THE PETROLOGY OF THE SULPHUR MTN. AREA, GLACIER PEAK QUADRANGLE, WASHINGTON

by

ARTHUR BARNES FORD

A thesis submitted in partial fulfillment of the requirements

for the degree of

MASTER OF SCIENCE

UNIVERSITY OF WASHINGTON

1957

Approved by Peter Misch

Department Geology

Date January 25, 1957

Abstract

The Sulphur Mtn. area is located in the northern portion of the Glacier Peak fifteen minute quadrangle in the northern Cascades of Washington. This area is in the western portion of the metamorphic-plutonic belt which constitutes most of the northern Cascades, and which lies within the western portion of the Paleozoic-Mesozoic Cordilleran eugeosyncline.

The isochemically metamorphosed rocks of the area are dominantly biotite schists, hornblende-bearing biotite schists, para-amphibolites, and ortho-amphibolites. Schists containing aluminum-excess minerals are less common, and marbles and lime-silicate rocks are rare. The dominant pre-metamorphic rocks accordingly were shales, greywackes, limy shales, dolomitic or tuffaceous shales, and basic volcanics, and much rarer carbonate rocks. The pre-metamorphic rocks therefore constitute a typical eugeosynclinal sequence. The isochemically metamorphosed rocks occur in the western part of the Sulphur Mtn. area, and form a northwest-southeast trending unit which projects into the migmatitic and granitic complex of the axial region of the Cascade range.

Weakly gneissose and directionless trondhjemites of migmatitic derivation occur just east of the isochemically metamorphosed schists and amphibolites. These coarse-grained migmatitic trondhjemites grade into less coarse-grained and more highly foliated migmatitic gneisses in the northeastern part of the area.

The regional metamorphism was dominantly synkinematic, but in many areas in the migmatitic units and occasionally in the isochemical units, crystallization continued under late-kinematic, and locally static, conditions. The highest temperatures of crystallization were everywhere in the warmest kyanite zone or possibly coolest katazone. The final period of recrystallization in many of the migmatitic rocks occurred at temperatures of the cooler-medium mesozone.

Following the regional metamorphism, the intrusion of quartz dioritic magma bowed-out the structures of the metamorphic rocks to the west. Deuteric alteration of some of the quartz diorites has resulted in an increase of quartz and potash feldspar. The extrusion of andesitic lavas from Glacier Peak was the final phase of igneous activity in the area.

TABLE OF CONTENTS

List of Illustrations

THE PETROLOGY OF THE SULPHUR MTN. AREA, GLACIER PEAK QUADRANGLE, WASHINGTON

INTRODUCTION

Location and Access

The Sulphur Mtn. area is located in the northern portion of the recent (1950) 15 minute U.S.G.S. Glacier Peak quadrangle just west of the crest-line of the northern high Cascades in north-central Washington. The area mapped in this investigation comprises over eighty square miles of wilderness immediately north of the volcanic extrusives of Glacier Peak. The eastern boundary is located approximately one mile west of the drainage divide of the Cascade Mountains. Sulphur Mtn. is situated near the center of the interesting series of amphibolites, schists, gneisses and granitics which constitute the metamorphic suite present, therefore it is used to locate the area. To be more precise however, the thesis area is bounded by longitudes 121°15' and 121°00' west and latitudes 48°15' and approximately 48°08' north.

The Sulphur Mtn. area is a part of the much larger area having the temporary designation "Glacier Peak Limited Area". Many outdoor groups such as the Seattle Mountaineers, Inc., the Mazamas, and the Sierra Club recently have been very active in attempting to change the area's classification to the more permanent "Glacier Peak Wilderness Area". Because of the forest-use classification "Limited Area", economic and recreational development on a commercial scale is restricted, and therefore access is rather poor. The best access to the area is a U. S. Forest Service maintained logging road which follows the Suiattle River a distance of about thirty miles from Darrington, Washington. This road ends about one mile past Sulphur Creek at the western boundary of the Sulphur Mtn. area and further access is by trail only. Access to the southern part of the area is by way of the Whitechuck River Road from Darrington. A well maintained trail leads up the Suiattle River to Suiattle Pass, a distance of about fifteen miles from the end of the Suiattle River Road. The Cascade Crest Trail, following up Milk Creek to Mica Lake, across Fire Creek Pass, and down to Kennedy Hot Springs on the Whitechuck River, is

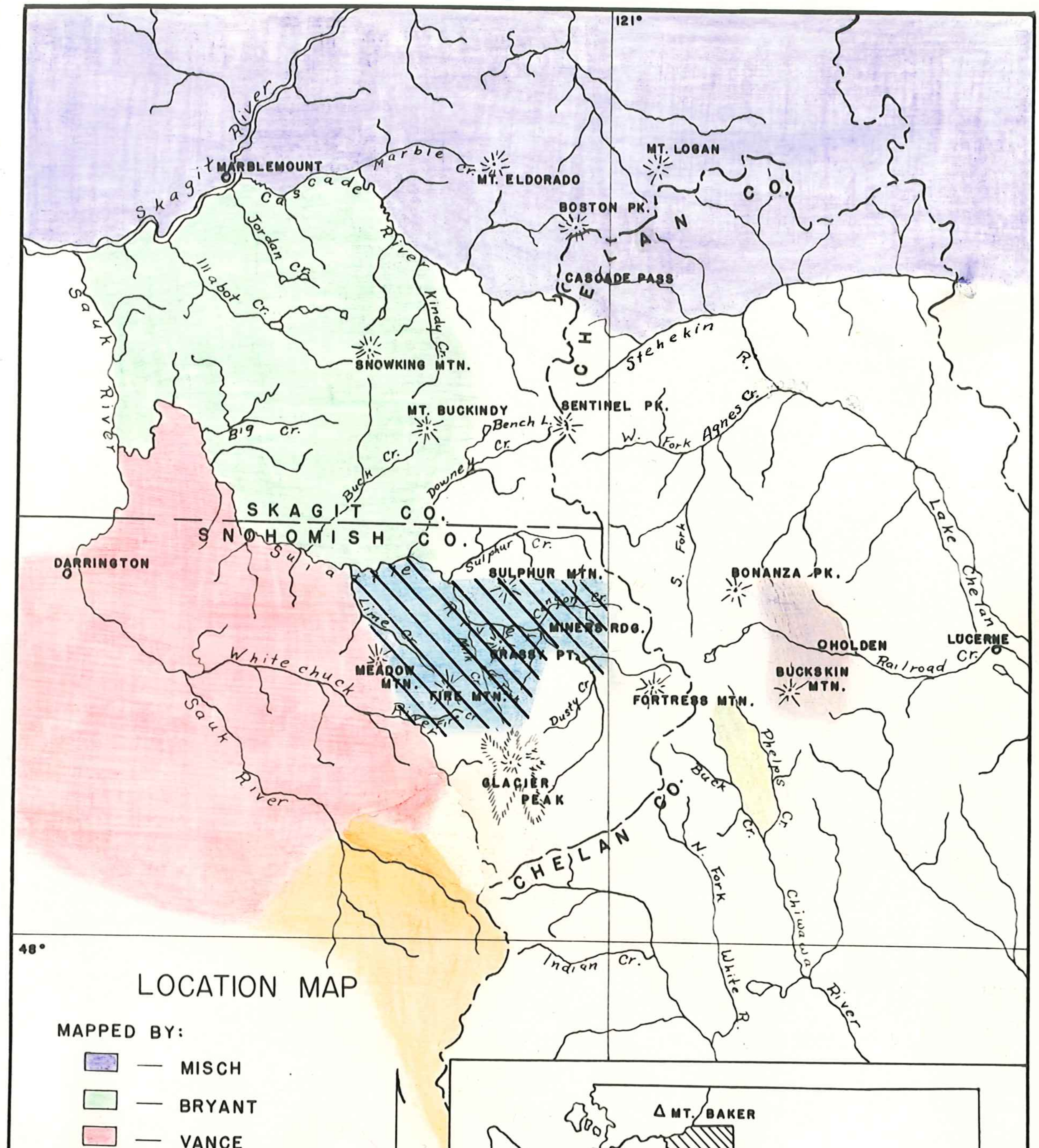

LOCATION MAP
MAPPED BY:
MISCH
BRYANT
VANCE
ZWART
DUBOIS
MORRISON
FORD
N
0
4
8
16 MI.
121°
48°
MARBLEMOUNT
MT. ELDORADO
MT. LOGAN
BOSTON PK.
CASCADE PASS
SNOWKING MTN.
MT. BUCKINDY
SENTINEL PK.
SKAGIT CO.
SNOHOMISH CO.
CHELAN CO.
DARRINGTON
SULPHUR MTN.
MINERS RDG.
GRASSY PT.
MEADOW MTN.
FIRE MTN.
FORTRESS MTN.
GLACIER PEAK
BONANZA PK.
HOLDEN
LUCERNE
BUCKSKIN MTN.
Skagit River
Sauk River
Cascade River
Marble Cr.
Jordan Cr.
Illabot Cr.
Kindy Cr.
Big Cr.
Buck Cr.
Downey Cr.
Bench L.
Stehekin R.
W. Fork Agnes Cr.
S. Fork
Lake Chelan
Railroad Cr.
Sulphur Cr.
Suiattle
White chuck
Dusty Cr.
Buck Cr.
Phelps Cr.
N. Fork
White R.
Chiwawa River
Indian Cr.
INDEX MAP
MT. BAKER
GLACIER PK.
EVERETT
SEATTLE
WASHINGTON
MT. RAINIER
0
25
50 MI.

Plate I.

also in good maintainance. The remainder of the trails are way-trails and therefore are only cleared every several years for fire protection. Several trails shown on the topographic maps have been abandoned by trail crews and therefore are only passable with difficulty and are impassable for livestock. Such is the condition of the trail up the Suiattle River south of Dusty Creek, the Vista Creek trail and the trail up Sulphur Creek past the four mile marker.

Previous Work

The earliest investigations in the Glacier Peak area were reconnaissance tours taken by I. C. Russell in the summers of 1897 and 1898. His traverse of the Cascades led up the White River and Indian Creek to Indian Pass and then to the summit of Glacier Peak for its first known ascent, returning to Indian Pass and then out by way of the Sauk River. This was also the last work done for over half a century until several members of the Department of Geology at the University of Washington began work in adjacent areas in connection with a project to map the geology of the northern Cascades. Keith Oles (MS thesis, 1951) mapped the area around Stevens Pass and is now studying (PhD thesis, unfinished) the rocks of the northern part of the Skykomish quadrangle just south of the Glacier Peak quadrangle. Bruce Bryant (PhD thesis, 1955) mapped the Snowking area which is northwest of the present area and contiguous to it at Sulphur Creek. Joseph Vance (PhD thesis, unfinished) has mapped the district immediately west of the Glacier Peak quadrangle. Henry Zwart as a post-doctoral research fellow has mapped the area southwest of the Glacier Peak quadrangle and south of that mapped by Vance but has not yet published his results. Melvin Morrison (MS thesis, 1954) has mapped Phelps Ridge to the southeast in the Holden quadrangle. The U. S. Geological Survey has engaged in a study of the Holden quadrangle to the east which has not yet been completed. The Sulphur Mtn. area however, has never been subjected to any prior geologic investigation.

Purpose of Investigation

The reconnaissance mapping of this area is part of a larger project of mapping the geology of the northern high Cascades which has for some time been in progress under the direction of Peter Misch at the University of Washington. More specifically, the study of the present area had the purpose to contribute to the understanding of the metamorphic and granitic rocks which occupy most of the northern Cascades.

Field and Laboratory Work

The writer became familiar with the area under discussion while he was employed by Bear Creek Mining Co. during the summers of 1954 and 1955 doing exploration work on the copper deposits of nearby Miners Ridge and Plummer Mtn. Weekends were spent studying this area until the middle of August, 1955 when subsequently an additional thirty days were used to finish the reconnaissance mapping, favored by exceptionally good weather during August and September. Over three hundred samples were collected in the field from which over a hundred thin sections were prepared and studied in the laboratory. Field mapping was done on aerial photographs taken by the U.S. Geological Survey in the summer of 1950. This information then was transposed to an enlarged copy of the Glacier Peak fifteen minute quadrangle published in 1950.

Acknowledgments

This report was prepared under the supervision of Professor Peter Misch who has given unlimited time, guidance, and encouragement. Appreciation is also given the other faculty members and fellow students at the Department of Geology, University of Washington with whom the writer has had occasion to confer on various subjects which arose during the prearation of the report. Thanks are due Mr. Charles C. Goddard with whom the writer was associated while working with Bear Creek Mining Co. on Miners Ridge. Appreciation is also given to Rangers Woodcock and Jerry Woods of the Suiattle River District, Mt. Baker National Forest, who were of much assistance. Last, but not least, are the thanks due my wife Carole, for her encouragement and financial support and the final typing of this thesis.

OUTLINE OF BEDROCK GEOLOGY

Regional Setting

The Sulphur Mtn. metamorphic and granitic rocks are situated near the axial zone of highly metamorphosed and crystalline rocks composing the high Cascades of northern Washington. To the northwest in the Snowking area, Bryant (1955) has mapped a series of argillaceous sediments, tuffs and volcanic flows which have been isochemically metamorphosed under synkinematic, mesozonal conditions to biotite schists, hornblende-biotite schists, para- and ortho-amphibolites, with subordinate quartzite and lime-silicate bands. No stratigraphic relationships were obtainable. These rocks have been named by him the Green Mtn. unit and this same name will be applied to this series of metamorphics in the Sulphur Mtn. area. Intrusive into the schists of the Green Mtn. unit on Downey Mtn. is a mass of trondhjemite whose mineral and textural relationships indicate a neomagmatic rather than orthomagmatic origin. Just southeast of Bench Lake, on the ridge between Bench Creek and Downey Creek, Bryant mapped a northwesterly trending series of trondhjemitic gneisses of migmatitic derivation in which quartzites, lime-silicate schists and amphibolites are conformably interbedded.

On Phelps Ridge just to the southeast of the Glacier Peak quadrangle, Morrison (1954) mapped a series of basic tuffs and flows metamorphosed into para- and ortho-amphibolites, overlain by argillaceous sandstones and argillites which were metamorphosed into biotite gneisses and granulites. These rocks trend northwesterly and are on strike with some of the migmatitic biotite and hornblende gneisses in the easternmost part of the present area.

Oles (1951) near Stevens Pass and Zwart (personal communication) southwest of Glacier Peak have mapped a series of biotite schists containing the aluminum excess minerals kyanite, staurolite, and more rarely sillimanite. Al-excess mineral-bearing schists were collected by the writer near Fire Mtn. and were mentioned by Bryant as relatively rare constituents of the Green Mtn. unit. Schists containing rare aluminum - excess minerals have also been mapped by Misch (personal communication) from just south of Cascade Pass to east of Marblemount.

Granitic rocks of the northern high Cascades are of three types, all genetically related. The initial stage in this evolution which has been outlined by Misch (1952 a & b) is the recrystallization, first under synkinematic and then under static conditions, of a metamorphic rock thus transforming it first into a gneiss and then into a directionless granitic rock. These stages are exemplified by the Skagit gneisses and the eastern portions of the Chilliwack granodioritic mass where the latter has formed by the recrystallization of the Skagit gneiss and has remained in situ (Misch, 1952a, pp.12-16). The second type, which is the intermediate stage, is characterized by those portions of the Chilliwack mass that have become mobilized and intruded the more isochemical western metamorphics while yet in the plastic and crystalline state. This second type leads, with all transitions, to mobilized masses which are characterized by the same manner of structural emplacement but whose texture and mineralogy indicate partial liquification. Lastly are the late igneous plutons in a fully magmatic state such as the Golden Horn granodiorite mapped by Misch (1952a, pp. 17-18) which shoulder aside the country rock in post-metamorphic time. Similar granitic types were mapped by Bryant (1955) in the Snowking area just north of the present area.

In summation, it can at present only be stated with confidence that the regional environment is that of a typical eugeosyncline which has undergone later orogeny, regional metamorphism and granitization. The age of the pre-metamorphic sediments is unknown as no fossils have survived the metamorphism in any nearby area. The sediments probably belong to the Paleozoic-Mesozoic Cordilleran eugeosynclinal system from which fossils have been found at widely scattered localities ranging in age from Ordovician (Smith, W. S., 1916, pp. 562-563) to late Jurassic and lower Cretaceous (Misch, 1952a, pp.9-10, and personal communication). Misch (1952a, pp. 7-8) has mapped rather large areas of late Paleozoic sediments and basic volcanics near Concrete and also north of the Nooksack River (Chilliwack series).

No evidence has been found in the Sulphur Mtn. area or in any immediately adjacent area to date the orogeny which produced the schists, amphibolites, gneisses, and granitics. Farther to the north, the first major Mesozoic orogeny seems to have occurred prior to middle Jurassic as Misch (personal communication) has found upper Jurassic-lower Cretaceous sediments underlain by probable middle Jurassic volcanics which have been only dynamically metamorphosed on a more local scale. Misch (1952a, pp. 10-12, and personal communication) has found evidence for a later, post early Cretaceous period of orogeny which produced folding, considerable overthrusting and some further metamorphism and was followed by extensive granitic activity. A still later and relatively weaker orogeny occurred during which the upper Cretaceous-Paleocene Chuckanut sediments were folded.

Outline of the Geology of the Sulphur Mtn. Area

Many of the features summarized above (pp. 5-7) are also present in the area now being described. Unmetamorphosed rocks are restricted to basaltic and andesitic dikes, a small outcrop area of Glacier Peak volcanic flows and breccias, and to the intrusive mass of granitic material on Miners Ridge.

The metamorphic rocks of the Sulphur Mtn. area form nearly an isophysical series; the temperature of metamorphism was rarely below that of the middle mesozone or above that of the meso-katazonal boundary. Many of the rocks studied such as the biotite schists and the amphibolites of the Green Mtn. unit could not be assigned accurately beyond being mesozonal for they contain no critical mineral or mineral assemblage such as kyanite or anorthite substitutes plus plagioclase. The close association and intercalation of these rocks with those definately assignable to the kyanite zone indicate a probable middle and upper mesozonal temperature for all. Metamorphism was chiefly synkinematic but in local areas in the Green Mtn. unit deformation slightly outlasted crystallization and in other areas as in the Sulphur Mtn. trondjhemites crystallization lasted well into the time of static conditions.

The variation of the rock types produced from the regional metamorphism,as far as not controlled by changing physical conditions (stress and temperature) must therefore be dependent upon different chemical conditions. The chemical environment depends upon the composition of the original sediment or volcanic and upon the nature of the solutions (if any) that were introduced during metamorphism. The first case is exemplified by those portions of the Green Mtn. unit in which shales, limy shales, shaly limestones, tuffs and basic volcanics were metamorphosed under isochemical conditions to biotite schists, hornblende bearing schists, lime-silicate-hornblende schists, para- and ortho-amphibolites. Introduced alkalies and silica play the major role in the allochemical transformation of the biotite schists, hornblende schists and amphibolites into migmatitic gneisses and migmatitic trondhjemites such as found on Sulphur Mtn. The first step in the transformation of an amphibolite into a trondhjemitic rock is the development of plagioclase porphyroblasts of a slightly more sodic nature than found in the original amphibolite. The biotitization of hornblende along cracks and cleavages at this stage suggests that minor potassium was introduced along with the sodium. As metasomatism proceeded, the amphibolite became more and more porphyroblastic until it had the appearance of a diorite. Continuing soda and increased silica introduction, with minor potash, changed this diorite to a quartz diorite and finally to a trondhjemite. By this time usually only relicts of the former hornblende are present, being replaced by the assemblage biotite plus epidote minerals. Locally, where late potash introduction occurred, a granodioritic composition was attained. The sequence of granitization of the amphibolites was completed when these advanced migmatites became mobilized and intruded the isochemical metamorphics of the Green Mtn. unit to the west, apparently moving away from the central core of granite generation. A small intrusion of this mobilized material was found on the west spur of Grassy Point and it is possible that the neomagmatic trondhjemite which Bryant (1955) found to be in intrusive contact with the Green Mtn. unit on Downey Mtn. is of the same type. To the east, the Sulphur Mtn. trondhjemites grade imperceptibly into the less coarse-grained and more strongly gneissose hornblende and biotite bearing migmatitic gneisses between Bath Lake and Totem Pass.

Following the regional metamorphism, an intrusive mass was emplaced by shouldering aside the earlier gneisses and trondhjemites. Structural relationships suggest that the direction of movement of this intrusive body had a horizontal component from east to west. These intrusive granitic rocks are located on the western end of Miners Ridge and have

The general pattern of structural trends in the area under discussion is also northwesterly, but local deviations are present. The biotite schists found between Box Mtn. and Fire Mtn. strike north ten to fifteen degrees west and dip from sixty-five to eighty degrees toward the west. To the southeast near Fire Creek Pass the strike gradually changes to north-south and where these schists disappear under the Glacier Peak volcanics, they strike a few degrees east of north. South of the Suiattle River the amphibolites on Grassy Point strike about north forty-five degrees west, and further south toward Glacier Peak the strike of the amphibolites becomes much more westerly, about north seventy degrees west. On Glacier Peak Ridge the amphibolites dip about sixty degrees to the southwest, whereas on Grassy Point they dip about sixty-five degrees to the northeast. This may indicate a broad open fold whose axis is hidden in the valley of the East Fork of Milk Creek. Minor folds were observed just north of the Suiattle River in the Green Mtn. unit whose axial planes strike north thirty degrees west and dip thirty-five degrees east. North of the Suiattle River where many of the amphibolites have been granitized to form the Sulphur Mtn. trondhjemitic mass, the structural trends are still visible in the more gneissic phases and are also indicated by the internal schistosity and alignment of the relict inclusions or skialiths. The schistosity of these gneisses and the relicts are nearly parallel, striking about north thirty degrees east and dipping about forty-five degrees southeast. From the accompanying geological map these trends may be seen to form a rough arc which is concave toward the western boundaries of the Miners Ridge quartz dioritic stock, thus constituting conclusive structural evidence for the intrusive nature of this mass by forcefully shouldering aside the country rocks. Bryant (1955) mapped on Downey Mtn. a local northeasterly trend in the Green Mtn. unit which also may be a reflection of the intrusive force of this mass of quartz diorite. East of the migmatitic trondhjemites and north of the intrusive body, between Bath Lake and Totem Pass, the gneisses again take on the usual northwesterly trend. No megascopic structures were seen in the Image Lake intrusive body.

In the few places where the bedding is distinctly visible in the field it is always parallel to the schistosity. Microscopically, however, a few specimens collected from the ridge south of Grassy Point show a distinct angle between the s planes and the bedding. This crosscutting relationship may be a result of the proximity of this location to the axis of the fold mentioned above.

PETROLOGY AND GEOLOGY OF THE CRYSTALLINE ROCKS

Isochemically Metamorphosed Rocks of the Green Mountain Unit

Introduction

Because of the ubiquitous evidence of chemical additions and subtractions on a small scale, very few of the schists and amphibolites of this unit could be strictly called "isochemical". Such mineral transformations as the formation of a calcic plagioclase from albite plus epidote or zoisite, and biotite from chlorite plus K_2O already present in the rock require only a rise of temperature, the bulk composition of the rock remaining constant. However, in many of these rocks at least slight changes in chemical composition may have occurred. Therefore "isochemical" is here used to mean "without significant or conspicuous change in chemical composition" (definition suggested by P. Misch, unpublished manuscript). Moreover, metasomatism may have occurred but has been of the "concealed" variety (Misch, unpublished manuscript) in which case chemical analyses would be required to determine the change in bulk composition. On the other hand, the presence of a few feldspar porphyroblasts in one of these rocks does not necessarily indicate the introduction of material from outside sources. The porphyroblasts may be merely due to a redistribution of feldspathic matter within a very small area on the scale of a thin section. The presence of many feldspar porphyroblasts does, however, indicate an introduction of alkalies and thus an allochemical metamorphism. The separation of "isochemical" from "allochemical" metamorphic rocks is therefore arbitrary in the absence of detailed mapping, accurate sampling and chemical analyses. In this report, for practical purposes of clarification, any rock containing over ten per cent of feldspar porphyroblasts will be called "allochemical". Wherever the word "isochemical" is used in this text, the word "essentially" is always inferred as a modifier.

Isochemically metamorphosed rocks are present only in the western part of the Sulphur Mtn. area, being limited to the Green Mtn. unit. A traverse across the trend of this unit between Fire Mtn. and Mica Lake shows a series of rather uniform,mostly westerly dipping biotite schists, a few of which contain kyanite or pseudomorphs after it. Between Mica

Lake and Milk Creek there is a very gradual increase in the amount of hornblende; hornblende-bearing biotite schists and hornblende-zoisite schists become rather common. In this part of the unit, amphibole garbenschiefer, the amphibole usually being green hornblende, are somewhat common. Most frequently the amphibole aggregates in the garbenschiefer have grown mimetically in the plane of schistosity, but occasionally they cut across it, thus indicating a totally static phase of crystallization.

Glacier Peak Ridge and the ridge south of Grassy Point are made up of amphibolites, both sediment- and volcanic-derived, interbedded with minor lime-silicate and quartzite bands and occasional lenses of marble. Exposures are too poor on Grassy Point and Glacier Peak Ridge to determine the stratigraphic relationships of these metamorphosed sediments and volcanics.

The oldest rocks in this Green Mtn. sequence may be the amphibolites as they appear to be overlain by the pelitic schists. This is indicated by the broad, open fold which is present between Grassy Point and Glacier Peak Ridge in which the amphibolites dip under the biotite schists to the west. This evidence is rather tenuous however, as isoclinal folding, faulting, and "megaplastic" deformation (Misch, unpublished manuscript) have undoubtedly been complicating factors, On Phelps Ridge, Morrison (1954) also found pelitic schists to overlie amphibolitic rocks with a gradational boundary. The rocks which Morrison mapped are not on strike with the Green Mtn. unit, nevertheless they possibly may be laterally equivalent.

Schists

Biotite Schists

The biotite schists are rather resistant to erosion as they form steep and angular hogbacks from Fire Creek Pass to just west of Fire Mtn. This resistance is probably due to the quartz content of these schists, which in some places is as high as fifty per cent, and to the many quartz segregation veins and dikes. Outcrops of these schists commonly show almandine garnets which stand out in relief on a weathered surface, especially near Mica Lake. Fire Creek and Fire Creek Pass were so named by the local residents for the great quantity of "rubies" found in their vicinity.

The plagioclase content of these rocks ranges from ten to nearly fifty per cent and the composition varies from sodic andesine (An_{35}) to calcic oligoclase (An_{24}). Biotite usually comprises about twenty-five per cent of the rock but varies from fifteen to almost fifty per cent. Almandine is a common constituent, ranging from two to seven per cent averaging about five per cent. Quartz varies from twenty to fifty per cent and averages about thirty per cent. Accessory minerals are graphite, rutile, sphene, apatite, and tourmaline. These rocks are almost free of hornblende, and they contain no main assemblage epidote minerals. A conspicuous absentee from the mineral assemblage is potash feldspar; the significance of this fact will be discussed under "Interpretation".

From Mica Lake to Milk Creek, there seems to be a gradation from the biotite schists into hornblende-rich schists and even into amphibolites. West of Mica Lake, the only amphibole bearing rocks observed were a few small pods of an actinolitic hornblendite in the garnet-biotite schists. These pods are four to five feet long and are between one and two feet in width. Their elongation is parallel to the schistosity which might be taken as an indication of a synkinematic development. Within these pods however, the presence of garbenschiefer growths composed of pale green (Z) actinolitic hornblende ($2V = 85^o$, $Z:c = 17^o$) indicates static conditions of growth. These masses possibly represent synkinematic segregations of basic constituents into areas which, for some unknown reason, were under less stress than the adjacent areas. If penetrative deformation had occurred in these areas, later recrystallization has erased most evidence of it.

Biotite is fine to medium grained and has anhedral to subhedral crystalloblastic form; the terminal faces (010 and 110) are never developed. The biotite shows absorption: $Z \gg Y \gg X$. Most commonly, Z is dark brown, Y also being dark brown but slightly lighter than Z, and X is a pale yellowish tan. Less commonly, the pleochroism is: Z = Y = slightly reddish medium brown, and X = pale tan. A specimen of a recrystallized mylonitic mica schist collected from near Grassy Point shows one band of biotite whose pleochroism is: Z = Y = dark greenish brown, and X = pale greenish, yellowish tan; the remainder of the biotite in the rock has reddish brown to tan pleochroism. Much of the biotite is synkinematic and older than the garnet. The presence of crystallization foliation in some of these rocks indicates that biotite crystallization lasted at least as long as or possibly longer than deformation. Biotite commonly also occurs as an alteration product of almandine. A specimen collected from just below Twin Lakes shows two stages of biotite growth: biotite I contains an internal s of graphitic inclusions and has undergone tensional fracturing accompanied by continuous recementing by graphite-free biotite II.

Plagioclase has anhedral to subhedral form and is fine to medium grained. The mineral lacks any porphyroblastic tendency in the rocks studied from this unit. The plagioclase ranges in composition from An_{25} to An_{35}, the average being about An_{30}. Most specimens show the plagioclase to be normally zoned with sodic andesine cores and calcic oligoclase rims. Reverse zoning is much rarer and only a few crystals were observed having one oscillation of zoning. The zoning is always gradational and anhedral. A specimen from south of Fire Creek Pass shows a few crystals with An_{25} cores and An_{30} rims. Joseph Vance (personal communication) found zoning of this same type in similar rocks west of Lime Creek. Southwest of Fire Creek Pass, anhedral rims of albite are present around some of the calcic-oligoclase crystals. The restricted occurrence of such rims argues against a general soda metasomatism as their cause. These late albite rims may be a retrogressive phenomenon.

Quartz is present in fine to medium sized anhedral grains which commonly show undulatory extinction. Quartz is the chief component of lenticular shaped masses and bands which probably represent synkinematic silica segregation. In these bands, the quartz is granoblastic with sutured boundaries and also usually exhibits undulatory extinction. The quartz in these bands has usually a slightly larger grain size than in the adjacent schist. Acessory minerals in the bands are plagioclase and biotite; the biotite being parallel to that in the surrounding schist.

The almandine is usually late-kinematic to post-kinematic as the abundant lined-up inclusions(s_i) of plagioclase, quartz, and/or graphite are usually in parallel alignment with the schistosity (s_e) of the surrounding rock. Only rarely is slight snowball structure or later rotation of the internal s with respect to the external s present. The garnets form small to large, sieve textured, idiomorphic to subidiomorphic porphyroblasts which are later than much of the biotite, although a minor amount of biotite is post-garnet. A specimen collected from near the Suiattle River shows garnet which is post-first generation biotite, to have been cracked and partly filled by second generation biotite. These two generations of biotite probably are only stages in one continuous period of biotite crystallization. The garnet shows two distinct types of alteration: 1. to biotite; and 2. to chlorite, with or without muscovite or sericite. Biotitization of the garnet along fractures and cracks is almost ubiquitous. Chloritization is rather rare. The type of alteration probably depended upon the temperature of retrogressive metamorphism. In one specimen collected from near Lime Lake, the garnet is about fifty per cent altered to chlorite plus muscovite whereas the biotite is entirely fresh. This indicates that the retrogressive conditions at this place were below the field of stability for the garnet yet still within that for biotite. The retrogressive alteration of garnet to biotite or muscovite requires the addition of some potassium. The absence of any effects of potassium metasomatism in the adjacent rock indicates that there was probably a local source of the potash.

Muscovite amounts to less than five per cent of the rock mass and is usually oriented across the schistosity. It often tends to cluster in "knots", suggesting that it may have replaced an aluminum-excess mineral, although no relicts were observed. Bryant (1955) reported muscovite and sericite knots with rare relicts of kyanite, in similar rocks to the north. Muscovite (or sericite) occurs occasionally as an alteration product of garnet.

Biotite Schists with Al-excess Minerals

Schists containing the aluminum-excess minerals kyanite and andalusite are limited to the westernmost part of the Green Mtn. unit in the Sulphur Mtn. area. They are found only on the ridge from just south of Fire Creek Pass to near Meadow Mtn. Similar schists have been mapped by Vance (personal communication) farther to the west and also just south of the Whitechuck River. They have also been mapped by Bryant (1955) north of the Suiattle River. Misch (personal communication) has mapped similar rocks farther to the north, southwest of Cascade Pass.

Megascopically, these aluminum-excess-mineral bearing schists are indistinguishable from the biotite schists found farther east which are free of such minerals. The schists with aluminum-excess minerals seem to be rather rare and are intercalated with biotite schists free of Al-excess minerals. These schists are treated in a separate chapter because they appear to be in a different part of the stratigraphic section from the ordinary pelitic schists to the east. These schists form part of a homoclinal sequence which may be the western limb of the anticline whose axis is in the valley of the East Fork of Milk Creek. As these schists are the farthest from the axial regions of this anticline, they are tenuously considered as the highest rocks in the section, the reservation always being kept in mind of such complicating factors as isoclinal folding, overturning, faulting, and pseudoplastic flowage which accompanied the regional metamorphism.

The typical Al-excess schist is a medium-grained garnet-kyanite-biotite schist, although some specimens are garnet-kyanite-two mica schists. The plagioclase in these rocks ranges from ten to twenty per cent, and its composition varies from An_{26} to An_{30}. Biotite averages about fifteen per cent. Kyanite varies from two or three to ten per cent, averaging about five per cent. One specimen contains minor andalusite which has formed from the kyanite. Almandine varies from five to eight per cent. Quartz comprises from thirty-five to forty per cent of the rock. Muscovite and sericite range from an accessory amount up to about five per cent. Other accessory minerals are tourmaline, rutile, graphite, and magnetite.

Texturally, these Al-excess mineral bearing schists do not differ

Figure 1.

Kyanite-garnet-two mica schist with a static phase of mesozonal recrystallization superimposed upon the earlier synkinematic phase. Most of the kyanite at this locality has been at least partially altered to andalusite. (k_1) = relict kyanite; (a_1) = andalusite pseudomorphous after kyanite; (k_2) = unaltered kyanite; q = quartz. Some andalusite pseudomorphs are free of relict kyanite (a_2). The enclosing schist material also shows evidence of static recrystallization.

Specimen 9-11-55-17, collected from station 189 just southwest of Fire Creek Pass.

Plane light.

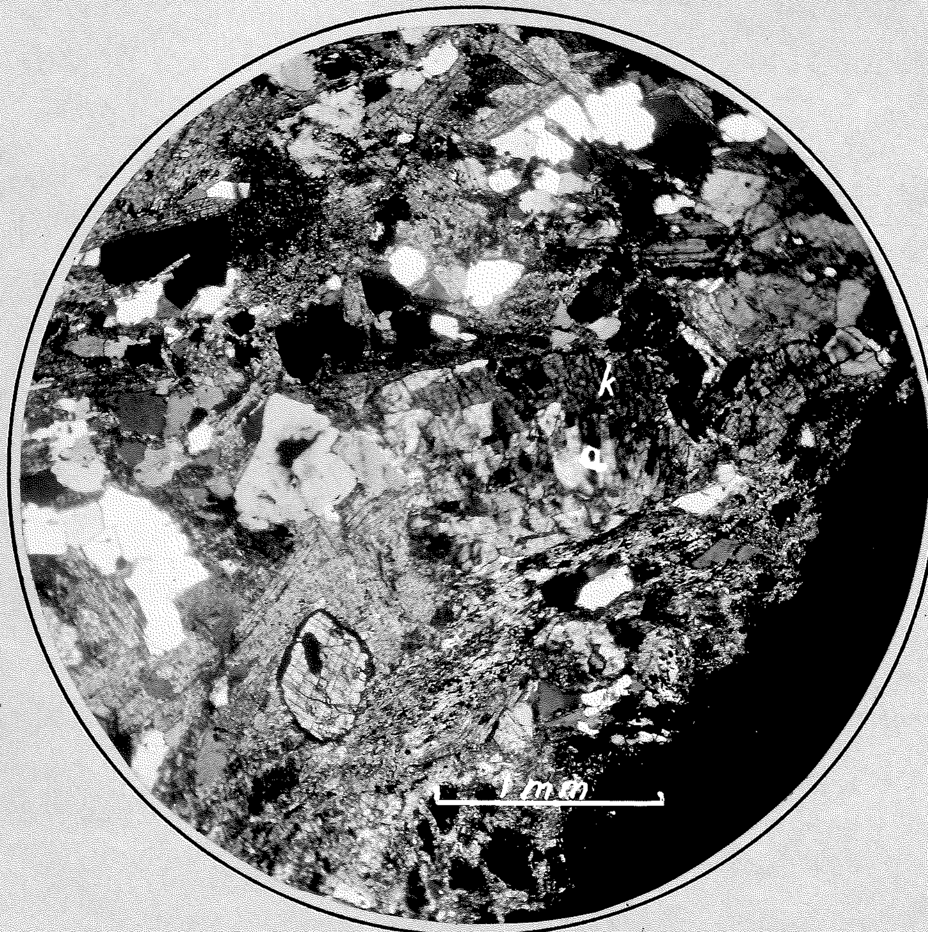


Figure 2.

Andalusite (a) pseudomorphous after kyanite (k) showing the irregular and somewhat radial extinction of the andalusite.

Same specimen as figure 1.

Crossed nicols.

from the ordinary pelitic schists to the east. Mineralogically, the only difference is the presence of kyanite. The kyanite exhibits rather well developed preferred orientation with the (100) faces tending to be parallel to the foliation planes of the rock. This fact is shown by the very small to almost parallel extinction of these crystals in thin sections cut normal to s. At least part of the foliation had been developed prior to the synkinematic growth of the kyanite as it has been bowed-out around the kyanite. Two types of alteration of the kyanite are present in the rocks studied. Nearly every kyanite crystal examined showed at least incipient rims of sericite. The sericitization has been controlled by the cleavages of the kyanite. All stages of this sericitization and muscovitization are present. Some rather large knots of muscovite glomeroblasts which cut across the schistosity contain small grains of relict kyanite. Other muscovite knots are free of relict kyanite. Not all such muscovite knots should be assumed to indicate the presence of former kyanite as it occasionally is also an alteration product of almandine. Some muscovite, however, appears to belong to the main synkinematic assemblage, its orientation being parallel to the schistosity. The second, and rather unusual alteration product of kyanite, is a peculiar type of mineral showing radial growth (see figure 2, page 19). Other optical properties (length fast, negative sign, 2V about 80^{o}, birefringence about .010) indicate that it is andalusite. The only specimen collected showing this type of alteration is from just southwest of Fire Creek Pass. Relict grains of kyanite are present in many of these radiating andalusite crystals; there is a preferential replacement along the cleavage planes of the kyanite. Others of these pseudomorphs are free of kyanite relicts. In this rock, the almandine is rather strongly altered to biotite, chlorite and sericite. These andalusite pseudomorphs seem to indicate a mesozonal, static phase of retrogression.

Hornblende-bearing Schists

East of Mica Lake the schists contain varying proportions of hornblende, quartz and plagioclase. The biotite content is also highly variable, and where present in amounts less than a few per cent, it usually has formed by biotitization of the amphibole. These hornblende-bearing schists occur mainly between Mica Lake and Milk Creek, but they also occur at other scattered outcrops of the Green Mtn. unit in the Sulphur Mtn. area. The transition between the biotite schists near Mica Lake and the rocks free of biotite belonging to the main synkinematic mineral assemblage near Milk Creek is, in gross aspect, gradational. In detail however, biotite-rich and biotite-free rocks are commonly interlayered and interbanded. These repetitions could have been caused by either: a repetition of compositional differences in the original sedimentary sequence; or, more probably, by later tectonic lensing and/or isoclinal folding of two or more units undergoing regional metamorphism. Metamorphic differentiation has been a contributing factor but probably only on an extremely local and small scale. The cause of this interlayering could not be determined because of poor exposures, but probably all the factors mentioned above have been in operation to some extent.

Megascopically, these rocks can be distinguished from the biotite schists to the west by the presence of amphibole minerals. They commonly have a more or less banded appearance on the scale of a hand specimen.

The amount of plagioclase in these rocks varies from five to nearly fifty per cent and averages about thirty-five per cent; its composition averages about An_{35}, but at one locality its composition is that of a calcic andesine, An_{47}. The biotite content ranges from one to thirty per cent and averages about ten per cent. Amphibole minerals, normally a green hornblende, comprise from five to thirty-five per cent and average about twenty per cent of the rock. Epidote - group minerals are usually present in amounts less than five per cent; the most common ones are zoisite and clinozoisite, but pistacite also occurs. Garnet, probably almandine, varies from two to about twelve per cent and averages about five per cent. Quartz varies from fifteen to nearly sixty per cent and averages about twenty-five per cent. Accessory minerals are sphene, apatite, rutile, graphite, magnetite, and muscovite in order of decreasing abundance.

Biotite is fine to medium grained and has anhedral to subhedral crystalloblastic form. It pleochroism is: Z = Y = slightly reddish dark brown and X = pale yellowish tan. In some rocks, the absorption colors of the Z and Y rays have a slight orange cast. Not enough specimens were studied to determine any systematic variation for the pleochroism. A specimen collected from just below Twin Lakes shows bands several centimeters wide which are almost entirely composed of biotite. As no known sedimentary rock has such a composition, these bands have probably resulted from metamorphic differentiation. A few rocks in this part of the section are free of biotite belonging to the main synkinematic mineral assemblage. In such rocks the biotite, where present, occurs in minute, irregular patches and along the amphibole cleavage planes, indicating a later alteration of the amphibole.

The amphibole is most commonly a green hornblende whose pleochroism is: X = light tan; Y = slightly brownish,dark-medium green; and Z = slightly bluish,brownish medium green.Its absorption seems to be $Y \geqslant Z \gg X$. The extinction angle Z:c on (010) is about 16°. The hornblende usually has anhedral to subhedral crystalloblastic form and fine to medium grain size. It seems to have developed under both synkinematic and static conditions of the regional metamorphism. Synkinematic conditions are indicated by subhedral green hornblende crystals, nearly free of inclusions, whose c axes lie in the foliation planes. In other rocks, static conditions of growth are indicated by anhedral, porphyroblastic crystals, full of inclusions of quartz, plagioclase, graphite and occasionally biotite. Undeformed delicate projections of this mineral along the intergranular prove static recrystallization. Graphitic inclusions form an internal s which is parallel to the foliation planes. Usually a courser grain size is associated with the static growth. The pleochroism and the extinction angles of these poikiloblastic hornblende crystals are essentially the same as those of the synkinematic crystals. The statically recrystallized hornblende has grown mimetically in the foliation planes in most instances. Near Lime Lake occurs an amphibole whose optical properties vary from the more common green hornblende discussed above. The optic angle of this mineral is nearly ninety degrees which accounts for the fact that in different positions of rotation, an almost centered optic axis figure seems to give both positive and negative signs. The extinction angle Z:c on (010) is nineteen degrees. The pleochroism is X = colorless; Y = light tannish green; and Z = pale bluish, greenish tan. According to data given by Winchell (1951), the mineral is probably an iron-rich member of the cummingtonite series. Radiating aggregates of the cummingtonite, which are in random orientation to the schistosity, make the rock a garbenschiefer. At several other localities of this part

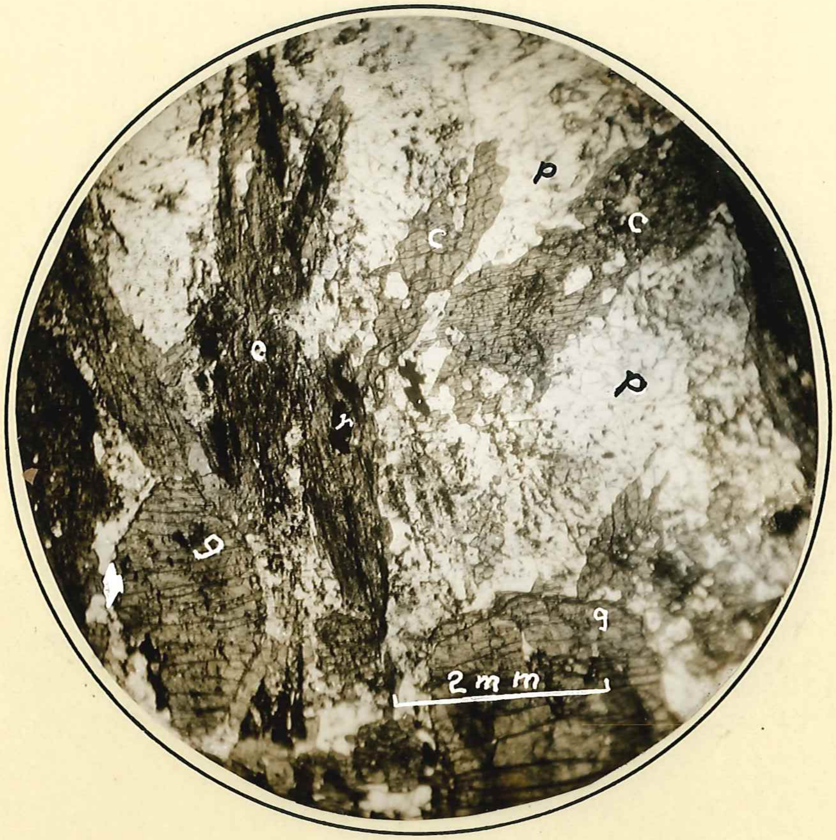


Figure 3.

Cummingtonite garbens (c) in a garnetiferous garbenschiefer from the Green Mtn. unit. Note the garbens transecting the schistosity marked by graphitic bands which form an internal s in the two central and nearly vertical cummingtonite crystals. (p) = coarsely recrystallized plagioclase; (g) = garnet ; (r) = rutile.

Specimen 9-6-55-6, collected from station 166 on the ridge northeast of Lime Lake.

Plane light.

of the section, garbenschiefer are present which contain aggregates of green hornblende lying in the foliation planes.

Plagioclase is fine to medium grained and is most commonly anhedral to subhedral. Zoned crystals seem to be somewhat more common in these rocks than in the biotite schists. The zoning is anhedral and gradational as in the biotite schists. Slight normal zoning with An_{35} to An_{40} cores is the most common type; however, slight reverse and oscillatory zoning also occur. A thin section of a specimen collected from just east of Mica Lake contains several crystals with one oscillation around cores of andesine averaging An_{40}. The much coarser grain size of the plagioclase suggests, but does not of course prove, soda metasomatism. The higher anorthite content of the plagioclase in these rocks from Lime Lake and the presence of main assemblage epidote minerals indicate that a slightly higher temperature - warmest mesozone - occurred than in the more common green hornblende bearing schists. The association of plagioclase plus epidote minerals is critical for temperature zoning (Misch, unpublished manuscript). The epidote minerals hold potential anorthite component which, if the temperature rises, causes a more calcic plagioclase to form.

Very rare secondary clinozoisite has formed by alteration of the plagioclase, which is indicated by its occurrence within some of the plagioclase grains; its growth was somewhat controlled by the cleavage planes of the host mineral. Almost without exception, such secondary epidote minerals occur only within the porphyroblastic types of plagioclase. The clinozoisite and zoisite and the less common pistacite essentially belong in the main synkinematic mineral assemblage and therefore act as a potential anorthite reservoir upon which the plagioclase can draw for calcium if a temperature rise occurs.

Other minerals such as quartz and garnet essentially occur in the same manner as in the biotite schists and therefore are not described again.

Interpretation

The rocks from the section of the Green Mtn. unit described above have undergone regional metamorphism, and in general the crystallization has lasted at least as long as, if not longer then, the penetrative deformation. This is indicated by the widespread occurrence of crystallization foliation in the schists. Locally, crystallization has lasted into static conditions following the period(s) of deformation as is indicated by the amphibole garbenschiefer in which the garbens transect the schistosity. Even more locally, rotated minerals such as garnet indicate that in other areas deformation has outlasted the crystallization. Local late weak shearing has also occurred.

Exact temperature zoning in the biotite schists is made rather difficult by the lack of a critical mineral assemblage. The presence of oligoclase-andesine (averaging An_{30}) suggests a medium to warmer mesozonal temperature. The occurrence of kyanite in similar rocks to the west also indicates temperatures of the warmer mesozone. The plagioclase of the kyanite-bearing rocks is slightly more sodic than that of the kyanite - free biotite schists, obviously owing to a lower calcium content of the Al-excess mineral bearing rocks. In the hornblende-bearing schists, the equilibrium assemblage of andesine (An_{35}) plus epidote minerals concurs with the medium to warmer mesozonal temperatures found in the associated rocks.

The sediments from which the rocks of this portion of the Green Mtn. unit have been derived must have been quite varied. The biotite schists have been derived in general from an argillaceous type of rock. The high quartz content probably indicates a sandy component to this parent rock. One or two of the rocks studied probably were derived from slightly impure quartzose sandstones. The rather high percentage of plagioclase in most of these rocks suggests that the parent sediment had a component of clastic feldspar and thus was geochemically still immature. The complete absence of visible potash feldspar suggests that the parent material may have been derived, at least in part, by incomplete weathering from a quartz dioritic terraine. If the potash is held within the plagioclase, this is not apparent as the rocks are free of antiperthite. No evidence of a general soda metasomatism is present. The kyanite in these rocks indicates that certain layers of the argillaceous sediment were richer in aluminum than others. A gradual increase in the amount of green hornblende from zero in the biotite schists to nearly forty per cent in the hornblende-rich schists, to more than seventy per cent in the para-amphibolites (discussed in the next chapter) probably represents a gradual increase of dolomitic and/or tuffaceous components in the original argillaceous sediment. As mentioned earlier, this overall gradation from biotite schist to hornblende-rich schist is in detail that of interlayering and interbanding. This repetition may indicate a higher, purer argillaceous unit and a lower, tuffaceous or dolomitic argillaceous unit, with a transitional member in which both rock types were interbedded, possibly with an overall upward increase in the purer argillaceous sediment. Tectonic repetitions have also undoubtably occurred to some extent.

Amphibolites

Para-amphibolites

Para-amphibolites are scattered throughout the area of amphibolites and hornblende-biotite schists which is represented on the accompanying geologic map. No continuous member of para-amphibolites could be defined within the Green Mtn. unit, however this may be due to the impossibility of distinguishing them from ortho-amphibolite or from many of the hornblende-bearing schists in the field. Microscopically they are easily recognized by their greater chemical variability and distinctly lesser plagioclase content than the ortho-amphibolites. Theoretically they would grade into the hornblende-bearing schists as the amount of hornblende decreases, however this gradation was not observed in the field. In this report the arbitrary boundary between para-amphibolite and hornblende-bearing schist of forty per cent amphibole content is used to separate them. This amphibole content is also used by Bryant (1955, page 89) to separate para-amphibolite from hornblende-bearing schist in the Green Mtn. unit north of the Suiattle River.

The hornblende content of these rocks varies from fifty to eighty per cent and averages about sixty per cent. Plagioclase varies from fifteen to forty per cent and averages thirty per cent. Quartz ranges from five to fifteen per cent. Biotite varies from zero to ten per cent. Lime-silicate minerals are present in a few of the para-amphibolites in amounts ranging from a few to eight per cent. Accessory minerals are: sphene, magnetite, and garnet.

The hornblende is fine to medium grained, but the finer grain sizes predominate. Hornblende is xenoblastic to subidioblastic and shows no porphyroblastic tendency. The pleochroism of the hornblende is: X = pale-tan; Y = slightly brownish, dark-medium green; and Z = medium-dark green. The extinction angle Z:c on (010) is about ninteen degrees.

Plagioclase is xenoblastic to subidioblastic and is fine to medium grained. The plagioclase is usually normally zoned with cores varying from An_{40} to An_{45} and rims varying from An_{25} to An_{35}.

Quartz is xenoblastic and fine to coarse in grain size. It occurs both in segregation veinlets and disseminated within the assemblage of the amphibolite. The coarser grain sizes occur in the veinlets whereas the finer grains are in the amphibolite assemblage.

Ortho-amphibolites

Ortho-amphibolites are rather common in the eastern part of the Green Mtn. unit in the Sulphur Mtn. area. In the Snowking area, Bryant (1955) also found the amphibolitic members to be in the eastern part of the Green Mtn. unit. In the present area they occur mainly on Glacier Peak Ridge and on the ridge of Grassy Point. They also occur in the valley of the Suiattle River where they are well displayed along with para-amphibolites at the end of the Suiattle River road and from there on, in intermittant outcrops along the Suiattle Pass trail. Along this trail they are interlayered and interbanded with para-amphibolites, hornblende-biotite schists, minor garnet-biotite schists, and occasional lenses of white to grayish and slightly banded marble. South of Grassy Point they are associated with very minor lime-silicate-mineral-bearing para-amphibolites. On Grassy Point some of these amphibolites contain porphyroblastic plagioclase on a scale which requires them to be termed allochemical (Cf. definition in Introduction, p.12). All stages of the transition from isochemical ortho-amphibolite, through slightly feldspathized amphibolite, to porphyroblastic amphibolitic schist, to hornblende-bearing augen gneiss, and finally to homogeneous trondhjemitic gneiss, are present from the southern slopes to the northern slopes of Grassy Point. This transition will be described in more detail in a later chapter (p.54). Although lush and widespread grassy alpine meadows obscure many of the relationships, these changes appear to occur in part along the strike of these units. To the north, just across the Suiattle River from Grassy Point, are the migmatitic trondhjemites of Sulphur Mtn. whose relict foliation trends southerly: toward the amphibolites of Grassy Point. Although no single member of isochemical amphibolite could be followed through all the stages into trondhjemite, it is probable, both on structural and petrographic evidence, that the migmatitic trondhjemites have been formed, at least in part, from the amphibolites of Grassy Point. At the southern end of Glacier Peak Ridge, near the contact of the metamorphics and the Glacier Peak lavas, the amphibolites again become rather strongly feldspathized and merge into medium to coarse-medium grained hornblende-bearing migmatitic gneisses. These rocks are discussed on pages 71-75. The attitudes of the foliation of these migmatitic gneisses are approximately the same as in the associated amphibolites.

Megascopically, the ortho-amphibolites are medium to dark greenish colored, and fine to fine-medium in grain size. Both in hand specimen and in thin section, these rocks commonly have a somewhat banded appearance. (See figure 4.) In the field, cross-cutting veins and dikes, as well as more subordinate concordant veins of leucocratic material, are rather common. Offsetting of some of the leucocratic bands in the amphibolites by these later cross-cutting dikes is of the magnitude required by the width of the dikes which indicates that emplacement by dilation has occurred (Goodspeed, 1940). In other dikes a lack of offsetting testifies to a replacement origin. Some of the veins which are parallel to the schistosity probably represent synkinematic segregations of acidic materials.

Microscopically, the ortho-amphibolites contain from forty-five to seventy per cent green hornblende, which averages about sixty per cent. Plagioclase, which varies from twenty to fifty per cent and averages about thirty-five per cent, has a composition which ranges from An_{27} to An_{40} and averages about An_{34}. Quartz varies from zero to fifteen per cent but averages less than five per cent. Epidote-group minerals comprise from zero to five per cent of the rock;the most common ones are pistacite and clinozoisite,but zoisite also is present. Sphene is the most common accessory mineral and in one specimen it makes up nearly three per cent of the assemblage. Rutile is a less common accessory and apatite occurs rarely. Biotite is a local accessory which occurs as an alteration product of green hornblende.

The hornblende is of fine to medium grain size and ranges in crystalloblastic form from anhedral to euhedral, with the subhedral type predominating. The pleochroism is: X = pale tan; Y = slightly brownish-olive, dark-medium green; and Z = medium green with a slight bluish tinge. The absorption is $Y \geq Z \gg X$. The extinction angle Z:c on (010) varies from seventeen to ninteen degrees. No porphyroblastic tendency of the green hornblende is present, and,except for minor sphene and rutile, it is free of inclusions. The hornblende crystals are usually aligned in a planar fashion, thus producing well developed s planes. Microscopically a b dir-

Figure 4.

Typical isochemical ortho-amphibolite from the Green Mtn. unit. The slight, but rather distinct banding shown in the photograph is common to nearly all of these rocks. The amphibole mineral is green hornblende. Most of the tiny dark grains, especially evident in the central light band, are sphene crystals. The colorless grains are all plagioclase.

Specimen 9-4-55-2, collected from station 129, on Glacier Peak Ridge.

Plane light.

ection is present in some specimens, but not well enough developed to be seen in hand specimen.

Plagioclase is predominately anhedral and fine grained, but occasionally becomes subhedral and medium grained. Polysynthetic twinning is rather rare in the rocks studied. Anhedral and gradational zoning is common, and is exhibited to some extent by between one-quarter and one-half of the plagioclase grains. Due to the small grain size and the poor development of cleavages and twinning, the exact type and amount of zoning is rather difficult to determine in most samples. In those grains which are identifiable, normal zoning seems to predominate with An_{35} to An_{40} cores and slightly more sodic rims. Some reverse and oscillatory zoning with only one recurrence also are present. Much of the plagioclase shows minor alteration to secondary epidote minerals and much less commonly to sericite.

The quartz, which varies from zero to fifteen per cent, never comprises more than five per cent of the mineral assemblage of the groundmass. Its most common occurrences are in the acidic segregations and the cross-cutting veinlets described above. In the groundmass, the quartz occurs as small, anhedral and separate grains. In the acidic segregations, it occurs as medium to coarse grained anhedral aggregates showing sutured grain boundaries and commonly exhibiting weak undulatory extinction. Clinozoisite and epidote are commonly associated with the quartz in these segregations.

Minor late, weak stresses have operated in these rocks causing fracturing, micro-faulting, some granulation of the minerals, and probably the undulatory extinction of some of the quartz.

Metamorphic Hornblendite

Associated with the amphibolites on Grassy Point are medium to coarse grained, dark green hornblendites which occur as massive, dike-like bodies cutting across the schistosity of the adjacent rocks. The only occurrences of these rocks found are immediately east of the summit of Grassy Point. The dimensions of the masses were unobtainable due to poor exposures however one of the dikes had an approximate width of five feet and extended for an undetermined distance on its long axis. Microscopically, these dike-like bodies are composed of from seventy to ninety per cent amphibole, possibly a "bleached" brownish hornblende. The nature of the "bleaching" is uncertain, but it probably involves removal of the ferric iron which causes the more normal brownish absorption. The pleochroism of this "bleached" amphibole is :X = colorless; Y = a mottled, slightly brownish to slightly olive- light greenish, to colorless; and Z = a mottled, light brownish-green to light green to colorless. The mottled brownish cast to the absorption colors of the Y and Z rays seems to rule out actinolitic hornblende or a common green hornblende; rather, its patchy brownish appearance suggests a bleaching-out of an earlier more uniformly colored brownish hornblende. Irregular inclusions of secondary biotite (Z = Y = light yellowish to orangish brown, and X = pale tan) are common in the amphibole crystals. The hornblende crystals have sutured boundaries where they are in mutual contact. The Y and Z rays usually become colorless at this contact. (See figure 5.) The hornblende often is colorless for small distances in parallel zones which are parallel with the cleavage planes of the mineral. This seems to indicate that the bleaching action may have commenced at the intergranular areas and then proceeded along the cleavage planes. In the areas of the crystals of hornblende which still have a brownish cast, the extinction angle Z:c is about 17° (no perfect optic normal section was found). In those portions of the crystals which have become colorless, the extinction angle shows a very slight increase. Besides biotite, the other accessory minerals are plagioclase, zoisite, epidote and sphene. A few weakly pleochroic haloes are present around tiny sphene inclusions within some of the biotite. These hornblendites possibly represent metamorphosed pyroxenites, although all traces of former pyroxene have been eliminated.

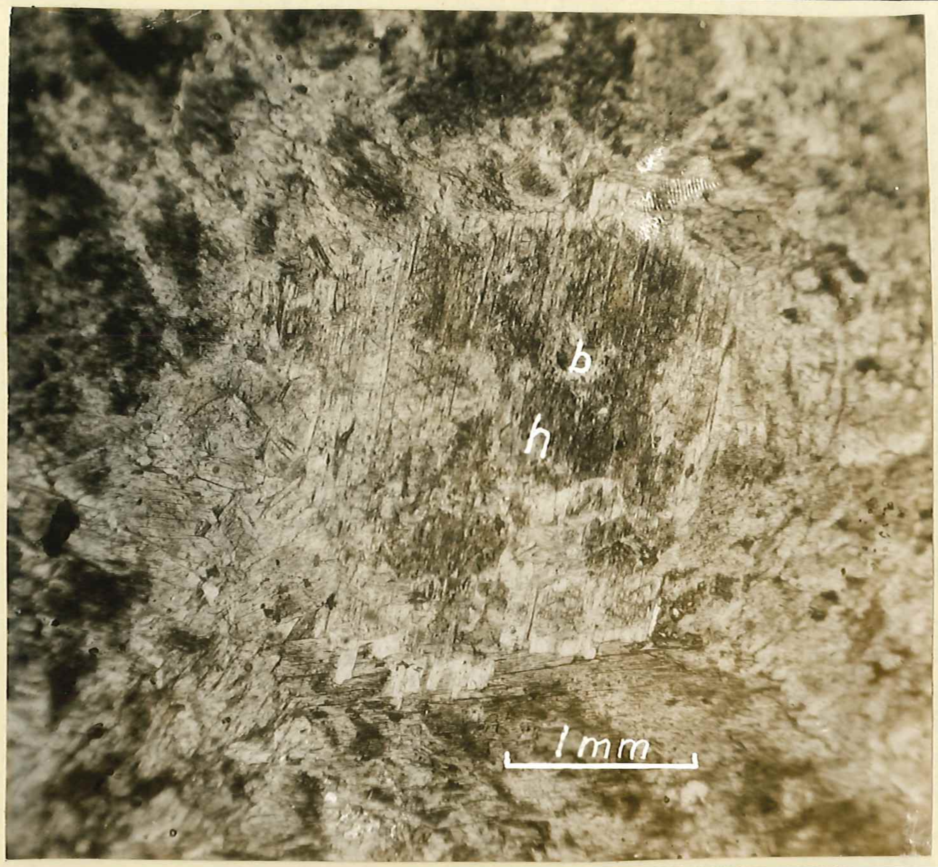


Figure 5.

Massive metamorphic hornblendite. The hornblende (h) is irregularly bleached and thus shows a patchy brownish pleochroism. The bleaching is most pronounced at the grain boundaries and along some of the cleavage planes. Note the sutured grain boundaries and the colorless Z ray near the grain contacts. Inclusions of biotite (b) and tiny sphene crystals are common.

Specimen collected from station 116, in the col just east of Grassy Point.

Plane light.

Summary

The Green Mountain unit seems to be a typical eugeosynclinal sequence which has been metamorphosed essentially under warmer mesozonal, synkinematic conditions of regional metamorphism. In local areas, deformation has slightly outlasted crystallization, whereas in other local areas crystallization has outlasted the deformation. Metamorphism was essentially isochemical throughout most of the area in which these rocks occur (see accompanying geologic map). Gradations between these isochemical rocks and migmatitic rocks occur on Grassy Point and near the head of Milk Creek and East Fork of Milk Creek.

The original geosynclinal sediments and volcanics from which the rocks of the Green Mtn. unit were derived, seem to have been a sequence of shales, limy shales, shaly limestones, tuffs and basic volcanics. These rocks were metamorphosed into biotite schists, hornblende-bearing schists, lime-silicate-hornblende schists,para-amphibolites and ortho-amphibolites. Occasional lenses and small bands of marble indicate that pure limestones were rather scarce in the original sedimentary sequence.

Temperatures of metamorphism seem to have been within the warmer part of the mesozone throughout the Green Mtn. unit. Kyanite,which occurs in some of the biotite schists near Fire Mountain, and the stable association of sodic andesine with epidote minerals in the hornblende-bearing rocks, are the critical mineral and mineral associations which indicate the temperatures of metamorphism. Diopside is locally present in lime-silicate bands and veinlets in a few of the amphibolites on Grassy Point and Glacier Peak Ridge. As the diopside is contemporaneous with epidote in these lime silicate bands, a temperature of the warmest mesozone is established.

Migmatitic and Granitic Rocks

Introduction

Before a discussion of the rocks which have undergone allochemical metamorphism in the Sulphur Mtn. area is attempted, the definitions of some of the terminology should be stated as used in this report. A "granitic" rock is a medium to coarse grained, leucocratic rock which may vary in composition from a true granite, through a quartz monzonite, a granodiorite, a trondhjemite, to a quartz diorite or even to a leucocratic diorite. No genetic significance is attatched to the term because, as evidenced in the area described, a granitic rock may form by crystallization from a dominantly liquid mass or by recrystallization and replacement of a pre-existing rock in the solid state by metasomatic processes. This latter mechanism is usually termed "granitization", which

> "...includes a group of processes by which a solid rock (without enough liquidity at any time to make it mobile or rheomorphic) is made more like a granite than it was before, in minerals, or in texture and structure, or in both." (Grout, 1941, p. 1540.)

As Misch (1952a and 1952b) has demonstrated elsewhere in the northern Cascades, such a granitized mass may become intrusive into adjacent rocks, either remaining essentially solid ,or becoming partially or even completely liquified. The term "intrusive" indicates only a mode of emplacement of a rock mass and carries no connotation as to the degree of liquidity of the mass. A "migmatite" is a heterogeneous metamorphic rock usually composed of more coarser grained granitic portions and more finer grained and darker remnants of an earlier metamorphic rock. In this sense, the term is chiefly a descriptive one. The term "migmatitic" is used to describe a granitic rock (see definition above) or a homogeneous gneissic rock which can be demonstrated to have been derived from migmatite, but which may have lost the high degree of heterogeneity characteristic of migmatites (restricted). Inclusions in a granitic rock, if of unknown origin will be merely called "inclusions". If the inclusion is an actual remnant of the original metamorphic rock, the term "relict" is used, and if the relict is indistinct and shadow-like the term "skialith" (Goodspeed, 1948, p. 515.) is applied. If the inclusion is foreign to the enclosing granitic rock, it is called a xenolith, following Goodspeed's genetic classification.

A three-fold classification of grain sizes will be used in the rock descriptions: fine, medium, and coarse. If the average diameter is less than one millimeter the rock is fine grained;if between one and five millimeters it is medium grained, if from one-half to three centimeters it is coarse grained,and if more than three centimeters it is very coarse grained.

Nearly directionless granitic rocks are found at several localities in the mapped area. On the basis of only a single hand specimen of each, the various genetic types are indistinguishable (compare figure 7 and 9 with figure 19), whereas in the total aspect of both field and microscopic relationships, a separation is possible. The Sulphur Mtn. trondhjemites have formed by metamorphic processes from a hornblende-bearing rock, at least in part probably an amphibolite. The intermediate gneissic phases of this transformation are common, whereas nearly isochemical relicts are rare. The granitic rocks found on the western end of Miners Ridge, from Image Lake to just beyond the confluence of Canyon Creek and the Suiattle River,have formed by the crystallization of a dominantly, if not completely, liquid intrusive mass. Certain textural and mineralogical features indicate that complete liquification of the parent material possibly did not occur. A possible intermediate type in this series of granitic rock evolution is present on the western spur of Grassy Point in which intrusion of plastic, but entirely crystalline, material has occurred. In the following chapter, the field and petrographic relationships of each type will be described, and in the final chapter a summary will be given in which the criteria for each will be compared and contrasted as found in the Sulphur Mtn. area.

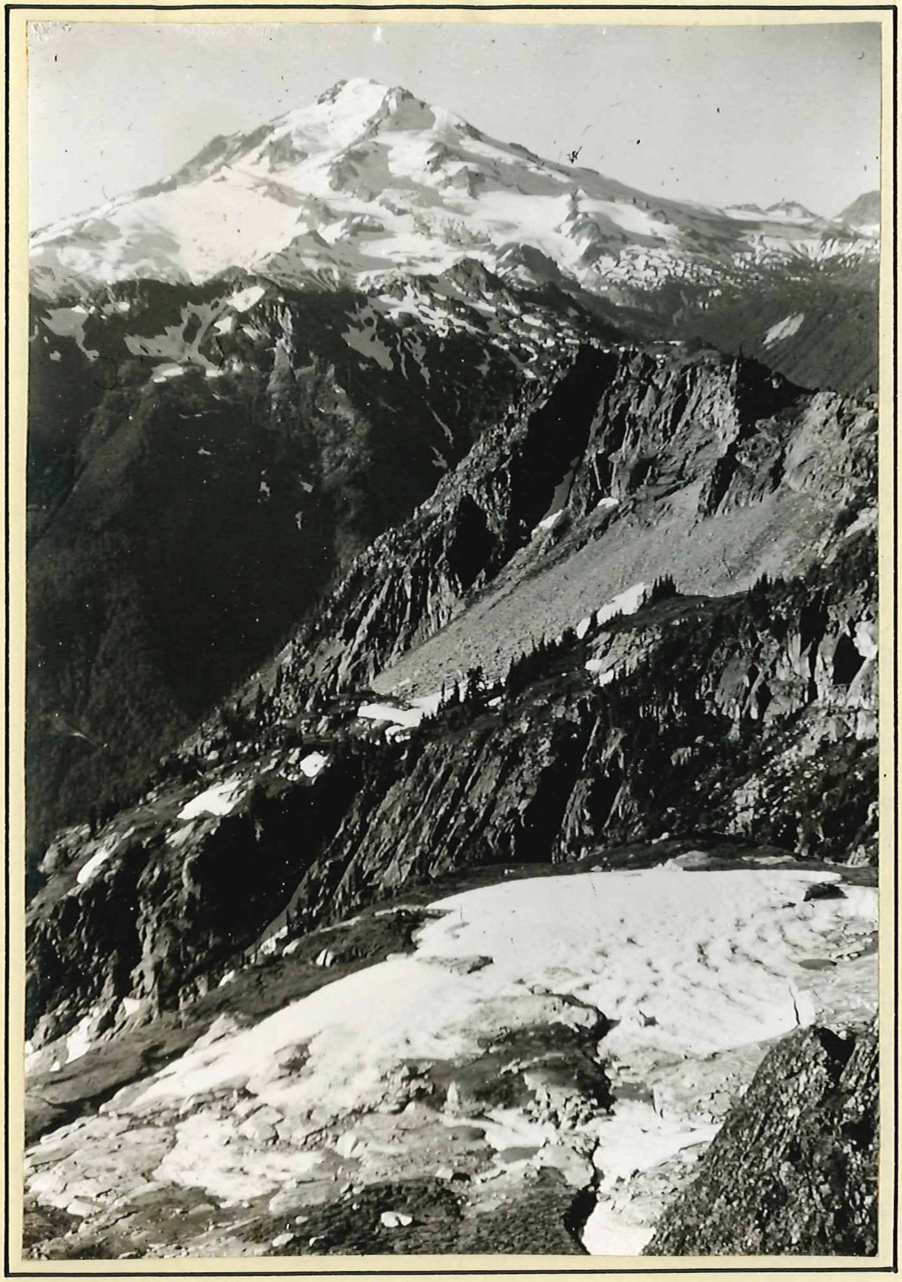


Figure 6.

Glacier Peak from ridge east of Sulphur Mtn. Rocks in foreground and on the near ridge in the right-center of photograph are leucocratic, migmatitic trondhjemites. Distant ridge below Glacier Peak in left-center of photograph is the ridge of Grassy Point, which is composed of trondhjemitic gneisses, amphibolites, and hornblende-bearing schists.

Sulphur Mtn. Trondhjemites of Migmatitic Origin

General Statement

Migmatitic trondhjemites and locally granodiorites form the central zone of the Sulphur Mtn. area, extending from the isochemical rocks of the Green Mtn. unit on the west to the migmatitic gneisses in the vicinity of Totem Pass on the east, a distance of over six miles across the strike. No contact was observed with the Green Mtn. unit as exposures are poor in the timber between Sulphur Mtn. and the Suiattle River. The contact is, however, probably a gradational one, as the trondhjemites become more strongly gneissose west of Lookout Lake. Just east of Bath Lake, these coarse grained migmatitic trondhjemites gradually merge into medium to fine grained migmatitic gneisses that lack the static recrystallization and minor potassium introduction which characterize the Sulphur Mtn. granitics. To the south, between the Suiattle River and Grassy Point, part of these granitics pass into the amphibolites of the Green Mtn. unit, but east of Grassy Point the relationships have not been studied. About seven miles northwest of Sulphur Mtn. near Bench Lake, Bryant (1955, page 138) has also mapped trondhjemitic gneisses which he has described as:

> "... microcline-bearing trondhjemitic gneiss containing 60% fine to coarse grained, anhedral plagioclase that is normally zoned with a range from An_{35} in the core to An_{23} on the rim. It includes quartz and biotite. Fine to fairly coarse grained, anhedral quartz constitutes 25% of the rock. Microcline replaces plagioclase starting from the grain boundaries. Biotite (10%) is late-kinematic and post-kinematic... Clinozoisite is associated with biotite... Muscovite occurs in scattered, medium sized to fairly large crystals... Orthite, garnet, apatite, sphene, and sericite are the other accessories. The sericite is late."

He concludes by stating (p.139):

> "The metasomatized rocks below Bench Lake were derived from hornblende(?) mica schists and underwent metasomatism accompanied by considerable late-kinematic and static recrystallization. Mainly soda was introduced, but some potash may have been added. Silica may have been introduced locally."

On the Bench Creek - Downey Creek divide, Bryant (p.138) has found quartzites, lime-silicate schists and amphibolites to be conformably interbedded with the trondhjemitic gneisses. The ridge between Downey Creek and Sulphur Creek, separating the Sulphur Mtn. migmatites from those at Bench Lake, has not as yet been mapped, nevertheless there can be but little doubt of their being essentially the same unit. To the south, no rocks have yet been mapped which belong in this unit.

In the field, these rocks are seen to be commonly slightly gneissose, medium to coarse grained, leucocratic granitics. All gradations are present between finer grained, strongly gneissose varieties and the coarsely recrystallized types with only vestiges of the former schistosity. Characteristic of this granitic rock is the development of quartz porphyroblasts which stand out in relief on a weathered surface. These porphyroblasts range from five to ten millimeters in diameter. Where later shearing has occurred as in specimen 8-24-55-5 (see figure 8), they have been dragged out to about fifteen millimeters. Also characteristic is the occasional development of coarse to very coarse grained pyroxene porphyroblasts with a subidiomorphic habit. These pyroxenes average three centimeters by five millimeters in size and are usually in random orientation to the schistosity, indicating static growth. Specimen 8-21-55-7 (figure 9) shows these pyroxenes to be somewhat mimetic after s. At one locality about three-quarters of a mile northeast of Sulphur Mtn., these porphyroblasts of pyroxene have attained a size of about six by seven-tenths centimeters. Usually they have been completely weathered and now only appear as rusty, limonitic areas.

Relict Inclusions

A few nearly isochemical relicts found at widely scattered outcrops within the trondhjemitic gneisses and granitics of Sulphur Mtn. provide another insight into the nature of the parent rock type from which the granitic rocks have been derived by the processes of granitization. The mineralogy of these relicts concurs with the structural relationships previously described, indicating that the Sulphur Mtn. granitics have formed at least in part from an amphibolitic terrane such as found on Grassy Point to the south. A few such relicts were observed in a col on the northwestern spur of Sulphur Mtn., in the cirque just north of Sulphur Mtn., and in the headwall of the cirque containing a small unnamed tarn east of Sulphur Mtn. The attitudes of the foliation in the relicts is always parallel to the attitudes of the foliation, where discernable, in the surrounding gneisses and granitics. Nearly all of the stages in the transformation from the isochemical relicts to faint, indistinct, and shadowy

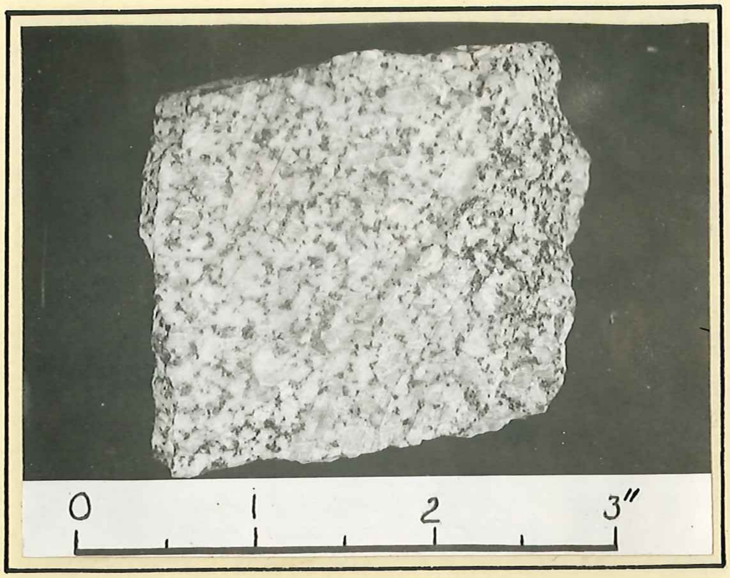


Figure 7.

Nearly directionless, homogeneous quartz diorite of migmatitic origin collected from station 12, about one mile west of the confluence of Canyon Creek and the Suiattle River. Quartz, although present in much lesser amounts than in the usual Sulphur Mtn. granitic rock, still has a porphyroblastic habit. (Specimen #7-2-55-12)

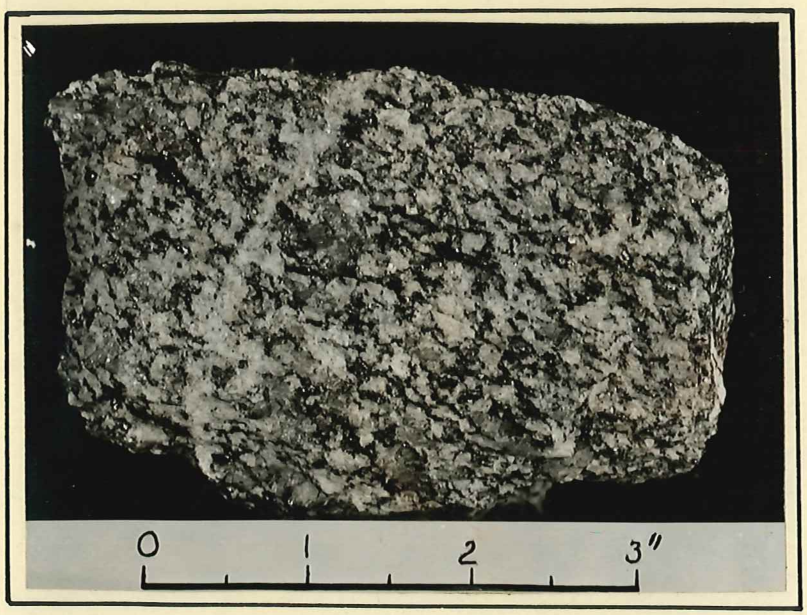


Figure 8.

Trondhjemitic gneiss of migmatitic derivation collected from station 88 on the ridge about one mile east of Bath Lake. Note the porphyroblastic habit of the quartz. A post-kinematic replacement veinlet of feldspar and quartz appears on left. (Specimen #8-24-55-5)

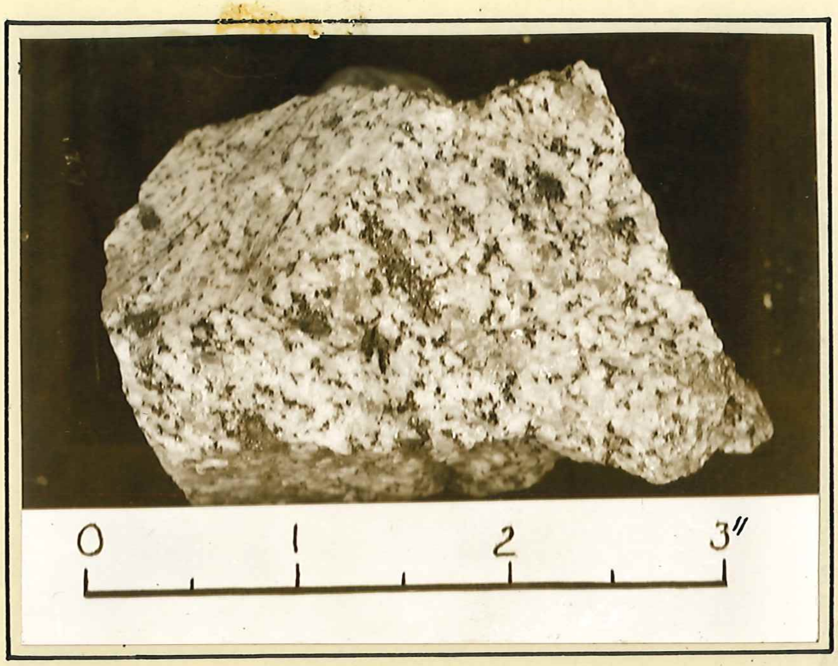


Figure 9.

Slightly gneissic, pyroxene - bearing trondhjemite collected from the summit of Sulphur Mtn. Note the porphyroblastic tendency of the quartz and the long crystals of pyroxene which appear as dark reddish stains in the rock due to weathering. In this specimen, the pyroxene has grown mimetically after the schistosity.

(Specimen #8-21-55-7)

relicts or skialiths which have undergone almost complete feldspathization are present in scattered outcrops within this trondhjemitic unit.

One such relict inclusion, collected from the northwestern spur of Sulphur Mtn. just south of Lookout Lake, is a highly contorted and folded ortho-amphibolite. Mineralogically, this relict is very similar to some of the ortho-amphibolites found just across the Suiattle River on Grassy Point (cf. Green Mtn. unit: Ortho-amphibolite, page 28). Whereas the amphibole mineral of the Grassy Point amphibolites is a green hornblende, the amphibole of the relict inclusion is an actinolitic hornblende. This relict amphibolite has the following mineral composition: 55 per cent actinolitic hornblende with an extinction angle Z:c on (010) of 18°, and a pleochroism of Z = Y = light green, and X = colorless; 40 per cent plagioclase which is unzoned and untwinned and whose composition is difficult to determine because of almost total obliteration of cleavages by sericite, although one slightly imperfect MP section seemed to indicate a sodic andesine; 2 per cent anhedral biotite which has locally formed as an alteration product of the amphibole; 1 to 2 per cent sphene; and accessory chlorite which has locally formed as an alteration product of the amphibole or of biotite.

Cataclastic textures predominate in this rock. The foliation planes exhibit a strongly contorted structure, as seen microscopically. These planes of foliation ($\underline{s}_1$) have been disharmonically deformed and folded, and where overturning of these micro-folds has occurred, an incipient $\underline{s}_2$ has developed in the stretched and thinned overturned limb. The alteration of the amphibole to biotite seems to have been controlled by some of the zones of shearing. The migmatitic trondhjemites which surround this relict inclusion are free of any effects of post-crystalline deformation. The deformation of the relict amphibolite must have taken place, therefore, prior to the last stages of the crystallization of the trondhjemites.

In general, this inclusion of relict amphibolite has remained essentially isochemical while the original surrounding rocks, also probably amphibolites, have been almost completely feldspathized and recrystallized. A few small plagioclase porphyroblasts whose composition is undeterminable due to complete alteration to sericite have developed and later, or possibly concomittantly, become slightly rounded by the shearing. The alteration of the amphibole to biotite along certain shear zones could be interpreted as evidence for minor potassium introduction along these zones of movement. Another interpretation might be that the shearing action has caused, or at least localized the effects of, a release of potassium held within the plagioclase crystal lattices. Thus the conclusion is reached that this relict amphibolite has remained essentially isochemical. No structural, or other control was determinable which would account for the isochemical nature of the relict, and therefore it may have only been the result of a fortuitous escape from the nearby conditions of granitization.

Homogeneous Trondhjemitic Gneisses

Throughout the area of the trondhjemitic unit of Sulphur Mtn., more strongly gneissose rocks occasionally crop out. They are usually measurable in only a few tens of feet across their strike. The sharp and distinct foliation of these gneisses gradually becomes undefinable as the more granitic appearing trondhjemites which comprise the bulk of this unit are approached. The foliation in these gneisses is parallel with the overall structural trends of the adjacent rocks. These trondhjemitic gneisses have a rather homogeneous gross appearance, whether on the scale of the field outcrop, the hand specimen, or even under the microscope. The mineral constituents of the gneisses seem to be rather evenly distributed and therefore the gneissose structure is shown by the preferred orientation of such elongate darker minerals as biotite and hornblende. Elongate masses of quartz also aid in lending a gneissic appearance to the rock. No banding or lit-par-lit structures are present. These gneisses, as well as the surrounding granitic rocks, are frequently transected by both replacement and dilation types of leucocratic aplite and pegmatitic dikes.

As mentioned earlier, no contact was observed between the trondhjemites and the isochemical rocks of the Green Mtn. unit to the west. On Downey Mtn., just across Sulphur Creek from the Sulphur Mtn. granitics, Bryant (1955) mapped an intrusive contact of trondhjemite, probably mobilized, against the schists and amphibolites of the Green Mtn. unit. The relationships of this intrusive mass to the rocks farther east on the Downey Creek - Sulphur Creek divide have not as yet been studied. Except for a rather small mobilized mass of trondhjemite against the amphibolites site in these clusters. The biotite is well aligned and thus is primarily responsible for the gneissic structure of the rock. Some of the grains of green hornblende give a suggestion of a porphyroblastic tendency and show minor sieve textures. Several of these green hornblende crystals exhibit a very marked elongation in a direction nearly normal to their c axes. Such an elongation gives the suggestion that the growth of the hornblende was not active but rather was due to a passive growth along any available channel such as fractures or the intergranular areas. This process has been termed by Misch (unpublished manuscript)"passive poikiloblastic growth", and is the result of a relegation of basic constituents such as iron, magnesium, and possibly calcium to the intergranular areas by the more actively growing crystalloblasts of feldspar. Such hornblende rarely becomes even subhedral in crystal form whereas the smaller, non-porphyroblastic crystals of green hornblende range from xenoblastic to idioblastic.

The clinozoisite, which has formed from the calcium released during the biotitization of the hornblende, forms clear and anhedral grains and seems to be in equilibrium with plagioclase where these two minerals are in contact. Biotite is nearly always associated with the clinozoisite: relict hornblende less commonly. Easily distinguishable from this type of epidote mineral is the fine-grained and patchy epidote whose growth has been controlled by the cleavages of the plagioclase of which it is an alteration product. In the gneisses being described, the plagioclase is usually fresh and clear and shows only local and minor alteration to epidote.

The gneissose structure of these rocks is somewhat strengthened by the sheared-out quartz lenses. These quartz lenses give the rock a rather distinctive appearance in hand specimen. Microscopically,they are composed of aggregates of medium to coarse grained, anhedral quartz crystals with sutured boundaries which ubiquitously exhibit undulatory extinctions. Partially enclosing several of these quartz lenses are polygonal arcs of biotite. This seems to indicate that, at least in part, silica introduction was contemporaneous with the crystallization of biotite. Silica metasomatism must have occurred if the pre-metasomatic rock was an amphibolite as structural and other evidence indicates. Local, late fractures have formed in the rock, which have been filled and healed by quartz.

Other gneissose portions of the Sulphur Mtn. unit are very similar to those previously described whereas still others vary somewhat from them.

This variation is probably dependant essentially upon two factors. The composition of these rocks prior to the time of granitization was probably just as highly varied as that of the isochemically preserved Green Mtn. unit to the south, since part of the trondhjemites seem to show structural continuity with the eastern portions of this more isochemical unit. Secondly, the intensity of the granitization was probably not everywhere exactly equal. In general however, the high degree of heterogeneity within the Green Mtn. unit has been greatly decreased in the migmatitic rocks to the north. The variations within the Sulphur Mtn. granitics were not correlatable to individual members within the Green Mtn. unit due to poor exposures in the critical transitional areas.

On the arete separating the two cirques which contain small unnamed tarns just east of Sulphur Mtn., fine to medium grained homogeneous gneisses also crop out. These gneisses are even more homogeneous than those described above, as they lack the characteristic quartz lenses and are richer in biotite and hornblende which are distributed very uniformly throughout the rock. In hand specimen, the rock appears almost schistose. These migmatitic gneisses are composed of about 65 per cent fine to medium grained anhedral plagioclase of which a few crystals show anhedral and gradational reverse zoning with An_{25} cores and about An_{35} rims. The mafics, green hornblende and biotite are about equal in amount and together make up 25 per cent of the rock. Clinozoisite constitutes from 2 to 3 per cent of the assemblage. Quartz, in contrast to its abundance in the granitics elsewhere in this unit, comprises only about 5 per cent of the rock. About 1 per cent sphene is present. Locally, muscovite occurs in accessory amounts as small grains which lie across the foliation. The biotite is anhedral to subhedral and is fine to medium in grain size. Its pleochroism is Z = Y = medium brown with a slight orange tinge, and X = pale, faintly yellowish tan. The biotite is frequently associated with anhedral grains of clinozoisite. The green hornblende is also fine to medium grained, and its form ranges from xenoblastic, through subidioblastic, and is occasionally idioblastic. It is free of a porphyroblastic tendency, either active or passive, and it seldom includes other minerals. Inclusions, where present, are most commonly sphene, less commonly epidote, and rarely plagioclase.

In summation, the patches of homogeneous migmatitic gneisses occur-

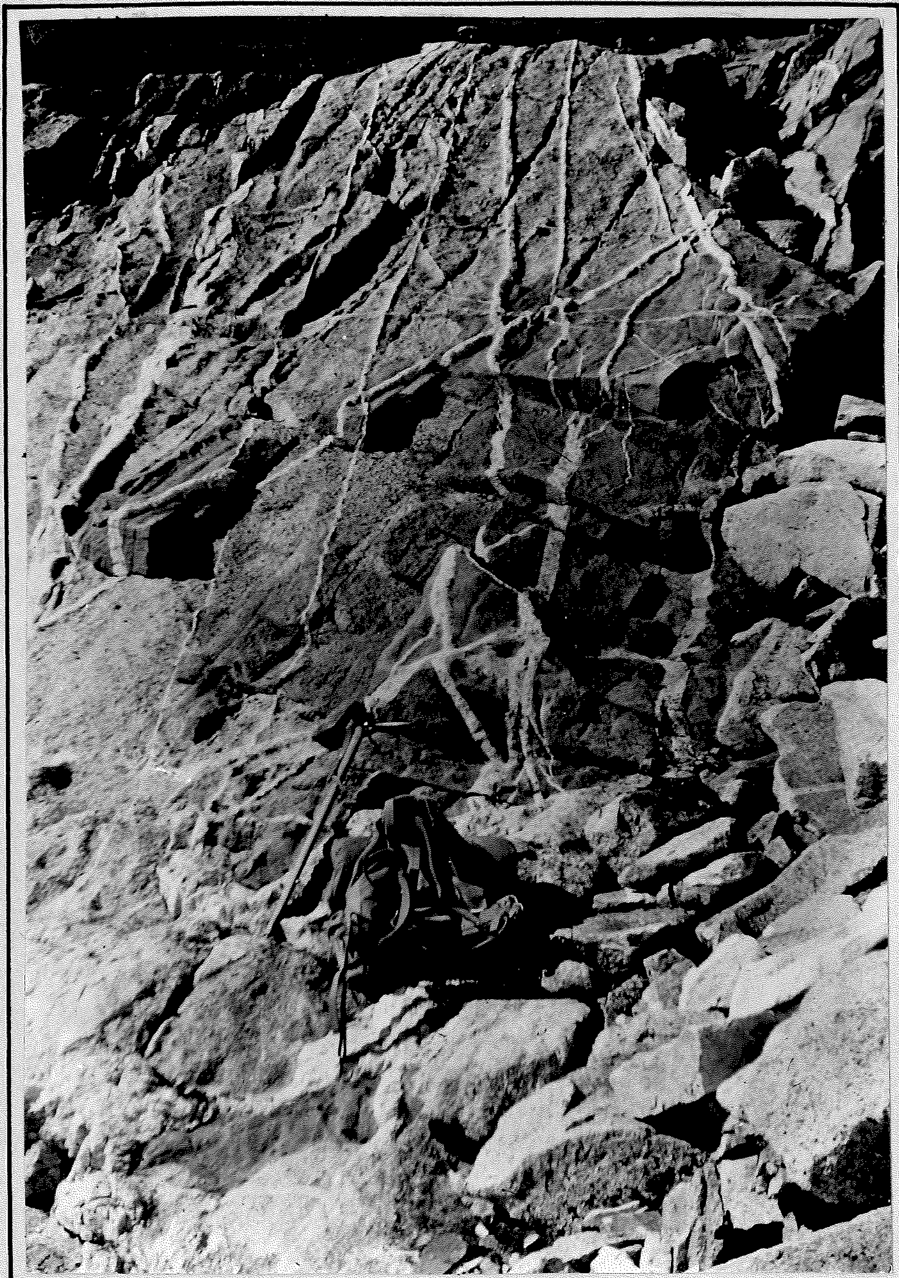


Figure 10.

Nearly directionless migmatitic trondhjemites on the ridge northeast of Sulphur Mtn. Here, the rocks are homogeneous, leucocratic, and coarse-grained. The aplite and pegmatite dikes have been more resistant to weathering than the trondhjemite, and therefore stand out in relief. Most of these dikes are of dilation origin.

ring within the more directionless trondhjemites are much finer grained than the enclosing granitic rocks. The development of potassium feldspars is completely lacking in these gneisses whereas microcline is a common constituent of the directionless granitic rocks. These gneisses therefore probably owe their existence to an escape from the conditions of static recrystallization and minor (in addition to the amount required to partially biotitize hornblende)potassium introduction which have occurred within the directionless trondhjemites.

Weakly Gneissose and Directionless Trondhjemites

Nearly directionless trondhjemites and locally granodiorites form the core of the metamorphic rock suite in the Sulphur Mtn. area. They extend from the nearly isochemical rocks of the Green Mtn. unit on the west to the finer grained migmatitic gneisses occurring between Bath Lake and Totem Pass on the east (see page 64). To the south, these trondhjemites extend in part to the amphibolitic rocks of Grassy Point, but east of the northern outlier of Glacier Peak lavas on Grassy Point, the rocks have not been studied. No mapping has been done immediately to the north on the Sulphur Creek - Downey Creek divide, but farther to the north near Bench Lake, Bryant (1955, p. 138) has mapped trondhjemitic gneisses very similar to those now under discussion (cf. description in Introduction, page 38).

All gradations occur between the directionless trondhjemites and the homogeneous trondhjemitic gneisses described in the previous chapter. The directionless trondhjemites have not undergone complete homogenization, as small, irregular patches of finer grained and more mafic-rich material still are present. These remnants of the earlier metamorphic country rock material are scattered throughout the area of granitic rock and are in all stages of transformation from dark, clearly defined inclusions to shadowy patches which can be distinguished only with difficulty from the enclosing granitic rock. Other relict inclusions were described earlier (see page39).

Microscopically, these medium to coarse grained directionless trondhjemites have the following mineral composition: plagioclase, mostly calcic oligoclase, varies from fifty to seventy per cent and averages about sixty-five per cent; quartz ranges from fifteen to thirty per cent and averages about twenty-five per cent; microcline varies from three to twelve per cent and averages about ten per cent; biotite varies from five to ten per cent and averages about eight per cent; green hornblende ranges from accessory amounts to about three per cent; pyroxene, belonging to the series diopside-hedenbergite, is present in accessory amounts in many of the rocks and it only rarely attains the rank of a major component; clinozoisite varies from accessory amounts to nearly five per cent and averages two or three per cent; sphene, orthite, pistacite, apatite, muscovite, sericite and chlorite are the remaining accessory minerals.

The plagioclase is most commonly medium to coarse in grain size and it occasionally shows a complete range from fine to coarse grain size within the area of a single thin section. The plagioclase is predominantly a calcic oligoclase, but occasionally it is sodic andesine. The composition varies from An_{33} to An_{20} and averages about An_{27}. Albitic rims are present around some of the plagioclase and are probably a late replacement phenomenon. Many of the grains show weak, gradational and anhedral, normal zoning. No recurrence was observed. Twinning most commonly is after the albite law, but both pericline and Carlsbad twins are also present. The Sulphur Mtn. trondhjemites are rather equigranular, and the plagioclase, although crystalloblastic and coarse-grained, only rarely becomes porphyroblastic. Within the plagioclase crystals are two types of inclusions which differ according to their time relationships to the development of the feldspar. Earlier than the plagioclase, and poikiloblastically included in it,are commonly grains of relict green hornblende, sphene, biotite and clinozoisite. The second type of inclusion has formed later, as an alteration product of an earlier, more calcic plagioclase, as the present oligoclase was being formed. These later-formed inclusions are predominantly epidote and clinozoisite, but secondary sericite and muscovite occasionally occur. These two generations of epidote-group minerals are rather easily distinguishable. The earlier epidote forms large, irregular grains and is commonly associated with biotite which indicates a derivation by biotitization of earlier hornblende. The occurrence of this earlier epidote is independant of cleavage planes or any other crystallographic directions of the plagioclase and no alteration of the plagioclase is associated with it. The growth of the later epidote, however, has been strongly controlled by its host's cleavages. The later generation of epidote-group minerals form fine needles which are arranged in a nearly rectangular pattern along the basal and (010) cleavages of the oligoclase (see figures 11 and 15.) Plagioclase with this type of alteration is very similar to that of the Schladminger granodiorite of Steiermark, Austria, which Franz Engle (1924, page 82) has described as "filled" plagioclase.

Microcline is the latest feldspar formed. It is xenoblastic (see figure 11) and forms irregular and branching amoeba-like projections along the intergranular areas. It is fine to medium in grain size. The microcline has partially replaced plagioclase, which has usually resulted in the formation of worm-like, myrmekitic intergrowths at their contact. The trondhjemites are occasionally free of microcline, but in general it is present at least in accessory amounts. A few of the granitic rocks from Sulphur Mtn. contain microcline in sufficient amounts to give them a granodioritic composition. As mentioned earlier, the potash feldspar seems to be primarily associated with those migmatitic rocks which have undergone a stronger phase of static recrystallization.

Biotite is fine to coarse grained and is xenoblastic to subidioblastic. Its pleochroism is Z = Y = medium brown with a slight orange cast, and X = pale, slightly greenish to yellowish tan. The biotite is commonly associated in clusters with clinozoisite and euhedral sphene, and occasionally with fine to medium sized grains of green hornblende. Such relicts of hornblende often show biotitization along the cleavages. It is obvious that much and probably all of the biotite has formed from hornblende, with segregation of clinozoisite.

Pyroxene is present in accessory quantities in many of the granitic rocks on Sulphur Mtn. It is fine to medium in grain size, xenoblastic, and it poikiloblastically includes biotite, plagioclase, quartz and sphene. The composition of the pyroxene lies within the series diopside - hedenbergite. The extinction angle Z:c is 42° which indicates a composition of approximately 40 molecular per cent of diopside and 60 of hedenbergite according to curves given by Winchell (1951, page 413). At one locality, just north of the 6600 foot bench north of the unnamed tarn east of Sulphur Mtn., this pyroxene has formed unusually large crystals and constitutes over twenty-five per cent of the rock. It is highly sieve-textured and includes biotite, actinolitic hornblende, oligoclase, quartz, microcline, clinozoisite, and sphene. Some of the prism faces are well formed, but (010) faces are never developed. Very well developed basal parting is present which can even be seen in hand specimen. At this locality, the pyroxene porphyroblasts are in completely random orientation which indicates a development under static conditions. Most of the pyroxene porphyroblasts seen on the ridge from Sulphur Mtn. to the 7145 foot peak about a mile to the northeast are also in random orientation with respect to any traces of relict foliation which may be present within the granitic rocks. A few pyroxene crystals however, as in figure 9, (page 41) have grown mimetically after the foliation.

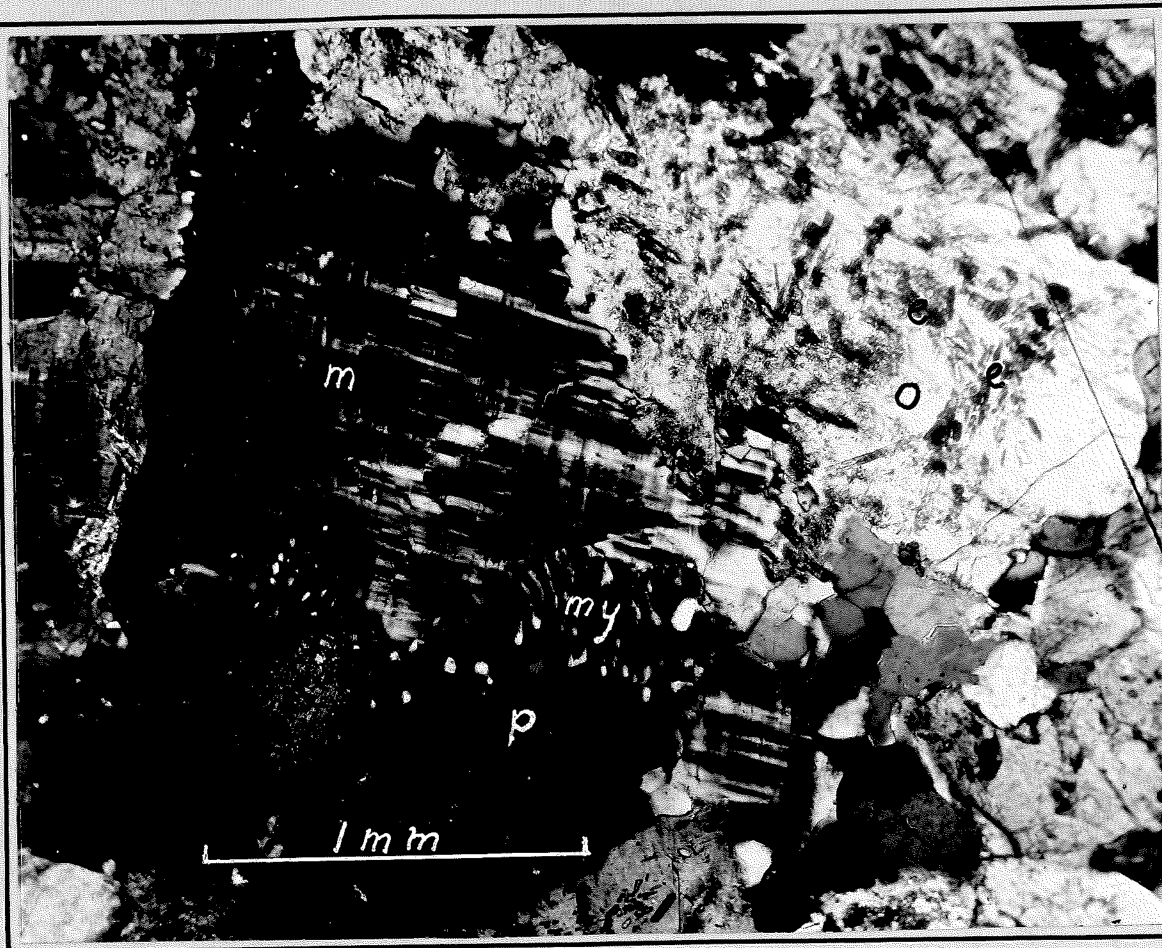


Figure 11.

Xenoblastic microcline (m) which has replaced earlier plagioclase (p), with the development of myrmekite (my) at their contact. Note the undisturbed amoeba-like projections of the microcline, which indicate static growth, and the slightly rounded original (pre-microcline) borders of the plagioclase, which suggest a pre- or synkinematic time of development. Oligoclase (o) has replaced an earlier, more calcic, plagioclase; the excess calcium formed secondary epidote minerals (e) which grew along the cleavages of the oligoclase.

Specimen collected from station 61, about $\frac{1}{4}$ mile west of Sulphur Mtn.

Crossed nicols.

Figure 12.

Crystalloblastic trondhjemite showing typical association of early clinozoisite (c) with biotite (b) indicating the replacement of a still earlier nornblende. Relict hornblende (h) also occurs.

Specimen #8-24-55-1, collected from station 84 on ridge 3/4 mile east of Bath Lake.

Plane light.

Feldspathized Amphibolite and Migmatitic Trondhjemite on Grassy Point

Nearly all stages of transformation from fine-grained, isochemically metamorphosed amphibolite to medium-and coarse-grained, leucocratic trondhjemitic gneisses are present between the Dolly Creek-East Fork ridge where amphibolites and hornblende schists underlie erosional outliers of Glacier Peak lavas, and the 5368 foot knoll west of Grassy Point which is composed of nearly directionless trondhjemite. The transition from amphibolite and hornblende-bearing schist to trondhjemite takes place both along and across the strike of the units involved. To the southeast these rocks pass beneath the cover of Glacier Peak lavas and pyroclastics, south of which they have not been mapped.

The isochemical amphibolites and hornblende-biotite schists have already been described in detail (see page 20 to page 31) and will only be mentioned in passing in this chapter. As was stated in the introduction to the chapter "Isochemically Metamorphosed Rocks of the Green Mtn. Unit" (see page 12), those rocks containing over ten per cent of feldspar porphyroblasts are classed as allochemical. All gradations occur between purely isochemical and distinctly allochemically metamorphosed rocks and their separation at ten per cent is wholly arbitrary.

If the metasomatic history of such a coarsely gneissose and in places directionless granitic rock as the trondhjemites on Sulphur Mtn. is to be understood, detailed study should be made in those areas in which the earlier chapters of the history of the rock have been preserved. Later stages of metasomatism, mostly under late-kinematic, but in places static conditions, have erased the details of the earlier history in most of the Sulphur Mtn. rocks. The feldspathized amphibolite, hornblende gneisses, and hornblende-rich trondhjemitic gneisses supply these details lacking in the rocks to the north.

The initial step in the transformation may or may not involve feldspathization. The plagioclase forms porphyroblasts which poikiloblastically include green hornblende, biotite, epidote and sphene. In some examples the porphyroblasts slightly exceed ten per cent of the volume of the rock, but the total plagioclase content is not in excess of that within some of the isochemical ortho-amphibolites described earlier (cf. page 28). The porphyroblasts may be simply the result of coarser recrystallization of material already present rather than due to the actual addition of soda. The composition of these early porphyroblasts averages An_{35} which is about the same as the average composition of plagioclase in the ortho-amphibolites. In addition to the larger crystals previously mentioned as being poikiloblastically included within the plagioclase, there are countless inclusions of exceedingly fine-grained material which give the porphyroblasts a turbid appearance. These inclusions are too fine-grained to be determined microscopically. Some of the hornblende also has recrystallized and has a slight porphyroblastic tendency at this stage, although by far most of it is still of a finer grain size and non-porphyroblastic, as it is in the ortho-amphibolite (cf. figures 13 and 4). Biotitization is limited to patchy and irregular areas along the cleavages of the hornblende, suggesting that minor potash has already been introduced at this stage; no potash feldspars are present as yet. The calcium released from the hornblende during this alteration has caused the development of tiny grains of clinozoisite and/or epidote which cluster about such an altered crystal. Possibly some of this released calcium has been taken up by the growing porphyroblasts of plagioclase, resulting in the weak, somewhat patchy and anhedral oscillatory zoning which is common to many of the porphyroblasts. Bands, lenticles and patches of clear quartz aggregates are also present in many of the rocks in this stage of the migmatization. As quartz is notably absent in the isochemical amphibolites, an introduction of silica is therefore indicated.

An amphibolite-derived feldspar porphyroblast gneiss collected from the col just east of Grassy Point represents a slightly more advanced stage of migmatization. In this rock, plagioclase porphyroblasts, averaging An_{28}, make up 60 per cent of the rock. Quartz comprises 20 per cent of the rock; green hornblende, 12 per cent; biotite, 6 per cent; epidote, 1 per cent; sphene and apatite are accessories. The notable difference between this rock type and those rocks described in the preceeding paragraph is the presence of a more sodic plagioclase, namely calcic oligoclase, rather than an intermediate andesine. The plagioclase porphyroblasts are still rather turbid. Most of the inclusions in the plagioclase still are of sub-microscopic size, although some of them are large enough to be determined as very minute clinozoisite and zoisite grains. A few of these inclusions show a poorly developed preferential alignment in the (001) and (010) directions of the plagioclase, but this alignment is much less marked than in the more advanced stages to follow. The plagioclase has weak, gradational and anhedral oscillatory zoning. It poikiloblastically includes quartz, green hornblende, biotite, and occasionally small grains of earlier plagioclase which have escaped recrystallization and which have a different optical orientation from the enclosing plagioclase. Much of the hornblende has undergone recrystallization and a considerable portion of it has been altered to biotite with simultaneous segregation of clinozoisite. Some clusters of biotite and clinozoisite are free of relicts of the parent hornblende. For the amount of alteration of hornblende to biotite, there seems to be a deficiency of epidote-group minerals; this suggests that some of the calcium released may have entered the plagioclase. In this rock, quartz is much more evenly distributed among the other constituents than in those rocks representing the earlier stages. In part, the quartz seems to have replaced plagioclase.

Trondhjemitic gneisses to the north and northwest of the erosional remnant of Glacier Peak lavas which comprises the 6596 foot peak east of Grassy Point, are still further advanced in this migmatitic series. These rocks are very similar to the more gneissic phases of the trondhjemites to the north on Sulphur Mtn., and therefore a detailed description is unnecessary here. The oligoclase porphyroblasts, averaging An_{25}, are filled with much coarser grains of clinozoisite and zoisite than are present in the plagioclase of the earlier stages. These epidote-group minerals are very well aligned in the (001) and (010) cleavage planes of the plagioclase (see figure 15, page 63). A very few microscopically undeterminable inclusions are still present; these are probably the same type of inclusion which give the plagioclase, in its earlier stage of development, the turbid appearance. The plagioclase is clear where it is adjacent to the larger inclusions of clinozoisite and zoisite, and has not been altered or decalcified as is usually the case if later epidote minerals have formed at the expense of earlier plagioclase; moreover, the contact between the two minerals is always sharp. This indicates that the plagioclase and the included epidote minerals were stable together. This stable association of calcic oligoclase plus epidote minerals indicates that the plagioclase crystallized under temperatures of the cooler-medium mesozone. Two possibilities exist with regard to the time relationship of soda metasomatism to the lowering of temperature in the rock from warmer mesozone to cooler-medium mesozone. (1.) All of the metasomatism occurred at a temperature of the medium to warmer mesozone, as indicated by the stable association of sodic to intermediate andesine plus clinozoisite which occurs in the earliest stages of migmatization (see page 55). The plagioclase was subsequently recrystallized at the lower temperature of the cooler-medium mesozone, with the contemporaneous segregation of some more epidote minerals. (2.) Soda metasomatism occurred as temperatures were falling from the warmer to the cooler-medium portions of the mesozone so that the total amount of albite component in the plagioclase was increased under a temperature at which calcic oligoclase was stable in association with epidote minerals. Conclusive evidence to prove either case is not present. The possible relationships of the epidote minerals to the plagioclase recrystallization and soda metasomatism are shown diagrammatically in Table 1. below. The very well developed alignment of the inclusions in the cleavage planes of the plagioclase seems to indicate that fluids (possibly related to the intergranular film) permeated the plagioclase via cleavage planes, and took the released calcium into solution; this calcium, along with aluminum, silica and hydroxyl, was deposited as clinozoisite and zoisite in the cleavage planes of the plagioclase. A dry mechanism such as ionic lattice diffusion probably could hardly produce such an alignment of the epidote-group minerals along the cleavage planes. In these more advanced trondhjemitic gneisses, the hornblende has entirely recrystallized and is restricted to scattered and isolated crystalloblasts. Biotite has become the dominant mafic mineral, and it is always associated with clinozoisite or epidote.

Leucocratic and coarse-grained, directionless and weakly gneissose trondhjemites are present on the ridge about one-quarter of a mile west of Grassy Point. They form a large outcrop in the alpine meadows just southeast of the 5368 foot knoll on this ridge. The contacts of this mass with the isochemical rocks to the southeast, south, and southwest are not exposed. The position of this stock-like mass so far to the west of the main area of migmatitic trondhjemite suggests that mobilization and intrusive movement has occurred. As far as the available field evidence is

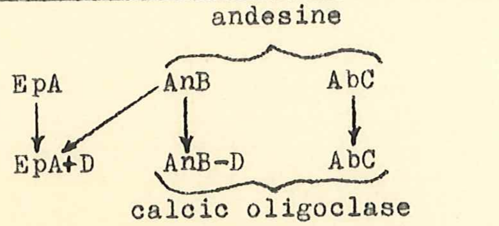
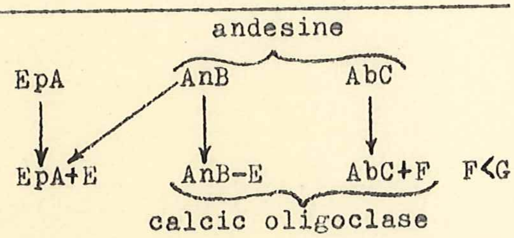
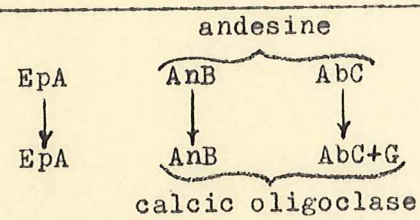
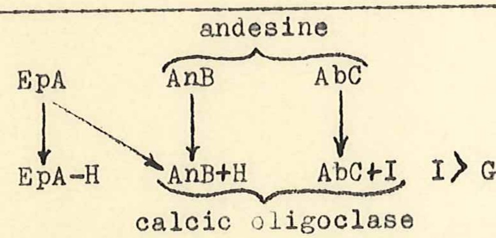
Case 1.	Time 1: warmer mesozone; time of metasomatism. Time 2: cooler-medium mesozone; no metasomatism	
Case 2a.	Time 1: warmer mesozone. Time 2: cooler-medium mesozone; relatively minor metasomatism.	
Case 2b.	Time 1: warmer mesozone. Time 2: cooler-medium mesozone; metasomatism.	
Case 2c.	Time 1: warmer mesozone. Time 2: cooler-medium mesozone; relatively major metasomatism.	

Table 1.

Possible relationships of the epidote minerals to plagioclase in the "filled" plagioclase crystalloblasts (See figure 15.) in migmatitic trondhjemite, (Case 1.) when only a decrease in temperature occurs, and (Case 2.) when soda metasomatism occurs along with a fall of temperature. A = epidote minerals; B = anorthite component of plagioclase; D and E = amount of anorthite component subtracted from andesine to form additional epidote minerals during stage 2; F, G, I = amount of additional albite component formed at stage 2 due to Na-metasomatism; H = increase in total amount of anorthite component in plagioclase and corresponding decrease in epidote minerals if considerable Na-metasomatism has occurred during stage 2.

concerned, it would be equally possible that these rocks have been granitized and remained in place. Microscopic structural features, however, indicate that movement has occurred; many of the plagioclase porphyroblasts and quartz grains have been severely strained and partially granulated along their borders. The movement took place while the material was in an entirely crystalline stage. On trend with this mobilized migmatitic trondhjemite is the neomagmatic trondhjemite which Bryant (1955) mapped on Downey Mtn. to the northwest. The Downey Mtn. intrusion seems to have a structurally controlled position, as it occurs at the boundaries of the isochemical rocks of the Green Mtn. unit on the west and of migmatitic gneisses similar to those on Sulphur Mtn. on the east. The textures of the Downey Mtn. intrusive trondhjemite are undoubtedly igneous as has been shown by Bryant (1955, p. 271). This is indicated by the euhedral crystals of plagioclase and biotite and by the fact that quartz fills in the interstitial areas between these earlier formed crystals, whereas in the migmatitic trondhjemites to the east and southeast the quartz is often porphyroblastic. The plagioclase of the Downey Mtn. trondhjemite has well developed oscillatory zoning,usually with from ten to fifteen recurrences. Such euhedral and highly zoned plagioclase is characteristic of the magmatic granitic rocks of Miners Ridge (see page 81). Remnants of an earlier crystalloblastic texture in the Downey Mtn.trondhjemites are only preserved by the green hornblende and garnet which indicates that at least these two minerals escaped complete melting. Apart from the similar zoning in the plagioclase, the Downey Mtn. neomagmatic trondhjemite is completely different from the large mass of intrusive granitic material of Miners Ridge (see page 76), both in textures and in mineralogy, and it could not have been derived from that magma. The Downey Mtn. trondhjemite has a very limited areal extent,as it is confined to the southern peak of Downey Mtn. Its origin was probably somewhere in the migmatitic complex to the east. The mobilized, but still crystalline, material on the western spur of Grassy Point is possibly related to the neomagmatic Downey Mtn. trondhjemite with which it is on trend. Although no contacts were observed, the structural setting of the mobilized stock on Grassy Point is similar to that of the Downey Mtn. intrusion; namely, it occurs at the boundary between the isochemical rocks on the west and migmatitic rocks on the east. The crystalloblastic textures in the mobilized rocks west of Grassy Point are modified by weak mechanical deformation which has resulted in incipient cataclasis, whereas the textures in the Downey Mtn. trondhjemite are predominantly igneous with only relicts of the earlier metamorphic textures. The textures in the mobilized trondhjemite of Grassy Point are similar to the textures in the Hidden Lake stock north of Cascade Pass (Misch, oral communication) in which mobilized and plastic, but still entirely crystalline material derived from the Eldorado gneisses (a variety of the Skagit gneisses) has invaded the isochemical rocks to the west.

Mineralogically, the mobilized trondhjemites west of Grassy Point contain from fifty-five to sixty per cent plagioclase, twenty-five to thirty per cent quartz, about five per cent microcline, five to ten per cent biotite, and accessory hornblende relicts, sphene, chlorite, clinozosite, epidote, and magnetite. The plagioclase ranges in composition from An_{35} to An_{25} and averages slightly under An_{30}. Weak, gradational, and anhedral normal zoning is common and slight reverse zoning is also present. Sodic oligoclase to albitic rims are present on some of the crystals. Myrmekite is well developed on the peripheries of many plagioclase porphyroblasts which are in the vicinity of the late microcline.

In summation, the mobilized trondhjemites west of Grassy Point are mineralogically very similar to the trondhjemitic gneisses on Sulphur Mtn. Texturally, the Grassy Point trondhjemites show weak to moderately strong cataclastic structures superimposed upon the earlier late-kinematic to statically developed crystalloblastic textures. This suggests that movement of the entire mass occurred while it was in a plastic, crystalline state. The main mass of trondhjemite on Sulphur Mtn. lacks these late cataclastic effects.

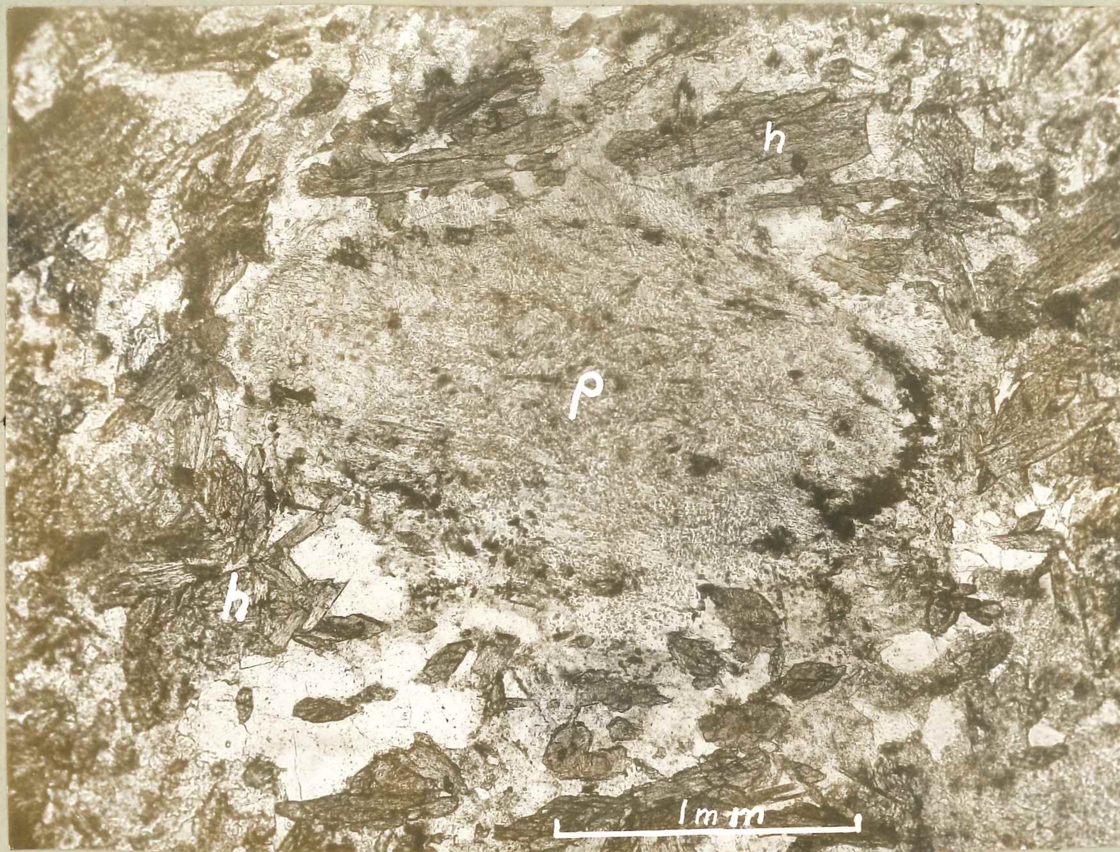


Figure 13.

Slightly feldspathized amphibolite. Plagioclase porphyroblast (p) has turbid appearance due to minute inclusions of clinozoisite and epidote. Green hornblende (h) is still fine grained, as is characteristic of the isochemical amphibolites, and has not yet begun to recrystallize. The hornblende is only very slightly biotitized along cleavages.

Specimen 9-1-55-15 collected from station 115 about one-quarter mile southeast of Grassy Point.

Plane light.

Figure 14.

Feldspathized amphibolite in a slightly more advanced stage of feldspathization than spec. #9-1-55-15 (figure 13). Plagioclase porphyroblasts (p) have a turbid appearance due to high content of very fine grained clinozoisite and epidote inclusions. These inclusions are much finer grained than the inclusions in the oligoclase of the more advanced trondhjemitic gneisses. Biotite (b) and clinozoisite (c) have formed at the expense of hornblende. Green hornblende (h) has not yet begun to recrystallize. High content of quartz (q) indicates that silica metasomatism has already occurred at this stage.

Specimen #9-1-55-16, collected from station 116 in first col east of Grassy Point.

Plane light.

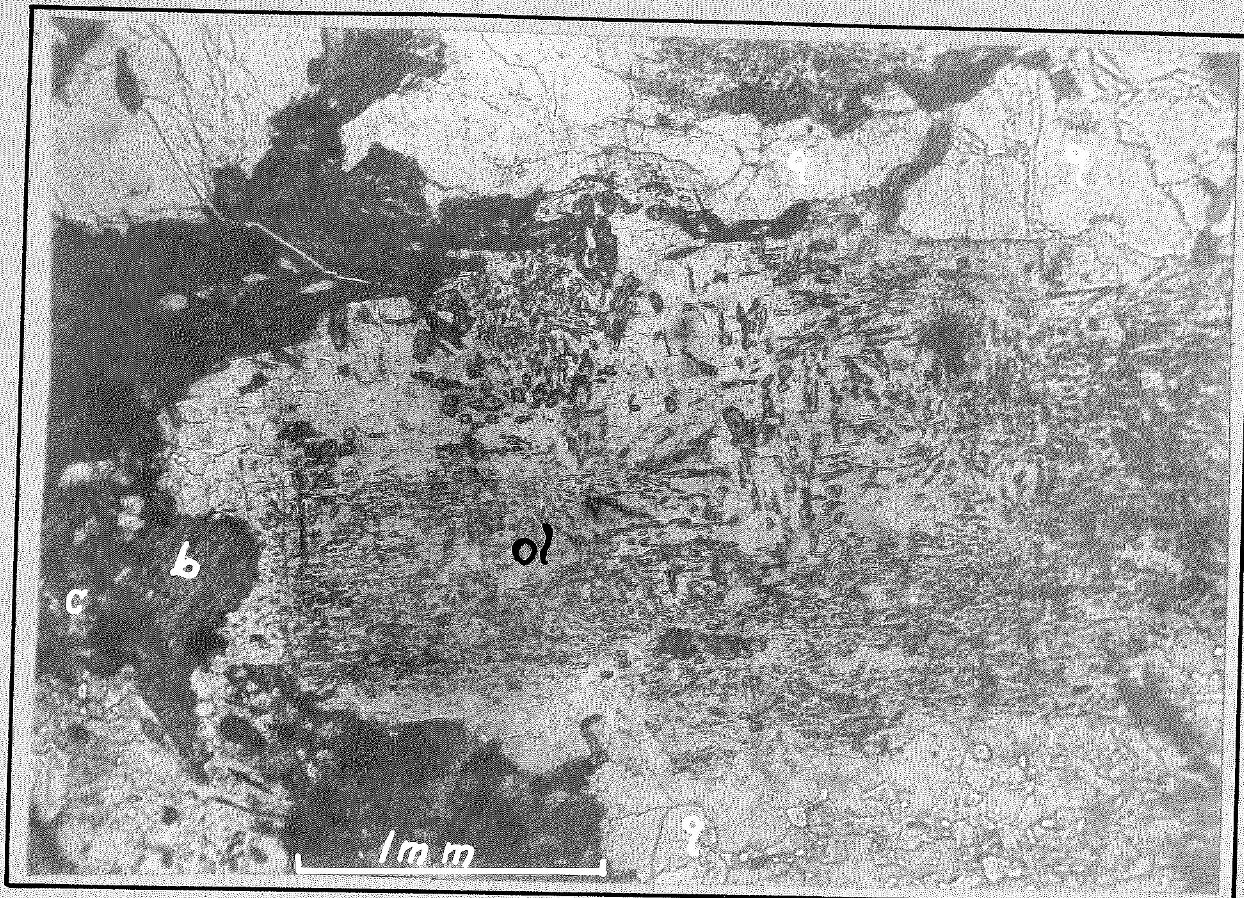


Figure 15.

Oligoclase porphyroblast (ol) in a highly advanced, weakly gneissose, migmatitic trondhjemite. The inclusions of epidote-group minerals which, in the earlier stages of feldspathization (see figures 13 and 14) gave the porphyroblasts a very turbid appearance, now show much coarser development and are well aligned along the (010) and (001) cleavage planes of the crystal. At this stage of feldspathization, hornblende rarely occurs and is replaced by the assemblage biotite (b) plus clinozoisite (c). Quartz (q) is by now a dominant mineral in the assemblage.

Specimen #7-12-56-13, collected from station 232, just northwest of the 6596 foot peak east of Grassy Point.

Plane light.

Migmatitic Gneiss in the Vicinity of Totem Pass

A heterogeneous assortment of migmatitic hornblende-biotite gneisses, and migmatitic biotite gneisses are present in the northeast portion of the area on the high, jagged ridge separating the upper Sulphur Creek drainage from that of Canyon Creek. Approximately one mile east of Bath Lake these gneisses gradually merge to the west, across their structural trends, with the more homogeneous migmatitic gneisses and granitic gneisses of Sulphur Mtn. This unit continues past Totem Pass into the Holden quadrangle to the east where the rocks currently are under study by the U. S. Geological Survey. To the southeast, Morrison (1954) has mapped a series of migmatitic biotite gneisses and granulites, amphibolites, and migmatitic hornblende gneisses on Phelps Ridge. The Phelps Ridge rocks are approximately on trend with those of Totem Pass. To the north they are unmapped as they trend well to the east of the Snowking area studied by Bryant (1955). Included in this discussion is the small area of pyroxene-bearing amphibolites and migmatitic hornblende gneisses which are present just southeast of Image Lake on Miners Ridge.

Structurally, these rocks show but little variation. The schistosity strikes from N 10° W to N 20° W and dips moderately to the west. Dips normally range from 30 to 50 degrees but occasionally dips as steep as 70 degrees are present. The attitudes of the foliation in the metamorphic rocks southeast of Image Lake are similar to those north of Canyon Creek. As such a northwesterly trend is generally characteristic of the rocks of the northern Cascades, it seems to be indicated that the overlying rocks and the rocks to the north were little disturbed by the intrusion of the large mass of granitic material on Miners Ridge. In contrast, the metamorphic rocks of Sulphur Mtn. and Downey Mtn. which are located to the west and northwest ofthe Miners Ridge intrusion have a very strong northeasterly trend.

In the field, the rocks near Totem Pass are rather dark in over-all appearance, due to their much higher mafic content as compared with the leucocratic gneisses of Sulphur Mtn. Leucocratic bands are common, however, as are cross-cutting dikes and irregular masses of more granitic material. Contacts of such dikes with the more schistose material are in some cases gradational, but most often they are sharp. Geometric relationships indicate that many of these dikes were emplaced by dilation of the enclosing rock mass. The hornblende content of many of the migmatitic gneisses near Totem Pass is so small that they were mapped in the field as biotite gneisses. The relationships between the hornblende - bearing gneisses and the hornblende-free biotite gneisses were therefore not observed in detail in the field, but the two varieties of gneiss appear to be interbanded. The high hornblende content in the rocks southeast of Image Lake makes the amphibole readily apparent in hand specimen. The metamorphic rocks southeast of Image Lake are much less migmatitic than those north of Canyon Creek.

Petrographically, the migmatitic gneisses near Totem Pass and southeast of Image Lake have the following mineral composition: plagioclase varies from seventy-eight to forty per cent and averages about sixty per cent; quartz ranges from thirty per cent to nearly zero and averages about twenty per cent; biotite varies from twenty-five to five per cent and averages about fifteen per cent; green hornblende ranges from thirty-five per cent to zero, and averages about five per cent. Diopsidic augite is an important local constituent in amounts varying from five to ten per cent; accessories are: clinozoisite, epidote, sphene, apatite, and garnet. The amounts of sericite and chlorite vary locally, depending upon the intensity of alteration of the plagioclase and biotite.

Plagioclase is of fine to medium grain size. It is granoblastic-xenoblastic and has sutured boundaries with adjacent mineral grains. The composition varies from An_{30} to An_{52}. The plagioclase with the higher anorthite content is found in the much less feldspathized rocks occurring southeast of Image Lake on Miners Ridge. In the rocks from near Image Lake, plagioclase composed of sodic labradorite (An_{52}) to calcic andesine (An_{48}) is associated with diopsidic augite, green hornblende, clinozoisite, and epidote. Some of the epidote-group minerals are the result of segregation during the biotitization of hornblende. Most of the clinozoisite is not associated with biotite or hornblende and it appears to be an original constituent inherited from an earlier isochemical amphibolite. Most of the epidote-group minerals are in stable association with the plagioclase, but a few tiny patches of highly pleochroic epidote are secondary after plagioclase and are a result of local retrogressive alteration. The assemblage of calcic andesine-sodic labradorite plus clinozoisite places the temperature of metamorphism near the meso-katazonal boundary. The presence of diopsidic augite also indicates a temperature of at least the warmest mesozone. On the ridge north of Canyon Creek, the anorthite content of the plagioclase is somewhat lower, ranging from An_{29} to An_{40} with an average of about An_{35}. Epidote-group minerals are in stable association with the sodic andesine in the gneisses north of Canyon Creek, which indicates that the temperatures during the last phase of crystallization were lower in these more migmatitic rocks than they were in the less migmatized rocks near Image Lake. Some of the rocks from about one-half mile west of Totem Pass show sodic andesine (An_{30} - An_{32}) to be in equilibrium with large, clear grains of epidote which indicates that the temperature of crystallization of the plagioclase was about the middle of the mesozone. This was not the maximum temperature of the metamorphism, however, as relict grains of diopsidic augite, now partially altered to biotite, indicate that temperatures were once as high as the warmer part of the kyanite zone, if not higher. The fact that the less strongly migmatized rocks near Image Lake are of a higher temperature grade means either that they escaped the late-stage, lower-temperature recrystallization which occurred in the rocks north of Canyon Creek, or that the soda metasomatism which produced the more migmatitic gneisses to the north occurred during falling temperatures. No evidence was found to indicate which process, if not both, were responsible.

Quartz is fine to medium in grain size and is granoblastic with sutured boundaries between adjacent quartz and plagioclase grains. Weak undulatory extinction is nearly ubiquitous in the quartz crystals, which probably indicates the incipient stage of cataclasis of a period of late, weak deformation. As will be described later, some of the biotite is locally shredded, probably resulting from the same weak deformation. The quartz content is highest in the gneisses which are free of hornblende or its derivatives (i.e. the association of biotite and clinozoisite) and is characteristically low in the hornblende-rich rocks. Silica metasomatism has probably occurred, although there is no irrefutable evidence for it.

Hornblende is mostly anhedral and granoblastic. It is poikiloblastic and has the appearance of having developed this poikiloblastic texture passively by relegation to the intergranular areas, a principle which has been discussed earlier (page 45). It includes quartz, plagioclase, and sphene and it shows minor alteration to biotite. The pleochroism is generally X = pale tan, Y = slightly brownish dark green, and Z = dark green. Occasional grains show a variation; for example, the brownish tinge of the Y ray may be absent, and the Z ray may show various shades of dark green. A few of the crystals are twinned. The grain size depends upon the stage of feldspathization of the rocksand of concurrent recrystallization of the hornblende. The hornblende of the nearly isochemical rocks southeast of Image Lake is predominantly fine grained but occasionally is medium grained, whereas the hornblende in the more migmatitic rocks near Totem Pass is dominantly of medium grain size.

Biotite is fine to medium in grain size and is subhedral. Its pleochroism is normally X = pale yellowish tan, and Y = Z = moderately dark reddish brown, but in some grains the absorption of the Y and Z rays is much lighter and more reddish. The biotite is often associated with grains of clinozoisite and/or epidote which indicates the former presence of an amphibole mineral. Some of the rocks collected near Totem Pass contain biotite which is somewhat shredded in certain zones. Tiny fragments of biotite are drawn out into stringers between some of the quartz grains. Slightly more intense chloritization of the biotite has occurred in these zones of weak, late deformation. The biotite is normally well aligned, but some transverse crystals seem to indicate that it continued to crystallize under post-kinematic conditions.

Pyroxene is usually granoblastic but it occasionally shows elongation within the planes of schistosity. It is of anhedral to subhedral form and fine to medium grained. Its composition seems to vary somewhat within the diopside-augite series. The extinction angle Z:c varies from a maximum -45^{o} in the amphibolites and hornblende gneisses near Image Lake to a minimum of about -38^{o} in the migmatitic gneisses near Totem Pass. In some of the rocks near Image Lake, tensional fracturing has occurred probably not long after the formation of the s planes (see figure 17). Solutional transfer of the components making up the pyroxene and the associated green hornblende took place along these cracks which are at nearly right angles to the foliation planes. Where these cracks cut crystals of green hornblende, the crystallization of the amphibole in the crack has occurred contemporaneously with the widening of the fissures as optical continuity with the fractured hornblende crystal is maintained. The fracture-filling amphibole, however, has a much lighter-green absorption than the adjacent green hornblende. Where these fractures cut the pyroxene and have been healed by pyroxene, no such optical continuity exists (note the pyroxene crystal in the lower right corner of figure 17).

In summation, metamorphism took place under conditions of at least the warmest kyanite zone but possibly of the coolest katazone. Crystallization was dominantly syn- and late-kinematic but continued locally under static conditions. The source materials seem to vary from Ca-free argillaceous sediments, to limy , impure argillites with minor to dominant admixtures of tuffaceous material, or to greywackes. The present interbanded relationships between these rock types suggest an interlayering of the original sediments although tectonic repetitions have undoubtedly occurred.

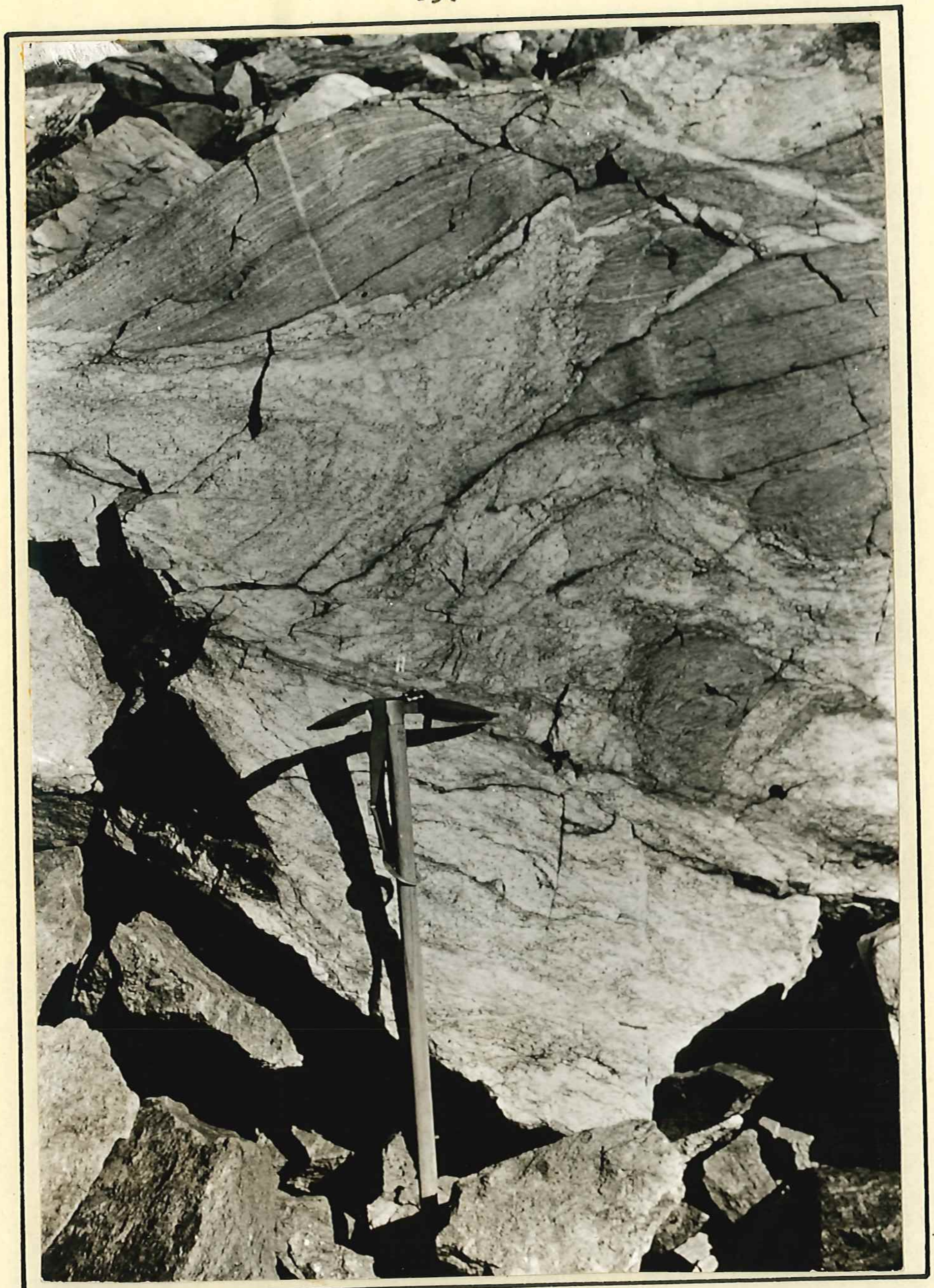


Figure 16.

Migmatitic gneisses southeast of Totem Pass. The darker and more highly schistose areas in upper right of the outcrop are nearly homogeneous migmatitic hornblende-biotite gneisses. The foliation of the more leucocratic areas is at a distinct angle to the foliation in the adjacent, darker gneiss, indicating that mobilization has occurred. The lower portion of the outcrop, behind the ice axe, has undergone later shearing.

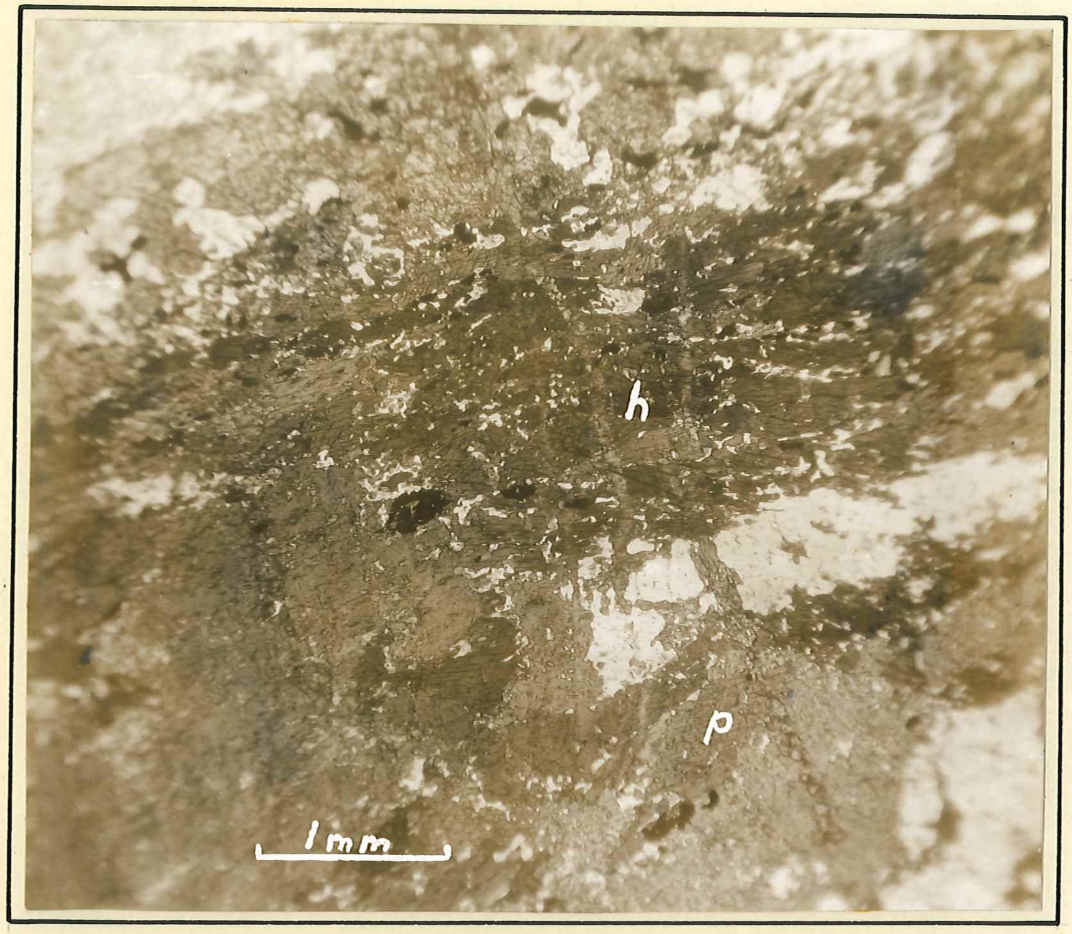


Figure 17.

Slightly hornfelsized, pyroxene-bearing migmatitic hornblende gneiss. Both the pyroxene (p) and the green hornblende (h) began crystallization under synkinematic conditions and continued to crystallize under static conditions as is indicated by the fractures nearly normal to s which have been healed by these minerals.

Specimen #8-14-55-2, collected from station 38, near the contact of the intrusive mass just southeast of Image Lake.

Plane light.

Migmatitic Gneiss In the Vicinity of Ptarmigan Glacier

The schists and amphibolites of the Green Mtn. unit are predominantly isochemical on the ridge near Fire Creek Pass and on Glacier Peak Ridge, but toward the southeast they increasingly lose this isochemical character and finally become completely migmatitic where the metamorphic rocks pass under the volcanic flows from Glacier Peak. Here, homogeneous, fine- to medium-grained biotite- and hornblende-bearing gneisses are well exposed in the cirque at the head of the East Fork of Milk Creek; below the 6967 foot peak at the southern end of Glacier Peak Ridge; and in the cirque below the Ptarmigan Glacier at the head of Milk Creek. The contact of the Glacier Peak lavas and the migmatitic gneisses is very well exposed on the ridges to the east and to the west of Ptarmigan Glacier, but within the cirque it is covered by the glacier.

To the north, near the junction of the Glacier Peak Ridge trail and the Pacific Crest Trail, isochemical hornblende schists and amphibolites are common, but they are intimately associated with cross-cutting, irregular masses of replacement pegmatite and aplite. Cross-cutting dilation dikes of leucocratic material are also common, as are concordant, sill-like bodies of the pegmatite. The structures within the isochemical portions of these intimately mixed rocks are, in general, parallel to the attitudes in the dominantly isochemical rocks to the north and northwest, thus indicating that no disruption of structure by intrusion of larger volumes of magmatic material has occurred.

In the easterly-facing cirque basins southeast of Fire Creek Pass, leucocratic material in the form of dikes, sills, and irregular masses becomes dominant over the isochemical portions by a ratio of from about 1:1 to nearly 3:1. Here again, however, the attitudes within the schist remnants are similar to those in the isochemical schists to the northwest and west. West of the 6900 foot peak south of Fire Creek Pass, the rocks become much less migmatitic although leucocratic material still is common. South and east of the 6952 foot peak at the head of Pumice Creek, the rocks have completely lost their isochemical character and been converted into medium to coarse grained and homogeneous migmatitic gneisses. These gneisses appear to be free of isochemical, schistose relicts of the parent rock. The transition from isochemical schist in the northwest, through the zone of heterogeneous migmatite, and finally to homogeneous migmatitic gneiss in the southeast occurs along the structural trends of the units involved.

Southeast of the cover of Glacier Peak lava and pyroclastics, the rocks on trend with the gneisses near the Ptarmigan Glacier have not been studied. Evidence that these gneisses continue for some distance southeasterly beneath the volcanic cover, at least to the vent of Glacier Peak, is afforded by the presence of megascopically very similar appearing rocks as accidental blocks within the Glacier Peak lavas. These inclusions of medium to coarse grained, homogeneous biotite gneiss are present in one or more of the flows just north of the headwaters of Dusty Creek, a few miles southeast of the Sulphur Mtn. area.

Petrographically, the gneisses near the Ptarmigan Glacier are somewhat varied, but the variations are not nearly so great as they are in the isochemical rocks on strike to the northwest. As is the case with the migmatitic rocks on Sulphur Mtn. (cf. page 38),the feldspathization and late-kinematic to static recrystallization has resulted in a relative homogenization of the parent material. The homogenization of the migmatitic gneisses near the Ptarmigan Glacier has not been as complete as in the directionless trondhjemites and trondhjemitic gneisses of Sulphur Mtn. The variation is only apparent microscopically,whereas in the field the gneisses appear to be quite uniform. In general two types of migmatitic gneiss are present: those in which hornblende and/or the hornblende-derived assemblage of biotite and epidote-group minerals are the mafic constituents; and those in which hornblende and its derivatives are absent from the mineral assemblage. The first type is interpreted as having been derived from hornblende-bearing schists or amphibolites, and the second type as having been derived from biotite schists. The hornblende-free gneisses predominate west of the southern end of Glacier Peak Ridge whereas the hornblende-bearing gneisses are dominant to the east. As noted earlier in the description of the Green Mtn. unit (page 12), a similar areal relationship of the hornblende-bearing schists and amphibolites to the hornblende-free biotite schists is present in the isochemical rocks to the north. The detail of the interbanding in the isochemical rocks to the north seems to have been eradicated by the processes of migmitization which have formed the gneisses to the south.

Microscopically, the hornblende-bearing migmatitic gneisses have the following average modal composition: 65 (55-70) per cent plagioclase, 25 (20-30) per cent quartz, 6 (5-10) per cent hornblende, 3 (1-5) per cent biotite, and accessory sphene, clinozoisite, apatite, orthite, sericite and pennine. The plagioclase is sodic andesine, An_{35}. It is xenoblastic and somewhat porphyroblastic. Anhedral weak normal zoning to calcic oligoclase rims is commonly present. Less common is weak, anhedral and gradational oscillatory zoning with a maximum of two recurrences. Green hornblende is xenoblastic, and it poikiloblastically includes quartz, plagioclase and sphene. The hornblende crystals exhibit all stages of biotitization from indistinct, patchy brownish areas along the cleavage planes, to faint and indistinct relicts of amphibole surrounded by large aggregates of biotite and clinozoisite. The sericite and a small part of the epidote are secondary after plagioclase. Biotite is partially altered to chlorite.

The hornblende-free migmatitic biotite gneisses are characterized by a distinctly higher quartz content and a corresponding lower plagioclase content as compared to the migmatitic hornblende-bearing gneisses described above. The average mineral composition of the migmatitic biotite gneisses is: 50 (40-55) per cent plagioclase, 34 (30-37) per cent quartz, 15 (10-20) per cent biotite, and accessory chlorite, opaques, sericite, epidote, sphene, and clinozoisite. The plagioclase is andesine, An_{40}, which has weak and gradational normal zoning to rims of sodic andesine and calcic oligoclase. The epidote is an alteration product of plagioclase; it frequently has a preferred orientation in the cleavage planes of that mineral. Rare clinozoisite is in equilibrium with the plagioclase, thus suggesting that either minor hornblende or minor clinozoisite was present in the parent schist. The presence of earlier hornblende is perhaps suggested by the occurrence of rare sphene in the assemblage.

The difference in the quartz and plagioclase content of the two types of migmatitic gneiss is undoubtedly a reflection of the composition of the parent material. To the north, the biotite schists on the ridge west of Milk Creek are rich in quartz and poor in plagioclase compared to the hornblende schists and amphibolites of Grassy Point and Glacier Peak Ridge to the east.

Since much of the parent material of the migmatitic gneisses near the southern end of Glacier Peak Ridge was amphibolite or hornblende schist, silica metasomatism must have occurred in those gneisses which were derived from these rocks, conversely, the biotite schist-derived gneiss has been increased in plagioclase and therefore here soda must have been the main introduced material. Biotitization of hornblende suggests that minor potash was introduced, although no potash feldspars are present.

The foliation of the migmatitic gneisses is in places well developed, but it is more commonly only moderately sharp, and in places it is quite indistinct. This is true in the field as well as microscopically. Crystallization has been dominantly late-kinematic, but occasionally it has continued under static conditions. Elongation of some of the biotite crystals normal to their basal cleavage suggests that some of the foliation is mimetic after earlier schistosity.

Figure 18.

Outcrop of medium-grained, homogeneous, migmatitic gneiss near the head of Milk Creek, at the base of Ptarmigan Glacier. The rocks on the skyline are lava flows from Glacier Peak.

Intrusive Granitic Rocks of Miners Ridge

General Statement

Granitic rocks of varying composition are present on the western ends of Miners Ridge and Middle Ridge and form the western extensions of a rather large stock which continues for an undetermined distance into the Holden quadrangle to the east. In the Holden quadrangle, these granitic rocks are currently under study by the U. S. Geological Survey but the results have not as yet been published. It is quite possible that the intrusive and almost fully magmatic quartz-labradorite porphyry stocks mapped by Morrison in his University of Washington thesis (1954) on Phelps Ridge, are genetically related to this much larger intrusive mass to the north. In the Glacier Peak quadrangle, the rocks have not yet been studied south of the Suiattle River, but it appears that, at least in part, the granitic mass passes under the lavas and pyroclastics of Glacier Peak which extend nearly to the Suiattle River.

For simplicity, the rocks of this intrusive mass are, in this report referred to as undifferentiated "granitic" rocks (see definition, page 35). Actually, the rocks show a complete gradation from quartz diorite, through granodiorite and quartz monzonite, to granite. This gradation of rock types is present on the scale of either a single thin section or a field outcrop. Rock names are given according to the classification used by Wahlstrom (1947, page 266), which is as follows:

> Granite: Ratio of alkali feldspars to soda-lime feldspars is greater than 5:3. Quartz exceeds 5% of the volume.
> Quartz Monzonite: Ratio of alkali feldspars to soda-lime feldspars lies between the limits of 5:3 and 1:1. Quartz exceeds 5% of the volume.
> Granodiorite: Ratio of alkali feldspars to soda-lime feldspars lies between the limits of 1:1 and 3:5. Quartz exceeds 5% of the volume.
> Quartz Diorite: Ratio of alkali feldspars to soda-lime feldspars is less than 3:5. Quartz exceeds 5% of the volume.

In estimating the mode, it should be emphasized that Wahlstrom (1947, page 265) includes with the alkali feldspars, not only orthoclase and microcline, but also anorthoclase, perthite, microperthite, and even individual crystals of albite (Ab_{100} to Ab_{90}). Soda-lime feldspars are those plagioclase crystals which are more calcic than Ab_{90}. Albite on the rims of more calcic plagioclase is used to compute the average composition of the entire crystal, and thus it is included with the soda-lime feldspars.

Rocks of quartz dioritic composition greatly predominate, with granodiorites, quartz monzonites, and granites occurring rather rarely and sporadically. The various rock types seem to be completely intergradational, depending upon the intensity of the replacement of plagioclase by deuteric quartz and potash-rich feldspars. Much controversy exists in the literature as to the specific limits of the late-magmatic, deuteric, and hydrothermal stages in the crystallization of a magma; the resolution of such a problem, however, is beyond the scope of this report. As applied to the granitic rocks of the Miners Ridge intrusion, these terms will be used in the following manner: Late-magmatic stage - The period of final consolidation of the magma during which quartz and potash-rich feldspars (if present) fill the interstitial areas between earlier-formed minerals and are in stable association with these earlier crystals. The textures are entirely igneous in the rocks which have crystallized only under late-magmatic conditions (see figure 20). Deuteric (auto metamorphic) stage - The period following the complete consolidation of the magma, during which the rock is still at a relatively high temperature and during which the residual and/or introduced silica- and potash-rich solutions attack and replace the earlier-formed plagioclase. The textures in the rocks which have undergone a deuteric stage of alteration show all gradations from slightly crystalloblastic (see figure 21) to highly crystalloblastic (see figures 22 and 23) with respect to the late quartz and alkali feldspars. These crystalloblastic textures, it should be emphasized, are later than the igneous textures and, in appearance, cannot be confused with the metamorphic textures which may be earlier than the igneous textures. Hydrothermal stage - The period of lower temperatures following the deuteric stage, during which all of the feldspars become unstable and alter to sericite and/or clay minerals. Sulphide deposition by the replacement of highly chloritized mafic minerals, occurs in this stage. In the rocks of the intrusive mass on Miners Ridge, igneous textures predominate in the quartz diorites, whereas late crystalloblastic textures predominate in the granites; all gradations of textures occur along with the gradations of composition. No structural or other controlling factor was found which has locallized the operation of the late solutions.

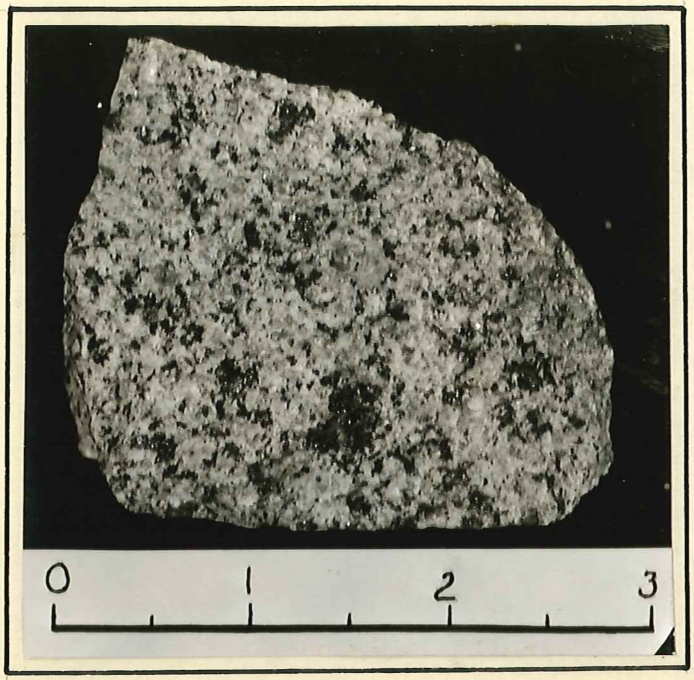


Figure 19.

Hornblende - bearing quartz diorite from the Miners Ridge intrusion. Mafic minerals are mostly hornblende, but minor biotite is also present.

Specimen #8-8-55-9, collected from station 30, just north of Image Lake.

Petrography

The rocks of the Miners Ridge intrusion are predominantly quartz diorites, however granodiorites, quartz monzonites and granites also are present. Table 2 shows the gradational relationships between these various rock types.

Spec. No.	Station	Plagioclase (incl. albite rims)	Alkali Feldspar (incl. albite in microperthite)	Quartz	Ratio Alkali Feldspar:Plagioclase
8.8.55.21	36	86%	1%	13%	1/86
7.2.55.5	5	79	3	18	Approx. 1/26
8.8.55.13	34	80	4	16	1/20
8.8.55.5	26	75	5	20	1/15
8.8.55.20	36	75	6	19	" 1/13
8.8.55.6	27	61	5	34	" 1/12
8.8.55.19	36	70	9	21	" 1/8
8.8.55.15	36	62	12	26	" 1/5
8.8.55.4	26	72	14	14	" 1/5
8.14.55.4	40	66	15	19	" 1/4
8.14.55.6	41	62	15	23	" 1/4
7.2.55.11	10	52	20	28	" 1/3
8.8.55.12	46	50	24	26	" 1/2
8.14.55.8	43	42	33	25	" 1/1
7.6.55.1	23	31	30	39	" 1/1
6.30.56.1	215	31	30	39	" 1/1
7.2.55.10a	9	30	33	37	" 1/1
8.14.55.11	46	36	39	25	" 1/1
8.8.55.17	36	21	50	29	" 2/1
8.14.55.7	42	21	63	16	" 3/1

Table 2.

Modal analyses of the leucocratic fraction of twenty rocks randomly sampled from the Miners Ridge intrusive mass. Per cent estimations were made by taking the average of the leucocratic portions of ten fields of view, using a low enough power of magnification so that the entire area of the thin section would be covered. Estimations were made to the nearest five per cent for each separate area. The late potash-rich feldspars are easily distinguished from the plagioclase and quartz in plain light by their turbidity.

Following Wahlstrom's classification (see page 76), the upper thirteen samples in Table 2. are quartz diorites, the next three are granodiorites,the next two are quartz monzonites, and the lowest two are granites. As shown in the last column of Table 2.,there is a rather gradual increase in the ratio of alkali feldspar to plagioclase. If these specimens, which were randomly sampled from both the upper and lower portions of the intrusive mass, are representative of the entire intrusive body, then the mass has a composition of approximately sixty-five per cent quartz diorite, fifteen per cent granodiorite, ten per cent quartz monzonite, and ten per cent granite.

Those quartz diorites which contain little or no alkali feldspars, have almost entirely igneous textures. These textures are characterized by early, euhedral and highly oscillatory zoned plagioclase, usually calcic andesine but occasionally sodic labradorite, in which the interstitial areas are filled with late-magmatic quartz. Euhedral to subhedral uralitized pyroxene may or may not be present. The dominant mafic mineral is green hornblende, but biotite occasionally is present. The quartz crystallized last, but it does not replace the earlier plagioclase. As the amount of alkali feldspar increases, the textures become increasingly crystalloblastic and in the rocks of granitic composition, textures are dominantly crystalloblastic. In the granites, the crystalloblastic textures of the quartz, the potash-rich feldspars, and of their granophyric intergrowths predominate, and only scattered relicts of plagioclase indicate the original igneous textures. The intermediate varieties, namely the alkali-feldspar-rich quartz diorites, granodiorites, and quartz monzonites, clearly show that these crystalloblastic textures have been superimposed upon the earlier igneous textures. These textural relationships are shown in figures 20 to 23. Even-grained varieties predominate, but porphyritic textures are common. The phenocrysts are dominantly plagioclase, but early pyroxene, now uralite, occasionally has also formed phenocrysts (see figure 20, page 84). The rocks are mostly medium to coarse in grain size,but some of the porphyritic rocks have a fine-grained groundmass. Fine-grained chilled border zones were not observed. The rocks are completely directionless and show no evidence of flow or later tectonic deformation other than occasional local and minor shear zones.

Because of the gradational relationship of the various rock types (see Table 2., page 79) a separation of them for individual discussion would probably not be significant. For example, specimen 8.8.55.12, a quartz diorite, is much more closely related to specimen 8.14.55.8, a granodiorite, than it is to specimen 8.8.55.21, also a quartz diorite. It is probably more significant, therefore, to discuss the relationships of the individual minerals for the entire intrusive mass.

Plagioclase varies from an average of 82 per cent in the quartz diorites which were not deuterically altered, to an average of 20 per cent in the highly deuterically altered granites. The average plagioclase composition of all the rocks is 52 per cent. The composition of the plagioclase varies from sodic labradorite, An_{55}, to calcic oligoclase, An_{25}, and averages calcic andesine, An_{45}. There is no significant change in the plagiocalse composition from the quartz diorites to the granites. There also seems to be no consistant difference in composition between the larger phenocrysts, the intermediate-sized phenocrysts,or much of the euhedral to subhedral plagioclase of the groundmass in the porphyritic varieties. The plagioclase phenocrysts in some of these rocks exhibit a glomeroporphyritic tendency. The intricate and compound twinning of some of the larger phenocrysts suggests that they may have formed by the coalescence of two or more individual crystals.[1] Well developed, euhedral normal zoning of the plagioclase is common, with compositions ranging from cores of usually calcic andesine, but occasionally of sodic labradorite, to rims of calcic oligoclase or sodic andesine. Euhedral and sharp oscillatory zoning also is common, with usually between ten and fifteen recurrences. Anhedral rims of albite and in some cases sodic oligoclase surround many of the well zoned crystals. Anhedral albite and oligoclase also are present in the interstices between larger and more euhedral crystals of more calcic plagioclase. The plagioclase is in various stages of replacement by quartz, potash-rich feldspars, and their granophric intergrowths (see figures 21, 22, and 23).

Quartz varies from 12 to 38 per cent and averages 23 per cent. It is lowest in the quartz diorites in which the quartz is entirely interstitial and is highest in the granodiorites, quartz monzonites, and gran-

1. This mechanism of the coalescence of two or more phenocrysts to form one large crystal which is usually intricately twinned is clearly displayed in the Glacier Peak lavas occurring southwest of Grassy Point. (See page 99, and figure 26, page 101.)

ites, in which at least a considerable portion of the quartz is crystalloblastic. In the quartz diorites containing little or no potash-rich feldspars, the quartz occurs as anhedral grains which fill the interstitial areas; the quartz, therefore, was the last mineral to crystallize and, as such, it marks the termination of the late-magmatic stage of crystallization. In other quartz diorites which are low in potash-rich feldspars,the quartz has a slight crystalloblastic tendency as it includes, and probably in part replaces, some ofthe plagioclase (see figure 21, page 85). As the quartz increases in amount and in crystalloblastic appearance, micro - graphic intergrowths become common (see figure 22, page 86), and in the rocks of granitic composition granophyric intergrowths have replaced most of the plagioclase (see figure 23, page 87). Occasionally the deuteric quartz becomes porphyroblastic.

The potash-rich feldspars are primarily microperthite and less commonly non-perthitic anorthoclase or microcline. The latter was determined by its patchy and irregular grid twinning; its optic angle could not be determined, thus no conclusive distinction could be made between anorthoclase and microcline. Because of the complex and intricate intergrowths between potash feldspar, perthite-albite, and quartz, the amount of potash feldspar alone could not be determined. In making quantitative mineral estimates for purposes of rock classification, the potash feldspars are grouped with perthite-albite as alkali feldspars. The alkali feldspar content varies from zero in some of the quartz diorites to about sixty per cent in the granites and averages about twenty per cent for the entire intrusive mass. No potash feldspars occur within the interstitial areas as a late-magmatic crystallization product along with interstitial, late-magmatic quartz. The potash-rich feldspars are only associated with the crystalloblastic varieties of quartz and not with the magmatic quartz, and they appear to only occur in a replacement relationship to plagioclase. There seems to be no uniform areal distribution of the various rock types; in other words, the rocks which have crystallized only in the magmatic stages are rather intimately associated with the rocks which underwent further crystallization during the deuteric stage. Such spatial relationships indicate that the potash was introduced at a later time, following the complete consolidation of the magma. It seems probable that if the potash was already present in the rocks at the time of their final magmatic consolidation, some potash feldspars should occur with interstitial and non-crystalloblastic quartz, assuming that the potash content was too high for the potash to have been held within the plagioclase. Fractures may have controlled the distribution of these late potash and silica rich solutions. During this stage of introduction of silica and its precipitation as crystalloblastic quartz, part of the already crystallized interstitial magmatic quartz seems to have recrystallized, and possibly some of it has been redistributed at this stage.

The mafic mineral content ranges from twenty-one per cent to two per cent and averages about seven per cent. Green hornblende is the dominant mafic constituent, and biotite is second in abundance. Relicts of a monoclinic pyroxene, probably augite, occur in a few rocks from near the eastern border of the intrusion. Usually, however, the pyroxene has been completely altered to deuteric uralite (see figure 20, page 84). The uralite is a felty mass of colorless to pale greenish amphibole, probably actinolite, in which the greenish absorption becomes much stronger toward the periphery. The uralitic masses are commonly surrounded by a discontinuous rim of biotite. The uralite usually occurs as ragged, irregular masses, but rarely it forms quite euhedral pseudomorphs after the earlier pyroxene. The well formed green hornblende is fine to medium in grain size and is mostly of anhedral to subhedral form; it rarely becomes as euhedral as the hornblende phenocrysts shown in figure 25 (page 91). The absorption of the hornblende is: X = pale tan, Y = patchy and irregularly mottled brownish-green, and Z = dark green. The extinction angle, Z to c on (010) is 18°. The hornblende is often highly altered to actinolitic hornblende, biotite, or to irregular masses of chlorite and epidote. The alteration of the hornblende to actinolitic hornblende and/or to biotite seems to have occurred in the latest magmatic to deuteric stages of crystallization, whereas the hornblende in the rocks which have undergone intense hydrothermal alteration has been nearly completely altered to chlorite and epidote. Biotite is fine to medium in grain size and is dominantly subhedral, but it occasionally is euhedral. The biotite has mostly formed from hornblende, with which it is commonly associated in irregular masses. In the hydrothermally altered rocks much of the biotite has been highly chloritized. Most of the euhedral biotite is not associated with hornblende relicts and therefore may be of primary, magmatic origin. Pyrite is present

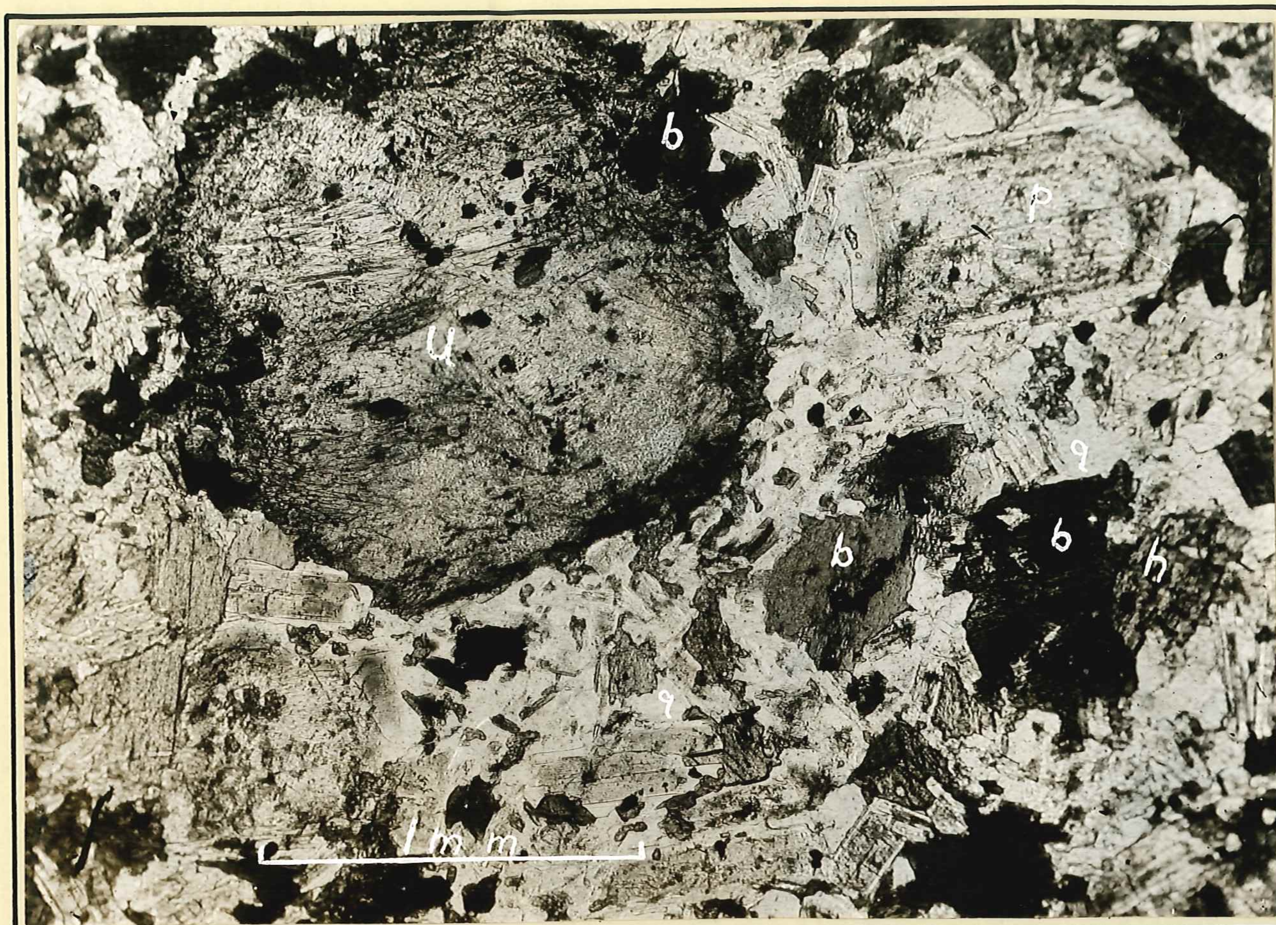


Figure 20.

Photomicrograph of Miners Ridge quartz diorite (specimen 8.8.55.13) from just east of Image Lake (station 34). Plane polarized light.

Pseudomorph of uralite (u) has formed after early pyroxene and has preserved the euhedral form of the pyroxene. The uralite is a felty mass of pale green to colorless amphibole which becomes darker green at the borders of the pseudomorph. Biotite and magnetite are present as inclusions within the uralite. Biotite (b) forms a discontinuous border around the pseudomorph,and is also present in the groundmass where it has formed partly after a brownish-green hornblende (h). Plagioclase (p)forms euhedral to subhedral,normally zoned crystals. Quartz (q) is interstitial.

Figure 21.

Photomicrograph of a slightly porphyritic quartz diorite (specimen 8.8.55.2) collected from about one-half mile northeast of Image Lake (station 26). Crossed nicols.

The quartz (q) is predominantly interstitial but in part it has become slightly crystalloblastic and has just begun to replace plagioclase (p_1). Note the strong oscillatory zoning of the plagioclase crystal (p_2) and the weakly developed albite twinning. The twinning as yet seems to have had little effect upon the zoning but in most cases where twinning is present the zoning is partially to completely destroyed. Mafic minerals are biotite (b) and green hornblende (h).

Figure 22.

Photomicrograph of a deuterically altered quartz diorite (specimen 7.2.55.11)collected from about one-half mile east of Canyon Creek on the Suiattle River trail (station 10). Crossed nicols.

The earlier plagioclase has been rather strongly attacked and altered by potash-rich feldspars and quartz, and granophyric intergrowths have been produced. The irregular albitic rim of the strongly zoned plagioclase crystal in the upper center of the photomicrograph may have been the result of this replacement action, but this is not certain since albitic rims are common around plagioclase grains in unaltered rocks also.

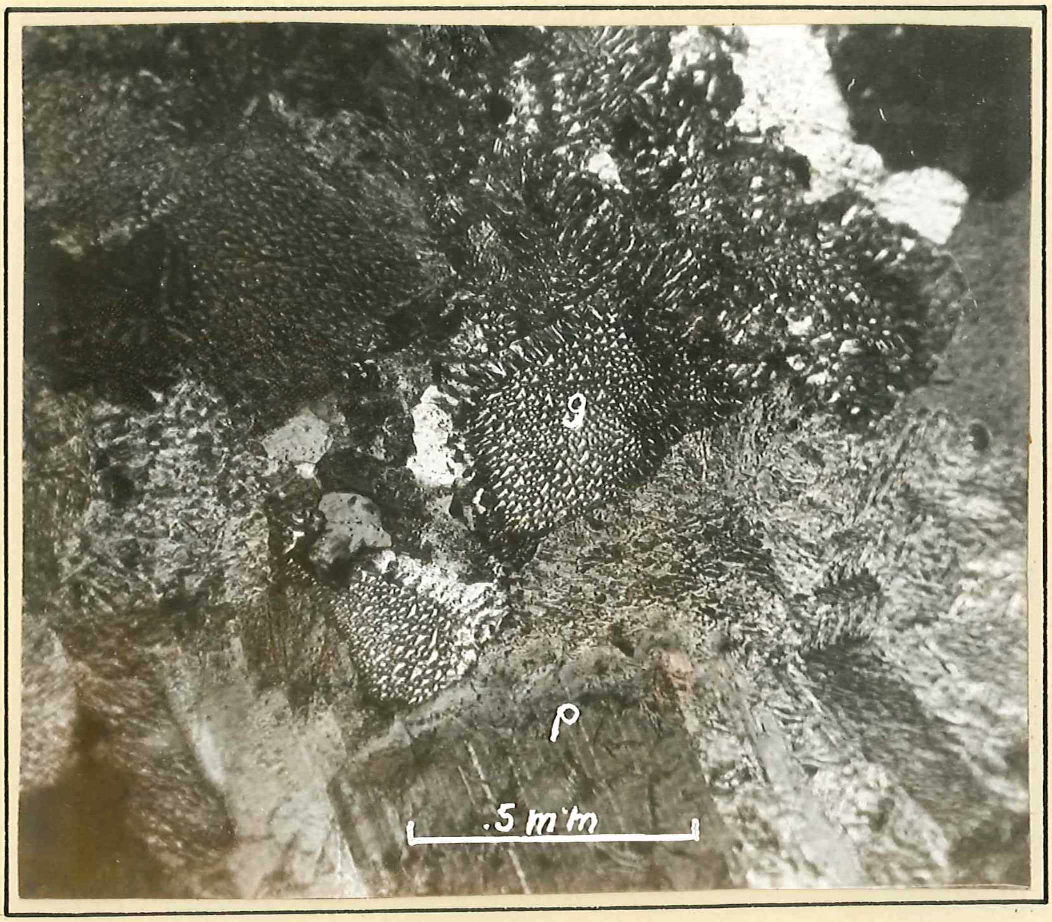


Figure 23.

Photomicrograph of a deuterically altered granite (specimen 8.14.55.7) collected from about one-half mile west of Miners Ridge lookout (station 42). Crossed nicols.

In this specimen, granophyric intergrowths (g) of quartz and potash feldspar have replaced most of the plagioclase. Only a few relicts of plagioclase (p) remain. In such a highly altered rock, the plagioclase only rarely shows oscillatory zoning, and the zoning is much weaker and more gradational than in the zoned plagioclase cryatals of fresh quartz diorite.

in a few of the masses of chlorite and epidote and probably represents a late hydrothermal stage of replacement.

Inclusions

Included blocks of darker and finer-grained hornblende-bearing micro-quartz diorite are rather common within the coarse-grained and leucocratic granitic rocks which occur along the top of Miners Ridge from Image Lake to the western end of the ridge. Granitic rocks which crop out along the Suiattle River are free of such inclusions; therefore the presence of these inclusions seems to be a function of depth within the granitic mass. They occur as angular blocks ranging in size from a few feet to more than fifty feet in diameter. Microscopically, there is neither evidence of reaction between the material of the inclusion and the enclosing granitic rocks, nor does the granitic rock change in grain size adjacent to the inclusion. In hand specimen, these inclusions are quite distinctive from the enclosing granitic rocks; they are fine-grained and dark-grayish in color, and contain abundant long needles of hornblende. The contact between the inclusion and the granitic rock is always sharp, both in hand specimen and microscopically. Microscopically, the micro-quartz diorite contains about eighty-five per cent plagioclase, seven per cent quartz, and eight per cent brownish-green hornblende. The plagioclase is euhedral to subhedral, and occurs as long laths which are haphazardly arranged,thus giving the suggestion of a slightly diabasic texture (see figure 24, page 90). The plagioclase is usually calcic andesine, but varies slightly to sodic labradorite. The plagioclase usually shows strong normal zoning from calcic andesine or sodic labradorite cores to sodic oligoclase rims. Occasionally oscillatory zoning is present, but it is never as well developed as it is in the enclosing granitic rocks. Quartz occurs interstitially, but it is much less abundant than in the surrounding coarser-grained rocks. Hornblende, on the other hand, is more abundant in the inclusions than in the enclosing granitic rocks. Similar inclusions have been described by Morrison (1954) in the quartz labradorite porphyry stocks on Phelps Ridge, and they are also present in many other pre- to early-Tertiary quartz dioritic intrusions in the northern Cascades (Misch and Vance, personal communication; Yeats, 1956, page 33). The origin of these inclusions is uncertain. If they are xenoliths of country-rock which have been brought up from depth, then it must be explained how such similar material can occur in the late, igneous, quartz dioritic intrusions throughout the northern Cascades. As no earlier, relict metamorphic textures are present within the inclusions, they cannot be conclusively demonstrated to have been derived from the melting of metamorphic xenoliths at depth; therefore they would have to be interpreted as being xenoliths of fine-grained, basic igneous rocks which occur as wall-rocks at depth. Such an hypothesis might account for these inclusions in one or two granitic intrusions, but it probably could not explain their widespread occurrence. Instead, it is possible that these inclusions are related to earlier stages in the magmatic history of the intrusive mass itself.

Just northwest of Image Lake occur a few scattered inclusions of hornfelsized schist. Xenoliths of this type, however, are very rare and, as they only occur near the contacts, indicate that magmatic stoping was probably an insignificant process and was not the dominant mechanism of emplacement of the quartz dioritic mass on Miners Ridge. These xenoliths are composed of thirty per cent plagioclase, ten per cent quartz, thirty-five per cent biotite, and twenty-five per cent green hornblende. Most of these small xenoliths have been highly biotitized and hornfelsized (see figure 25, page 91). Euhedral hornblende crystals, and occasionally phenocrysts, are commonly present around the hornblende-rich xenoliths. The amount of hornblende in the granitic rocks near such inclusions is about twenty per cent, which is much more than the usual per centage present in the granitic rocks elsewhere; this probably indicates that basic material from the inclusions has been assimilated by the magma in the vicinity of such inclusions.

Interpretation

Structural evidence indicates that the granitic mass on Miners Ridge was probably emplaced by the forceful shouldering aside of the adjacent metamorphic country rocks. The evidence consists of bowing-out of the trends of the schistose wallrocks on the western and northwestern sides of the intrusive body. South of the Suiattle River, the amphibolites, hornblende-bearing schists and trondhjemitic gneisses strike northwesterly, whereas to the north on Sulphur Mountain, the gneissose

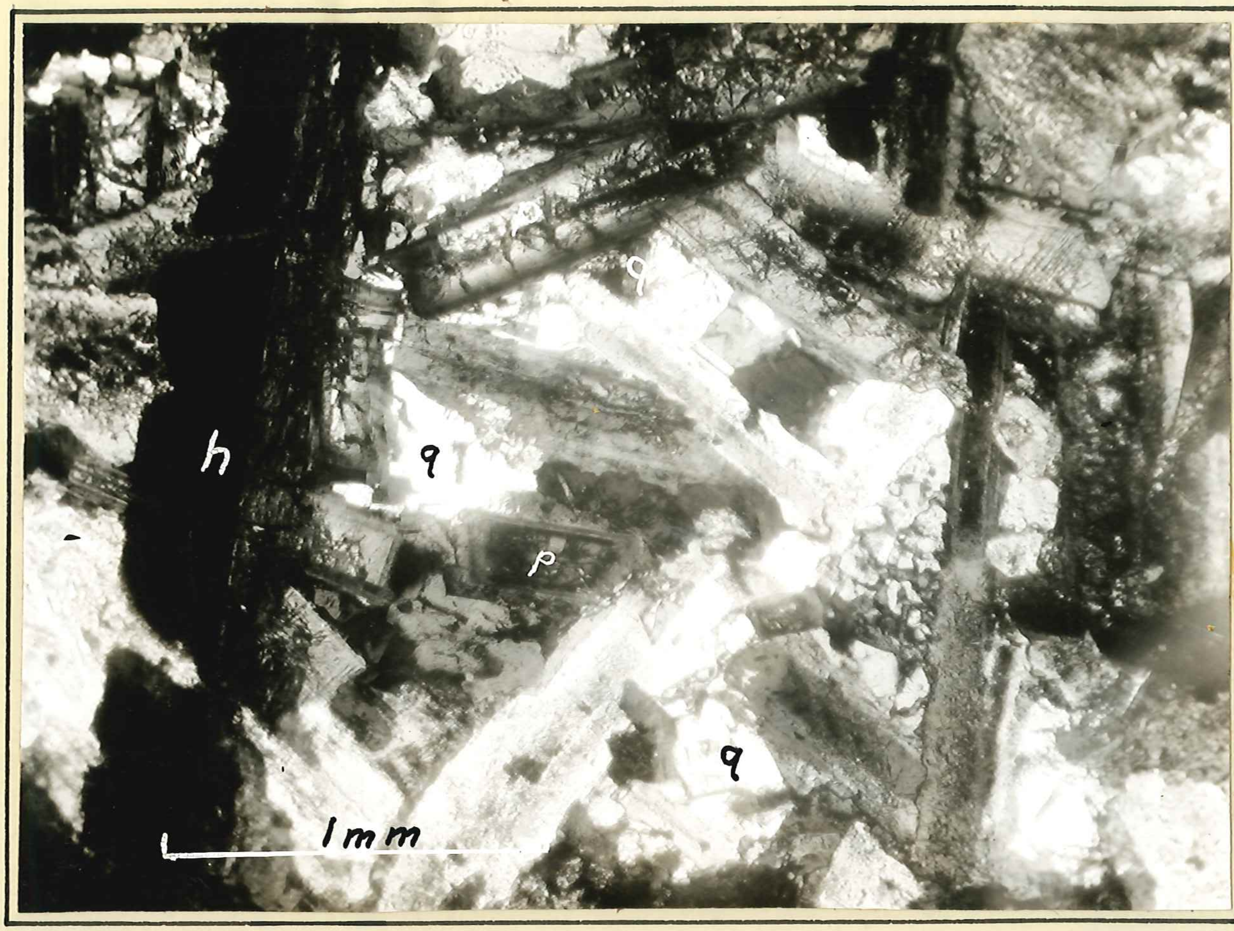


Figure 24.

Photomicrograph of a slightly diabasic-textured, hornblende - bearing micro - quartz diorite (specimen 8.14.55.13), typical of the included blocks in the intrusive quartz diorite. This specimen was collected from the western end of Miners Ridge (station 48). Crossed nicols.

Plagioclase (p) forms elongated crystals which are haphazardly arranged. The plagioclase is usually normally zoned, but oscillatory zoning is also present (note darker crystal near center of photomicrograph). Quartz (q) is interstitial. Hornblende (h) forms long, thin crystals which usually have irregular, light green actinolitic borders.

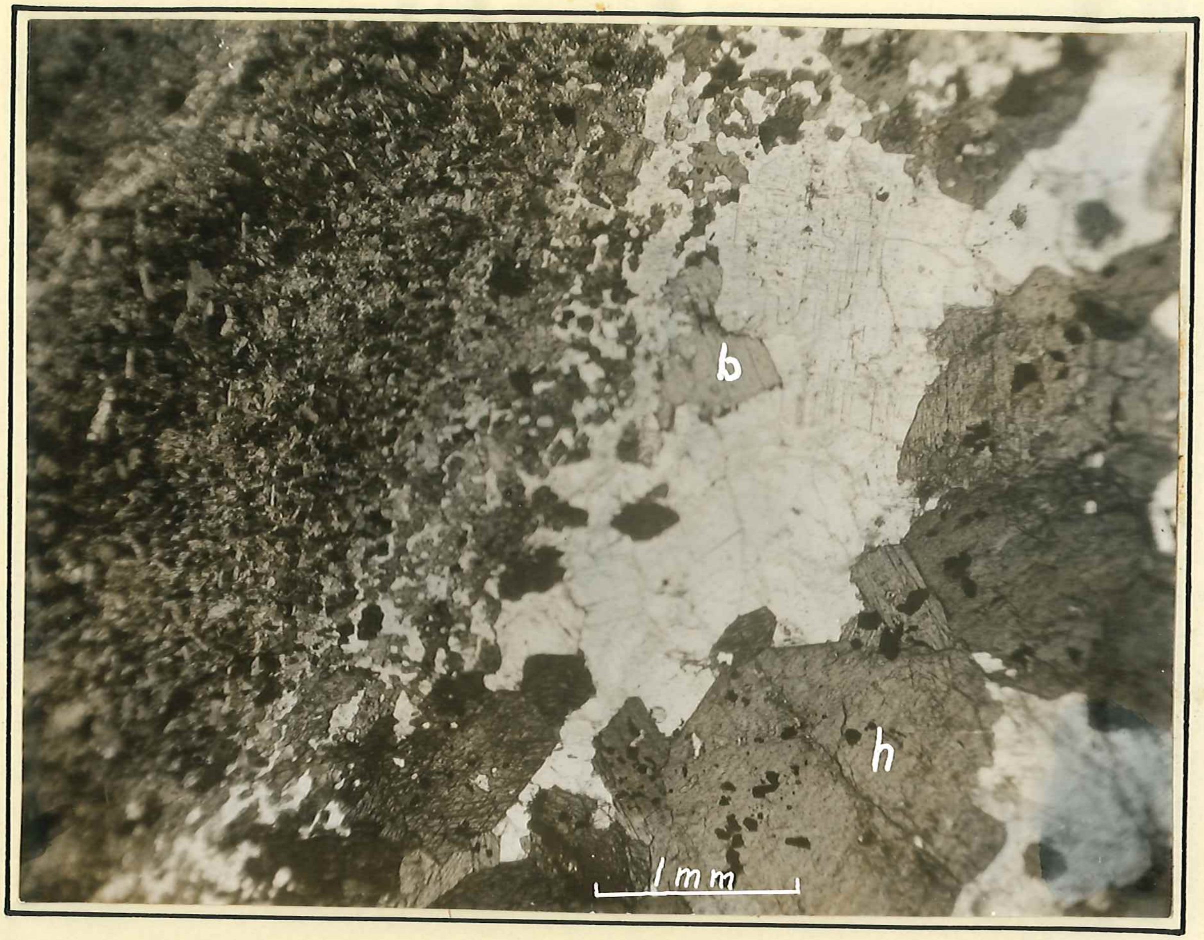


Figure 25.

Photomicrograph of the contact between a hornfelsized and biotitized originally schistose,hornblende rich xenolith (left) and the intrusive granitic rock (right). This specimen (8.8.55.10) is from the peak just northwest of Image Lake (station 31). Plane polarized light.

Large,euhedral green hornblende crystals (h) are common in the granitic rock near the contact with the xenolith. The granitic rock is richer in hornblende in a narrow zone around such biotitized, hornblende-rich schist inclusions; this suggests that some basic material has been incorporated in the magma. Biotite (b) is usually quite euhedral.

portions of the migmatitic trondhjemites, and the isochemical relicts occurring within the more directionless trondhjemites, strike from seventy to eighty degrees northeast. The isochemical rocks of the Green Mtn. unit which Bryant (1955) mapped on Downey Mtn. also have east-northeasterly trends. The metamorphic rocks west of the intrusion thus form an arc which is concave toward the intrusive body of quartz diorite on Miners Ridge. It is therefore probable that the intrusive movement of this granitic mass was not only upward, but also westward; this is indicated by the fact that the metamorphic rocks on the west are bent out, whereas those to the east of the intrusion are still parallel to the northwesterly regional trends. Similar structural relationships were used by Misch (1952a, pages 14-18) in the area north of Cascade Pass to demonstrate the forceful intrusion of such masses as the Hidden Lake Peak granodiorite and the Golden Horn granodiorite, and the northeastward movement of the latter from a magma-generating region within the Skagit gneisses to the southwest.

Obviously igneous textures within the intrusive mass are shown by the euhedral and highly zoned plagioclase crystals, by the euhedral early pyroxene, by the euhedral biotite, and by the interstitial nature of the quartz.A few aggregates of anhedral green hornblende and biotite crystals are very similar to some of the mafic-mineral aggregates in the metamorphic rocks on Sulphur Mtn.,and therefore they may be relicts of an earlier metamorphic rock from which the magma possibly was derived by liquifaction. Time relationships between the magmatic, euhedral plagioclase crystals and these anhedral mafic-mineral aggregates could not be determined conclusively, however. Similar mafic-mineral aggregates, and also the occurrence of quartz as phenocrysts, have been described by M. E. Morrison (1954, page 63) from the intrusive quartz-labradorite porphyry stocks on Phelps Ridge. These features were interpreted by Morrison as suggesting that the magma from which the quartz-labradorite porphyry consolidated, was derived by the liquifaction of an earlier metamorphic rock. The dominance of igneous textures in the granitic rocks of Miners Ridge, indicates that the parent material was in an almost completely, if not entirely, liquid state at the time that it began to consolidate. Misch (1952a, page 14) has observed similar features in the mobilized and intrusive portions of the Chilliwack granodioritic mass north of Cascade Pass, in which the textures of the intrusive rocks indicate every gradation from a completely crystalline to a liquid state of the intrusive material. The intrusive granitic rocks of Miners Ridge seem to belong in the same major tectonic belt with the mobilized portions of the Chilliwack granitic body northwest of Cascade Pass.

Finer-grained borders are absent where the contact of the intrusive quartz diorites with the metamorphic country rocks is exposed east of Image Lake. The contacts of the intrusive mass with the migmatitic gneisses to the west and north are not exposed. The absence of finer-grained granitic rocks near the contacts could be explained by intrusion at considerable depth or by intrusion during the late stages of the orogeny which produced the regionally metamorphosed rocks and while the wallrocks were still warm, although it is equally possible that the intrusion was connected with a later orogeny.

Following the consolidation of the magma, the plagioclase in some of the quartz diorites was attacked and partially replaced by late quartz and potash-rich feldspars. In such deuterically altered rocks, the latest textures are crystalloblastic, and they have been superimposed upon the earlier igneous textures. These late crystalloblastic textures are unrelated to, and easily distinguished from, the possible relicts of early metamorphic textures. As the potash-rich feldspars always have late-crystalloblastic textures, it seems to be indicated that the potash was introduced in the deuteric stage and was not present in the magma at the time of its final consolidation. Quartz, on the other hand, is a common interstitial constituent of those quartz diorites which have only igneous and no superimposed deuteric textures, and therefore quartz was present at the time of final magmatic consolidation. The quartz seems to have become crystalloblastic and started to replace the plagioclase (see figure 21, page 85) before the potash-rich feldspars began to form.

The age of the intrusion of the granitic rocks on Miners Ridge, other than being post-metamorphic (post lower Jurassic?), cannot be demonstrated within the area of this report as no post-metamorphic sedimentary rocks are present. The intrusion is, however, probably related to the late Cretaceous or early Tertiary periods of granitic intrusive activity which have been dated elsewhere in the northern Cascades.

Summary of the Migmatitic and Igneous Granitic Rocks

The weakly gneissose and directionless trondhjemites and locally granodiorites which occur primarily on Sulphur Mtn. and locally on the ridges east and west of Grassy Point, are of migmatitic derivation as is indicated by:

(1.) Crystalloblastic textures are dominant throughout the area. Locally, late cataclastic effects are present which were probably the result of the mobilization of material that was still in a crystalline state.

(2.) The abundant epidote minerals which are contemporaneous with plagioclase indicate that temperatures were too low for the material to be in the magmatic state.

(3.) Apart from epidote minerals, other metamorphic minerals such as garnet are occasionally present.

(4.) The foliation of the more isochemical relicts within the highly migmatitic rocks is parallel to the relict foliation in the more gneissose portions of the trondhjemites and is also parallel to the schistosity of the isochemical rocks of the Green Mtn. unit which occur to the northwest on Downey Mtn.

(5.) The contacts of the migmatitic trondhjemites with the more heterogeneous migmatitic gneisses west of Totem Pass and with the isochemical schists and amphibolites of the Green Mtn. unit are extremely gradational.

(6.) The isochemical rocks which occur to the south on Grassy Point strike northwards into the migmatitic trondhjemite mass on Sulphur Mtn., thereby indicating that no large scale forceful intrusion and shouldering aside of the surrounding rocks have occurred.

The migmatitic trondhjemitic gneisses, and granodiorites on Sulphur Mtn. have formed by the allochemical metamorphism of hornblende-rich, probably in part amphibolitic, rocks such as are present on Grassy Point to the south. This type of parent material is indicated by:

(1.) Nearly isochemical relicts of retrogressively altered amphibolite are occasionally present within the migmatitic, granitic mass.

(2.) Biotite is nearly everywhere associated with clinozoisite,thus indicating a derivation from former hornblende by the addition of potash to form the biotite and with the concomitant segregation of clinozoisite. The green hornblende which is present shows all stages of this biotitization from nearly unaltered grains to tiny, faintly pleochroic relicts surrounded by biotite and clinozoisite.

(3.) Relict structures within the trondhjemitic mass trend , in part, into the isochemical amphibolites and hornblende bearing schists to the south on Grassy Point.

(4.)The rocks on Grassy Point show all stages of this transformation from isochemical amphibolite and hornblende-bearing schist, through the intermediate stages of feldspathization and recrystallization, and finally into leucocratic and coarse-grained trondhjemitic gneisses.

Silica, soda, and minor potash were metasomatically added to the amphibolites and hornblende-bearing schists to produce the migmatitic trondhjemites which occur on Sulphur Mtn. The potash metasomatism was very minor throughout the period of migmatitization.In the earlier stages, potash was introduced only in amounts sufficient to cause the biotitization of much of the hornblende; whereas in the very latest stages of static metamorphism potash was locally introduced in sufficient amounts to allow up to ten per cent microcline to form. The late potash introduction is absent in the migmatitic gneisses near Totem Pass and those in the vicinity of Ptarmigan Glacier, which did not recrystallize appreciably during the static phase of the metamorphism.

The temperatures of the final stage of recrystallization of the migmatitic rocks vary somewhat within the mesozone. The latest recrystallization of plagioclase in the weakly gneissose and directionless trondhjemites of Sulphur Mtn. occurred at temperatures of the medium to cooler mesozone,as is indicated by the stable mineral assemblage of calcic oligoclase plus clinozoisite and epidote. Relict crystals of diopsidic pyroxene in some of these trondhjemites indicate that temperatures were once at least as warm as the hotter portion of the kyanite zone, however. The migmatitic gneisses near Totem Pass contain sodic andesine in stable association with epidote minerals which place the temperature of crystallization of the plagioclase at least in the middle mesozone. Here also, as in the migmatitic trondhjemites of Sulphur Mtn., the presence of relict pyroxene indicates that temperatures were once at least as high as the hotter mesozone. In the less strongly migmatized rocks southeast of Image Lake on Miners Ridge, the plagioclase varies from calcic andesine to sodic labradorite, which, as it was stable with clinozoisite, indicates a temperature near the meso-katazonal boundary. Diopsidic pyroxene is abundant in these gneisses from southeast of Image Lake.

Following the static phase of metamorphism, the highly migmatized trondhjemites of Sulphur Mtn. locally became mobilized and formed an intrusive contact against the isochemical rocks of the Green Mtn. unit to the west. The material comprising the stock-like mass on the western spur of Grassy Point was mobilized as a completely crystalline body, whereas the material forming the intrusive, trondhjemite stock mapped by Bryant (1955) on Downey Mtn. was almost completely liquified.

This sequence of events, although on a smaller scale, is somewhat similar to that described by Misch (1952a)from north of Cascade Pass where Skagit gneiss has been further granitized on the west to form the Chilliwack granodiorite. The eastern portions of the Chilliwack granodioritic mass remained in place, whereas the western portions became mobilized and intrusive against and into the isochemically metamorphosed rocks on the west. Several smaller bodies of granodiorite became entirely detached from the main Chilliwack granodiorite mass and migrated westward and upward, forming small, isolated stocks such as that at Hidden Lake Peak. Textures indicate that the mobilized portions of the Chilliwack mass in some places were crystalline, although sufficiently plastic to move, and in other places were liquid (Misch, 1952a, page 16). All gradations occur between these two extreme types.

Following the orogeny which produced the schists, amphibolites, gneisses, and granitic rocks of migmatitic origin, was the emplacement of the mass of intrusive quartz diorite and other related granitic rocks which occur on Miners Ridge. These directionless granitic rocks appear to have been almost completely, if not fully, magmatic. The magmatic origin of the granitic rocks on Miners Ridge is indicated by the following facts:

(1.) The textures of most of the quartz diorites which have not undergone deuteric recrystallization are dominantly igneous; that is,the plagioclase is euhedral and is highly oscillatorily zoned, the quartz is interstitial, and some of the biotite and green hornblende is highly euhedral. Porphyritic textures are locally present. Crystalloblastic textures are limited to (a) a few anhedral aggregates of mafic minerals which possibly represent earlier metamorphic relicts from the rocks which otherwise were melted to form the intrusive magma, and to (b) the far more widespread deuteric crystalloblastic, and occasionally porphyroblastic, growth of quartz and potash feldspars.

(2.) The rocks are completely directionless and entirely free even of traces of metamorphic relict parallel structure.

(3.) Early, euhedral pyrogenic pyroxene was present. The pyroxene now only occurs as relicts in pseudomorphs of uralite. Typically low temperature minerals such as epidote only occur as the result of hydrothermal alteration and were never in equilibrium with the plagioclase.

The intrusive emplacement of this magma is conclusively demonstrated by the bending out of the trends of the metamorphic rocks toward the west, which thus form an arc which is roughly concave toward the granitic mass of Miners Ridge. Stoping and assimilation were very subordinate compared to the forceful intrusion of the magma, as is indicated by the relatively few xenoliths occurring within the granitic mass and by their presence only near contacts. As the metamorphic rocks to the east of the Miners Ridge intrusion are not bent out, the intrusive movement of the magma appears to have been not only upward, but westward as well. Similar structural relationships were used by Misch (1952a, page 18) to show that the fully magmatic Golden Horn granodioritic mass moved upward and eastward from the central zone of Skagit gneiss. The Golden Horn granodiorite is the most recent large granitic intrusion in the area mapped by Misch, as it has displaced folds in Lower Cretaceous sedimentary rocks and also has displaced a thrust sheet of older greenstones which overlie Lower Cretaceous rocks.

Until the entire area surrounding the Miners Ridge intrusion has been geologically mapped, and especially the area to the east and northeast, the nature of this intrusion cannot be fully known: that is, whether it is an older mobilized and liquified mass such as some of the stocks related to the Chilliwack mass that have been mapped and described by Misch, or whether being fully magmatic, it is a much later pluton such as the fully magmatic Golden Horn granodiorite.

Glacier Peak Andesite Flow Remnants Southeast of Grassy Point

Two small erosional outliers of a former more extensive lava cover are present on the ridge to the east and south of Grassy Point. The northernmost remnant makes up the 6596 foot peak just east of Grassy Point. The 5958 foot knoll on the north-south trending ridge between Glacier Peak and Grassy Point is composed of the southern flow remnant. This southern flow remnant extends for an undetermined distance down into the valley of the East Fork of Milk Creek.

Abundant fragments of schist, amphibolite and leucocratic gneiss are present in the basal portions of the northern lava outlier. These accidental inclusions of the volcanic breccias are very similar to the underlying metamorphic rocks on this ridge; therefore they are probably the result of the picking up of talus material by the lavas as they advanced across the old, pre-lava erosion surface. Accessory blocks of older volcanic rocks are also present within these volcanic breccias.

The source of these flows undoubtably was Glacier Peak, the crater of which lies only about five miles to the south. The nearest Glacier Peak lava flow to the south is less than a mile away on this ridge which separates Dolly Creek from East Fork of Milk Creek. These andesite flow remnants probably represent one of the earliest phases of Glacier Peak activity as is indicated by the amount of erosion which has occurred following their extrusion. The lavas of these flow remnants also display a higher degree of weathering than most of the lavas on the flanks of Glacier Peak to the south; this also seems to indicate their higher age. In some of the samples from these flows, the plagioclase has been moderately to completely altered to sericite and calcite, the mafic minerals have been intensely chloritized, and the glass of the groundmass has been somewhat altered to chlorite and calcite.

Plagioclase is the dominant phenocryst, and as such, makes up nearly twenty-five per cent of the rocks. In hand specimen the plagioclase often has a blocky appearance which in thin section is seen to be due to a glomero-porphyritic clustering of smaller crystals. Glass inclusions frequently separate these individual crystals which have coalesced. Similar blocky plagioclase "phenocrysts" have been described by Howard A. Coombs from the Mt. Baker lavas (1939, page 1503) and also from the Mt. Rainier lavas (1935, page 72). The largest phenocrysts of plagioclase average about 3.3 mm in diameter and the smaller crystals in the groundmass range from microlites to about .1 mm. As all size gradations occur between groundmass plagioclase and the largest phenocrysts of plagioclase, no distinct types based upon size can be distinguished. The large phenocrysts display strong oscillatory zoning; from ten to fifteen recurrences are common. These phenocrysts range in average composition from An_{35} to An_{45}, and the cores of zoned crystals are frequently sodic labradorite, An_{55}. The groundmass plagioclase is only weakly zoned or unzoned. Its composition also varies between An_{35} and An_{45}. Many of the larger crystals have been fractured and sometimes fragments of the same crystal have become separated. In some of the crystals the zones are truncated, suggesting that part of the original crystal has broken off. The medium-sized and smaller phenocrysts rarely show fracturing, and the plagioclase of the groundmass never does.

Hypersthene is the dominant mafic constituent, and augite is minor. The hypersthene occurs both as phenocrysts and in the groundmass. The hypersthene makes up only a few per cent of the phenocrysts and about five per cent of the groundmass. Only the orthorhombic variety of hypersthene was observed, but only a few thin sections were studied and in some of them the mafic minerals are considerably chloritized. A more detailed study of the Glacier Peak lavas will probably show that the monoclinic variety of hypersthene, which is common to the other Pleistocene Cascade andesitic lavas, is also present. The hypersthene tends to be somewhat more euhedral than the augite. Augite is much less common than hypersthene and makes up only a fraction of a per cent of the groundmass. It does not occur as phenocrysts.

Glass, filled with fine grains and dust of opaque matter, probably magnetite, comprises nearly twenty per cent of the hyalopilitic groundmass. The microlites and fine-grained plagioclase laths are usually aligned by flowage.

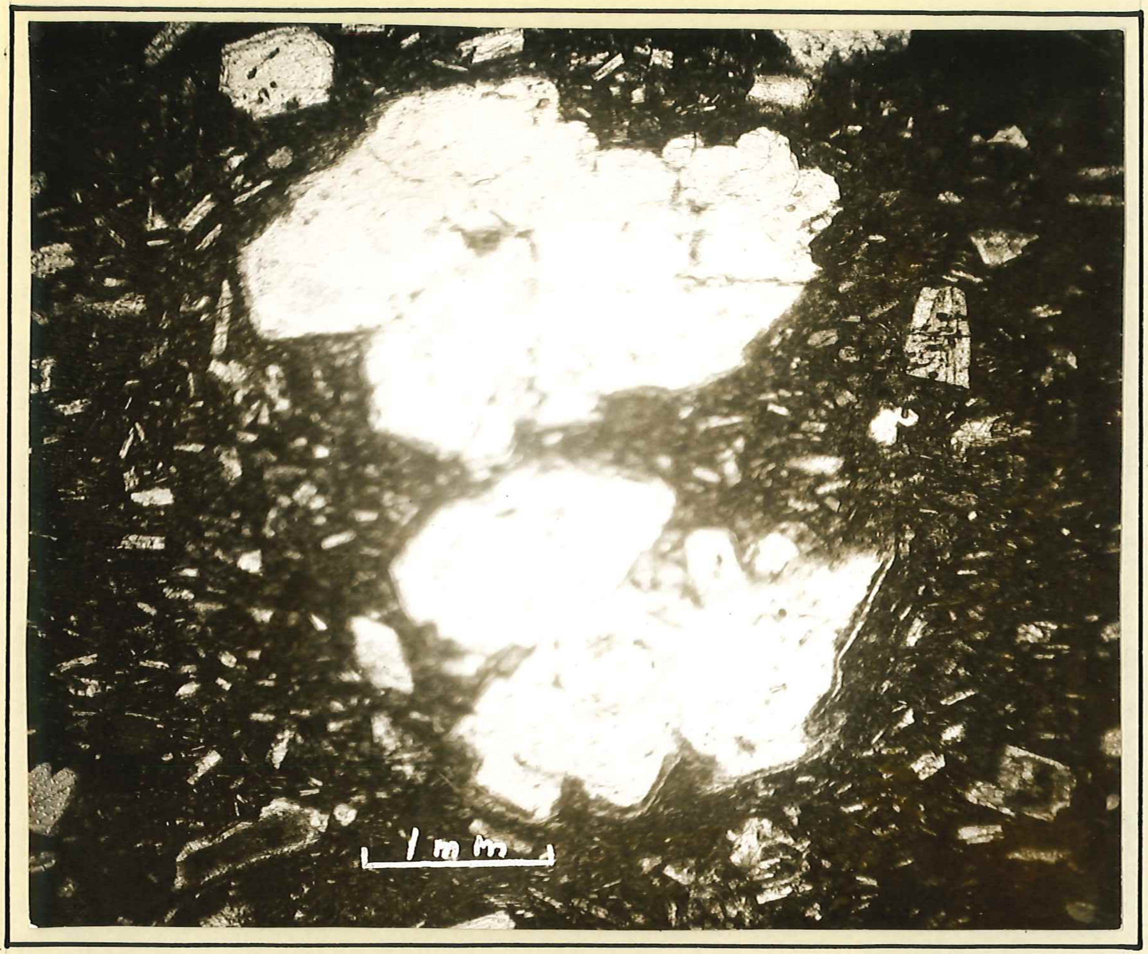


Figure 26.

Photomicrograph of a glomero-porphyritic andesite from a Glacier Peak flow (specimen 7.12.56.1) collected just north of the 5958 foot hill south of Grassy Point (station 222). Plane polarized light.

Each of these two larger plagioclase "phenocrysts" are actually composed of two or more smaller crystals which have coalesced. Note the inclusions which mark the boundaries of these joined crystals. Also note the strong resorption of the lower margins of the lower "phenocryst". The groundmass has a hyalopilitic texture and a very dark color which is due to the abundance of magnetite dust.

REFERENCES

Angel, Franz. (1924) Gesteine der Steiermark. Band 60, der Mitteilungen des Naturwissenschaftlichen Vereines fur Steiermark.

Bryant, Bruce H. (1955) Petrology and Reconnaissance Geology of the Snow-king Area, Northern Cascades, Washington. PhD thesis, Department of Geology, University of Washington.

Coombs, Howard A. (1935) The Geology of Mount Rainier National Park. PhD thesis, Department of Geology, University of Washington.

__________. (1939) "Mt. Baker, A Cascade Volcano". Geol. Soc. Am. Bull., vol. 50, pp. 1493-1510.

Du Bois, Robert L. (1954) Petrology and Genesis of the Ores of the Holden Mine Area, Chelan County, Washington. PhD thesis, Department of Geology, University of Washington.

Goodspeed, G. E. (1940) "Dilation and Replacement Dikes". Journ. Geol., vol. 48, pp. 175-195.

__________. (1948) "Xenoliths and Skialiths". Amer. Journ. Sci., vol. 426, pp. 515-525.

Grout, Frank F. (1941) "The Formation of Igneous-looking Textures by Metasomatism". Geol. Soc. Am. Bull., vol. 52, pp. 1525-1576.

Misch, Peter. (1952a) "Geology of the Northern Cascades of Washington". The Mountaineer, vol. 45, no. 13, pp. 4-22.

__________. (1952b) "Syn- and Post-orogenic Granite Evolutions in the Northern Cascades of Washington". (abst.) Geol. Soc. Am. Bull., vol. 63, pp. 1339-1340.

__________. (1952c) "Some Special Criteria for Granitization". (abst.) Geol. Soc. Am. Bull., vol. 63

__________. (1954) "Zoned Plagioclase in Metamorphic Rocks". (abst.) Geol. Soc. Am. Bull., vol. 65, p. 1267.

Morrison, Melvin E. (1954) The Petrology of the Phelps Ridge - Red Mountain Area, Chelan County, Washington. MS thesis, Department of Geology, University of Washington.

Oles, Keith F. (1951) <u>The Petrology of the Stevens Pass - Nason Ridge Area, Washington</u>. MS thesis, Department of Geology, University of Washington.

Russell, I. C. (1900) <u>A Preliminary Paper on the Geology of the Cascade Mountains</u>. U.S.G.S. 20th Ann. Rept., pt. 2, pp. 83-210.

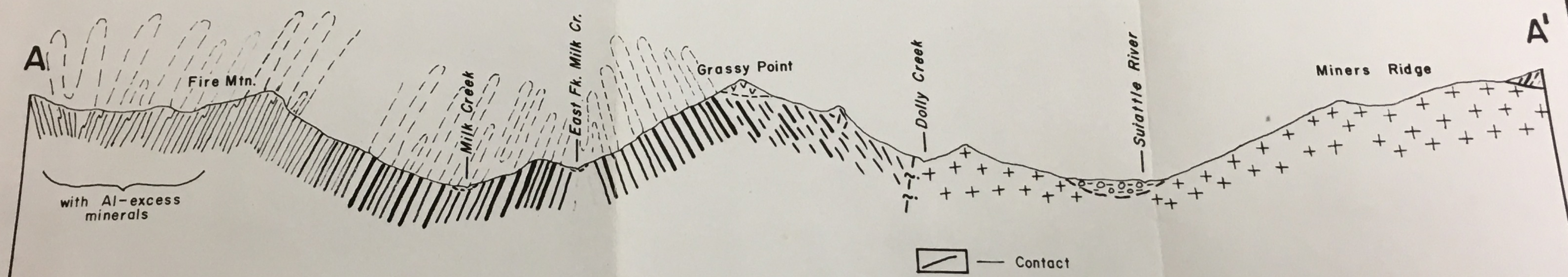
Smith, Warren S. (1916) "Stratigraphy of the Skykomish Basin". <u>Journ. G eol.</u>, vol. 24, pp. 559-582.

Wahlstrom, Ernest E. (1947) <u>Igneous Minerals and Rocks</u>. New York, John Wiley and Sons, Inc.

Winchell, Alexander N. and Horace Winchell. (1951) <u>Elements of Optical Mineralogy</u>. New York, John Wiley and Sons, Inc.

Yeats, Robert S. (1956) <u>Petrology and Structure of the Mt. Baring Area, Northern Cascades, Washington</u>. MS thesis, Department of Geology, University of Washington.

GEOLOGIC CROSS – SECTION
OF THE
SULPHUR MTN. AREA



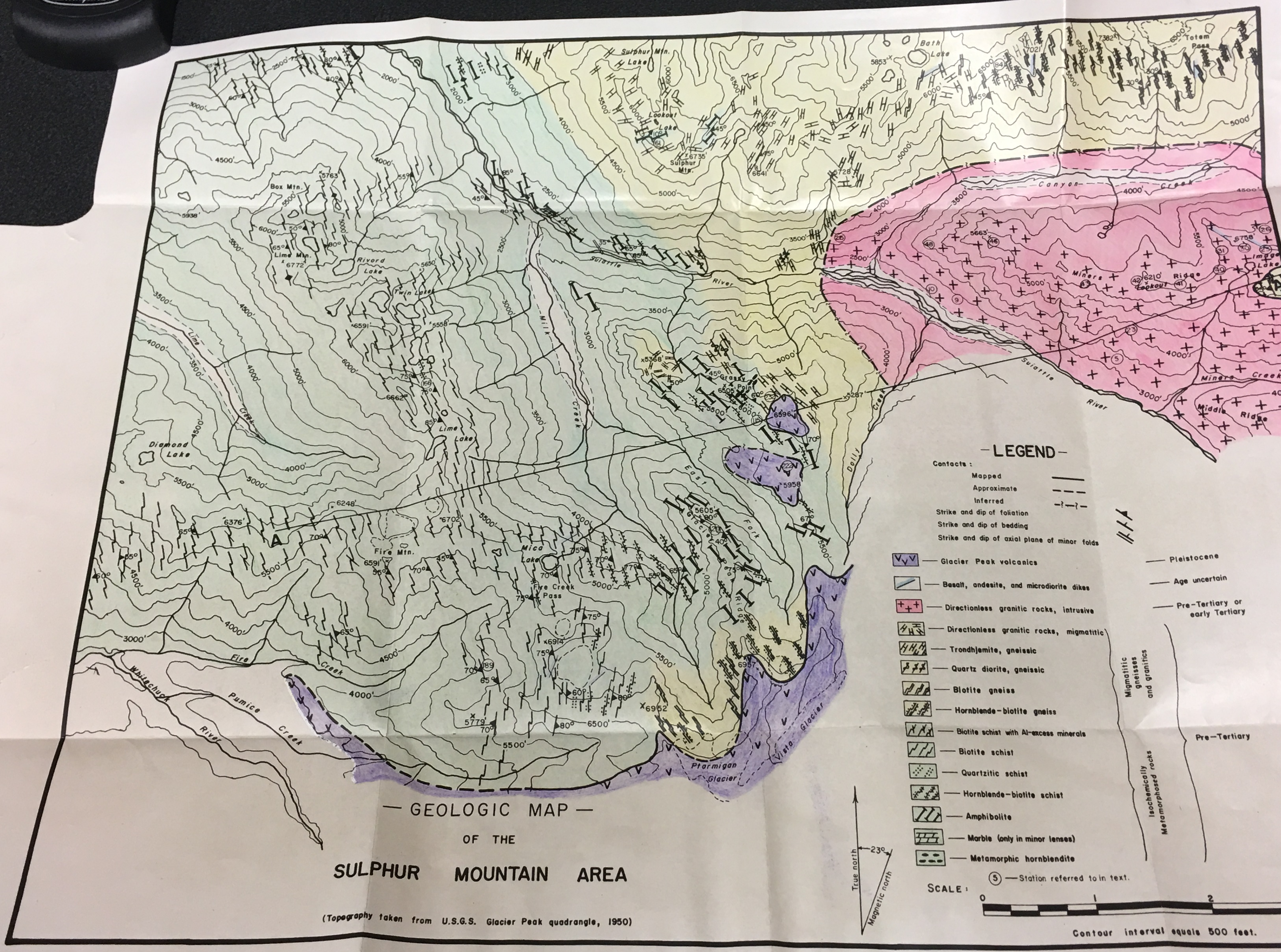
- Contact
- Alluvium
- Directionless granitic rocks, intrusive.
- Homogeneous migmatitic gneisses
- Migmatitic gneiss with amphibolitic remnants.
- Biotite schist.
- Hornblende-bearing schist.
- Amphibolite

Plane of section is approximately normal to regional structural trends.
Elongation of symbols indicates approximate dip of foliation.

Scale : (vertical = horizontal)
0 1 2 3 mi.

A. B. Ford

PLATE 3



— GEOLOGIC MAP —
OF THE
SULPHUR MOUNTAIN AREA
(Topography taken from U.S.G.S. Glacier Peak quadrangle, 1950)
Sulphur Mtn.
Lookout Lake
Bath Lake
Totem Pass
Canyon Creek
Suiattle River
Box Mtn.
Lime Mtn.
Rivord Lake
Twin Lakes
Milk Creek
Lime Creek
Diamond Lake
Lime Lake
Grassy Point
East Fork
Dolly Creek
Miners Ridge
Lookout
Image Lake
Miners Creek
Middle Ridge
Fire Mtn.
Mica Lake
Fire Creek Pass
Fire Creek
Whitechuck River
Pumice Creek
Ptarmigan Glacier
Vista Glacier
— LEGEND —
Contacts :
Mapped
Approximate
Inferred
Strike and dip of foliation
Strike and dip of bedding
Strike and dip of axial plane of minor folds
— Glacier Peak volcanics
— Basalt, andesite, and microdiorite dikes
— Directionless granitic rocks, intrusive
— Directionless granitic rocks, migmatitic
— Trondhjemite, gneissic
— Quartz diorite, gneissic
— Biotite gneiss
— Hornblende-biotite gneiss
— Biotite schist with Al-excess minerals
— Biotite schist
— Quartzitic schist
— Hornblende-biotite schist
— Amphibolite
— Marble (only in minor lenses)
— Metamorphic hornblendite
— Pleistocene
— Age uncertain
— Pre-Tertiary or early Tertiary
Migmatitic gneisses and granitics
Isochemically Metamorphosed rocks
Pre-Tertiary
True north
Magnetic north
23°
5 — Station referred to in text.
SCALE: 0 1 2 3mi.
Contour interval equals 500 feet.
A.B. Ford