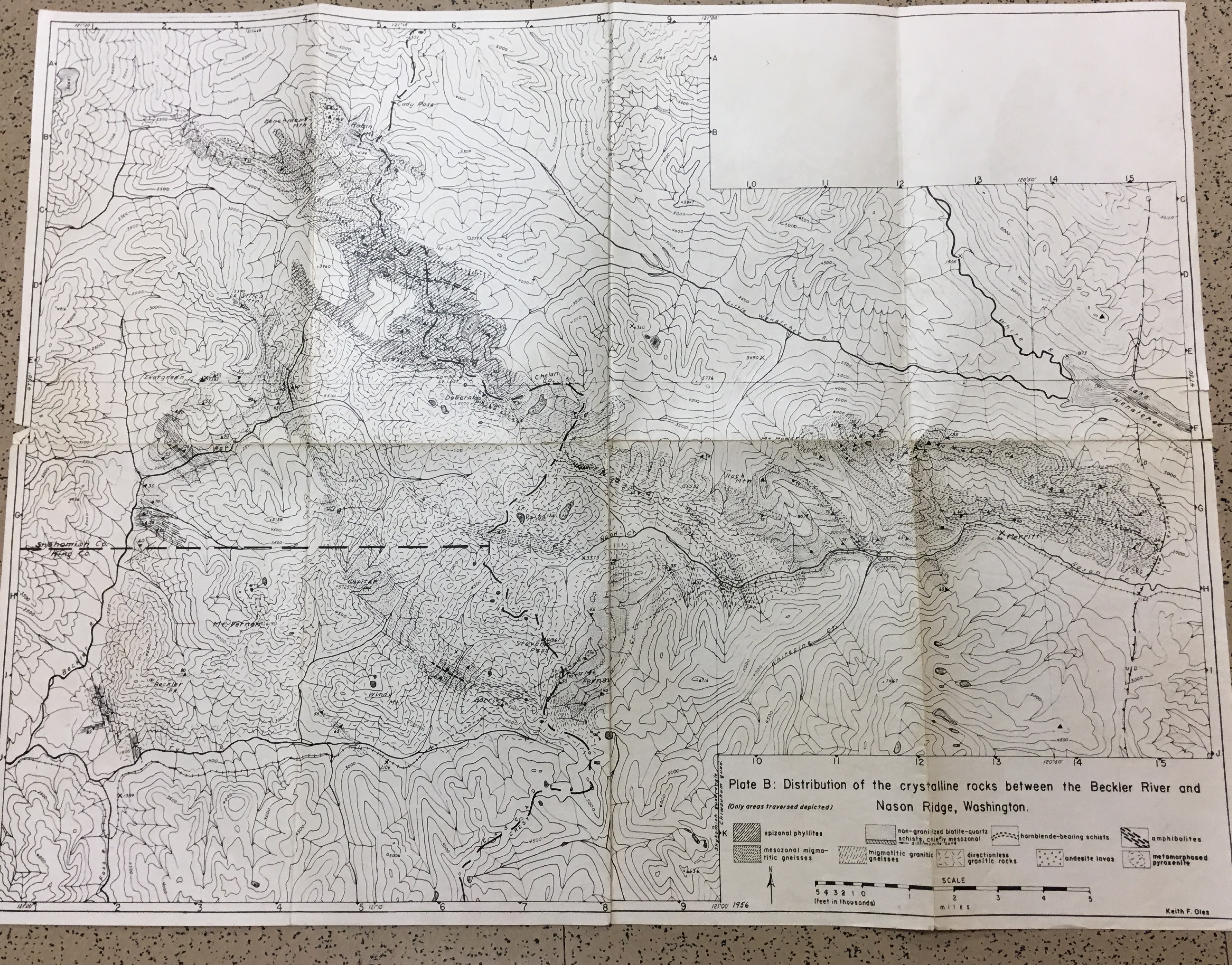
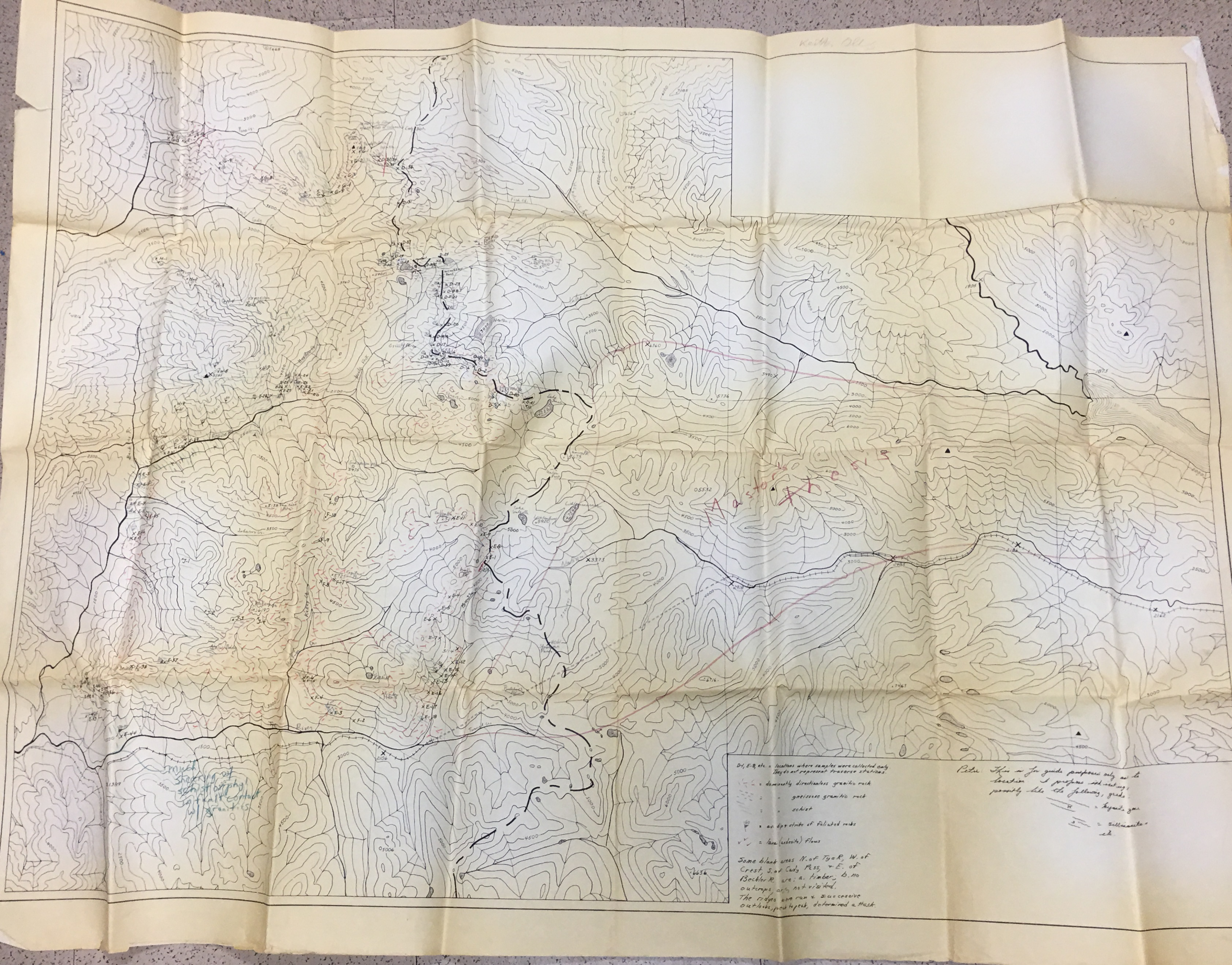


Plate B: Distribution of the crystalline rocks between the Beckler River and Nason Ridge, Washington.
(Only areas traversed depicted)
epizonal phyllites
mesozonal migmatitic gneisses
non-granitized biotite-quartz schists, chiefly mesozonal
sillimanite zone
migmatitic granitic gneisses
hornblende-bearing schists
directionless granitic rocks
amphibolites
andesite lavas
metamorphosed pyroxenite
N
SCALE
5 4 3 2 1 0
(feet in thousands)
1 2 3 4 5
miles
1956
Keith F. Oles
Cady Pass
Snohomish Co.
King Co.
Lake Wenatchee
Merritt
Nason Cr.


D-1, E-8, etc = locations where samples were collected only
They do not represent traverse stations.
= dominantly directionless granitic rock
= gneissose granitic rock
= schist
= dip + strike of foliated rocks
= lava (andesite) flows
Some blank areas N. of Tye R., W. of Crest, S. of Cady Pass, + E. of Bechler R. are: a. timber, b. no outcrops, or c. not visited.
The ridges were run + successive outlooks, peak to peak, determined a track.