PETROLOGY AND STRUCTURE OF THE HIGGINS MOUNTAIN AREA, NORTHERN CASCADES, WASHINGTON

by

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I. INTRODUCTION

LOCATION

The Higgins Mountain area is in the western foothills of the Northern Cascade Mountains, about 60 miles northeast of Seattle, Washington (Fig. 1). More than three-fourths of the area mapped for this report is in Skagit county and the remainder is in Snohomish county. The area covered by the geologic map is bounded on the south by the North Fork of the Stillaguamish River and on the west by Rollins Creek and Ricks Creek. On the east, mapping was done up to about the 3,000 foot contour on North Mountain. The northern boundary is very irregular since it reflects the emphasis on "ridge running" during the field work. Generally the mapping was done further to the north on the ridges than in the valleys. Most of the mountainous part of the area is in the Mt. Baker National Forest. The lower slopes of the Stillaguamish Valley and the area north and west of Granite Lake are owned by the State of Washington or are privately owned.

None of the roads leading into the area are shown on any of the maps in this report. The state, county, and permanant Forest Service roads are shown on any reasonably detailed highway map that can be obtained at a gasoline

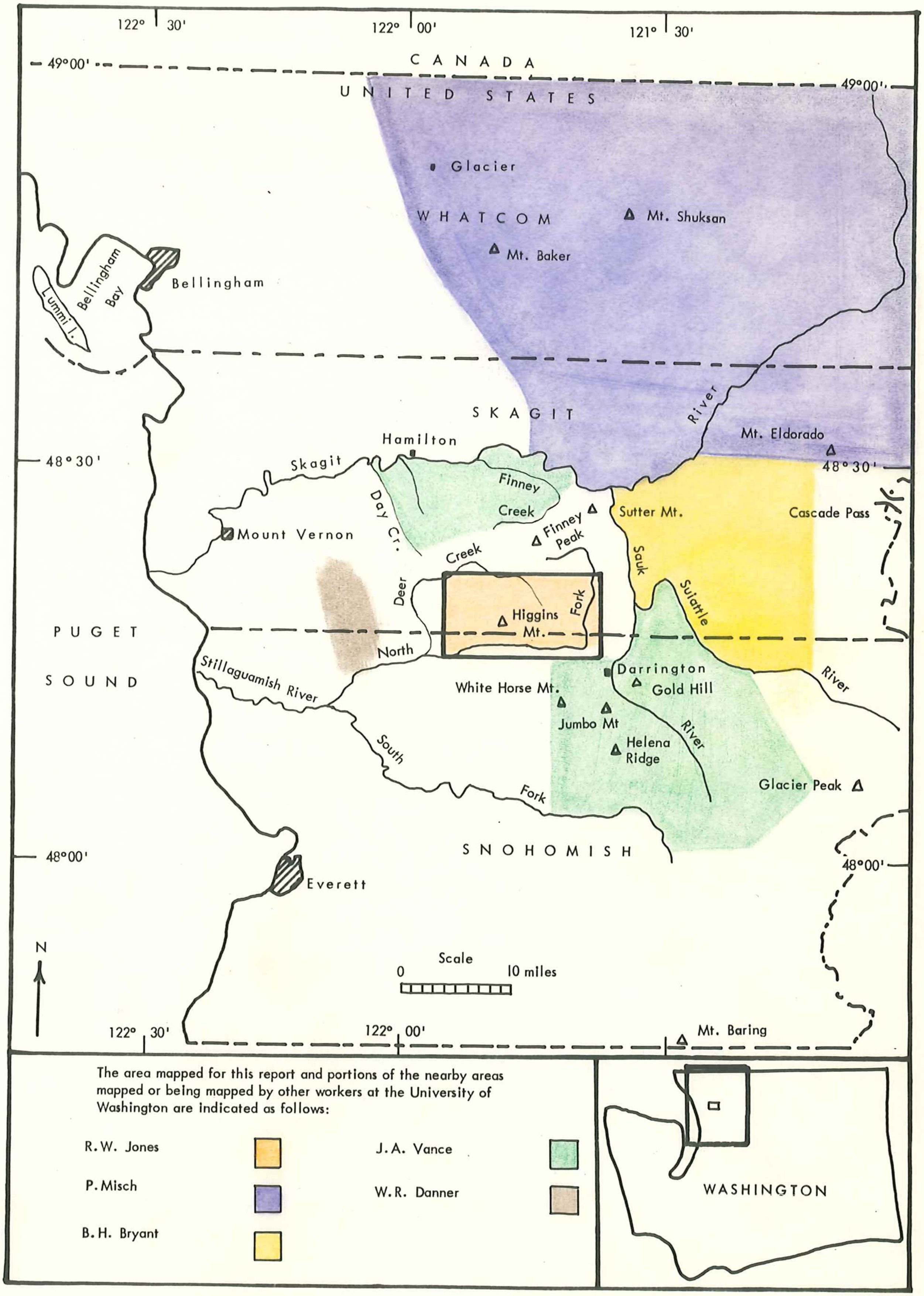


Fig. 1 Index and locality maps of the Higgins Mountain Area

station. Forest Service maps and county maps show some of the logging roads but since these are quite ephemeral, few such maps will be accurate.

Access to the area is provided by the Arlington-Darrington highway, a paved road which is open the year around although it is very rough in the late winter and early spring. In most of the mapped area, this road is on the south side of the Stillaguamish River. A county road crosses the Stillaguamish River at the foot of Swede Heaven and proceeds westward for several miles beyond Segelson Creek. The Forest Service maintains access roads on Swede Heaven and up the canyon of the Stillaguamish River between South Fork Ridge and North Mountain. From these access roads, numerous logging roads have been constructed on Swede Heaven, North Mountain, and the lower slopes of South Fork and Middle Fork Ridges. After logging ceases, these roads are not maintained. They can be traveled by jeep or truck for several years but eventually wash out and are impassable except on foot. In the summer of 1956, the Forest Service surveyed a road route along the west slopes of South Fork Ridge to the vicinity of Coney Pass and another route along the eastern slopes of South Fork Ridge. These roads probably will be constructed during the next few years. Information on currently passable roads may be obtained at the Forest Service office in Darrington. Access to the northwestern portion of the area is obtained on privately owned logging roads controlled by Puget Sound Pulp and Timber Company. Permission to travel these roads must be obtained from the company's logging superintendent at Clear Lake. A gate-keeper lives the year around at the company's Deer Creek Operations headquarters. The logging roads are passable from the late spring until the late fall.

The mountainous portions of the area may be reached by the remnants of a once extensive system of trails. With the exception of the trail to the Higgins Mountain Lookout, the trails have not been regularly maintained for many years. In many places, they have been obscured by fallen trees or washouts. Even in their present wretched state, these trails provide easier travel than cross-county "brush smashing". The approximate locations of these trails are shown on Forest Service maps and some county maps.

TOPOGRAPHY

The area consists of the east-west trending ridge which is a northerly extension of Higgins Mountain, and Round Mountain, South Fork Ridge, and North Mountain, which are north to northwesterly trending ridges. The highest point on Round Mountain is 5396 feet above sea level. The lowest point in the valley of the Stillaguamish River is about 270 feet above sea level. The north and south faces of Higgins Mountain and the northeast face of Round Mountain are precipitous cliffs. Most of the rest of the mountains are not as steep and usually can safely be climbed without resort to rock climbing techniques.

Precipitation is heavy, particularly as snow during the winter and rain in the fall and spring. The summers are usually cool and dry. There is considerable snow in the higher elevations from late fall to early summer. It is not uncommon for several feet of snow to remain in the lower elevations for a month or so in midwinter. Scattered patches of snow persist through much of the summer only in the highest elevations.

Vegetation is dense, especially in the valleys where in many places it fully deserves being called jungle. Most of the slopes support a heavy growth of Douglas Fir, hemlock, and cedar. Undergrowth in the wooded areas ranges from absent to jungle. Fallen trees up to 4 and 5 feet in diameter litter many of the wooded areas and make travel off of the trails exhausting, particularly under heavy pack. Nor are falling trees any respecters of trails. Except for the Higgins Lookout trail, downed trees require a certain amount of detouring. There is little if any true alpine country in the area. Barren rock slopes, heather meadows, and stunted trees are limited to the dip slopes and joint-controlled surfaces of the highest parts of the area underlain by the Swauk formation. Almost equally high areas underlain by the low grade metamorphic rocks usually support large trees up to the crests of the ridges. Soil cannot accumulate on the dip slopes and joint surfaces of the Swauk formation and therefore a "pseudo Alpine" country results since there simply is nothing in which large trees may grow.

GEOLOGIC SETTING

The present relief of the Cascade Mountains is the result of a late Tertiary uplift along a north-south axis. This structure plunges to the south. Broad areas of pre-Tertiary rocks are exposed in southern British Columbia and northern Washington but the width of exposure narrows to the south as it passes under Tertiary sedimentary and volcanic rocks. Pre-Tertiary rocks are very subordinate south of Snoqualamie Pass.

The pre-Tertiary history of the Northern Cascades has been summarized by Misch (1951,1952). The Northern Cascades consist of a northwest trending gneissose core surrounded by Paleozoic sedimentary rocks and andesitic to basaltic volcanic rocks, which are thrust out west and east from the core over Jurassic and Cretaceous sedimentary and volcanic rocks. The Paleozoic rocks are largely Upper Paleozoic and locally fossiliferous. The lithologies are typical of the eugeosynclinal depositional environment: shales, impure siltstones, graywackes, ribbon cherts, limestones, and basic to intermediate volcanic rocks. Part of these sedimentary and volcanic rocks were metamorphosed into slates, phyllites, greenschists, biotite schists, and amphibolites during the Mesozoic orogenies. The gneissose core was also formed during regional metamorphism in Mesozoic time. The Jurassic and Cretaceous rocks are (?)Middle Jurassic intermediate volcanic rocks overlain by Upper Jurassic and Lower Cretaceous graywackes, siltstones, and conglomerates. Following the deposition of these sedimentary rocks, there was large scale overthrusting.

In latest Cretaceous and early Tertiary time, the Swauk-Chuckanut arkoses, siltstones, and conglomerates accumulated in a rapidly subsiding continental basin extending over much of the Central and Northern Cascades. The deposition of these sedimentary rocks was followed by renewed folding and by Eocene and Oligocene volcanism which laid down the Teanaway basalts and the Keechulus andesites. Then granodiotite and quartz diorite intruded the older rocks as stocks and small batholiths. In Miocene time, the Columbia River basalts accumulated in eastern, central and southern Washington. Following the Pliocene uplift the Pleistocene andesite volcanoes formed. The topography which developed following the uplift was greatly modified by Pleistocene continental and alpine glaciation.

The Higgins Mountain area lies in the western foothills of the Northern Cascades, beyond the central gneiss core but within the range of the overthrusting. The low grade metamorphic rocks were probably derived from the Paleozoic sedimentary and volcanic rocks but no definite dating is possible. Beyond the area covered in this report, unmetamorphosed shales, impure siltstones, graywackes, and altered volcanic rocks outcrop west and north of Deer Creek, in the vicinity of Sutter Mountain, and east of the Sauk River. The age of these rocks is uncertain and could be either Paleozoic or Mesozoic. These pre-Tertiary sedimentary and volcanic rocks do not outcrop in the area covered by this report. North, east, and southeast of the Higgins Mountain area, Misch (oral communication), Bryant (1955), and Vance (1957) have shown that low grade metamorphic rocks which may be correlated with rocks of the present area have been thrust over the unmetamorphosed pre-Tertiary sedimentary and volcanic rocks. The relations of the rocks of the Higgins Mountain area to these unmetamorphosed pre-Tertiary rocks are not known, but it is possible that the entire low grade metamorphic sequence comprises a klippe of the overthrust which has been mapped to the east. Additional field work beyond the present area is needed to evaluate this possibility.

PREVIOUS WORK

A small portion of the northwest corner of the Higgins Mountain area is shown on Jenkins' (1924) map of the "Coal Measures " (Swauk-Chuckanut formation) of Skagit county. This map also shows the "Coal Measures" north of the present area, in the vicinity of Day Creek. The Quaternary till and alluvium in the valley of the North Fork of the Stillaguamish River is shown on the geologic map in Newcomb's (1952) report on the ground water of Snohomish county. Neither Jenkins or Newcomb attempted mapping the pre-Cenozoic rocks. Except for the small part of the Cenozoic rocks shown in these two maps, the Higgins Mountain area has never been mapped before.

It is small wonder that the remote, rugged, densely wooded and sparsely inhabited Northern Cascades long remained untouched except by occasional geological reconnaissances and a few economic investigations of limited areal extent. In the old reconnaissance studies, Russell (1900) mapped greenstones on the lower part of the Sauk River and Smith and Calkins (1904, p. 24) briefly described low grade metamorphic rocks on the south side of the Skagit River between Sauk and Hamilton. In nearby economic studies, Shedd (1922, p. 97) described the schistose hematitic iron ores and associated glaucophane schists south of Hamilton, and Jenkins mapped the "Coal Measures" of Skagit county (op. cit).

In 1948, workers at the University of Washington began a program of systematic reconnaissance mapping of the Northern Cascades. Students under the supervision of Professor H. A. Coombs generally have worked south of the Skykomish River and students under the supervision of Professor P. Misch have generally worked north of the Skykomish River. Professor Misch is mapping the area north of the Skagit and

Cascade Rivers. Reports on these investigations in areas near the Higgins Mountain area include (Fig. 1): Misch's non-technical preliminary report on the area north of the Skagit River (1952); Bryant's PhD dissertation on the Snow King area, east of the Sauk River (1955); Vance's PhD dissertation on the Sauk River area, east of the Sauk River and south of the Suiattle River (1957); and Danner's PhD dissertation on the stratigraphy of parts of the west foothills of the Northern Cascades which includes an area to the west of Deer Creek (manuscript in preparation). In the summer of 1956, J. A. Vance began work on a post-doctoral study north of Finney Creek and south of the Skagit River.

PURPOSE OF THE REPORT

This report is the result of a reconnaissance study of a previously unmapped portion of the western foothills of the Northern Cascade Mountains. As originally proposed, the scope of the investigation was to be primarily mapping the sedimentary rocks in and around Higgins Mountain with a secondary study of the underlying rocks. As the work progressed, the author's interest in the underlying metamorphic rocks increased, and the sedimentary rocks became the object of the secondary study.

METHODS OF INVESTIGATION

About 30 days were spent in the field in the late summer and early fall of 1955 and about 60 days during the

1956 field season. The field data were plotted on U.S.G.S. air photos taken in 1954 or on U. S. Forest Service photos taken in 1949. The field data were transferred to U. S. Forest Service planimetric maps at a scale of 1:31,680. The only topographic map available during the field work, the U.S.G.S. 30' Stillaguamish sheet (1:125,000), surveyed in 1897-9, was unsatisfactory as to accuracy and detail but was certainly better than nothing at all. New 15' minute maps are being prepared for part of the area by the U.S.G.S.

The traverses generally were along the ridges where maximum exposure was found. Although most of the stream valleys are choked with jungle and covered with Quarternary deposits, the streams themselves often run on bedrock. Therefore the "ridge running" was occasionally supplemented by literally wading up the streams.

About 220 hand specimens were collected, many of them oriented. About 150 thin sections were studied. The petrographic microscope was used for routine petrography. In certain rocks, semi-statistical information the range of composition of the plagioclase crystals and the distribution of compositions within that range was considered important. For these rocks (Swauk-Chuckanut arkoses, Granite Lake Labradorite Porphyry), the three axis universal stage was used to increase the number of plagioclase determinations per thin section. Twinned plagioclase crystals were rotated on the stage until the 010 twin plane and the 001 clevage were parallel to the microscope axis. The compositions were then determined by the extinction angles of the oriented crystals.

Three arkoses selected as representative of the Swauk-Chuckanut formation were disaggregated by a combination of crushing and boiling in sodium hyposulfite. The disaggregated samples were put through a standard nest of screens on a Ro-Tap machine for mechanical analyses. Heavy minerals were separated from several fractions in bromofrom. The detrital heavy minerals were examined in oils under the petrographic microscope.

ADKNOWLEDGEMENTS

Professor Peter Misch gave abundant and generous time, guidance, and encouragement in supervising the preparation of this report. Fellow graduate students contributed advice and discussion in problems in geology. J. A. Vance was particularly helpful in discussing related problems in the Sauk River area and permitting the use of the manuscript of his thesis. Dr. R. W. Chaney of the University of California examined the fossil leaves. The U. S. Forest Service Office at Darrington furnished advice on roads and trails and granted permission to enter closed areas. Puget Sound Pulp and Timber Company gave permission to use their logging roads and to work on their property. The Simmons family of Seattle generously gave the use of their cabin at the Stillaguamish Club. Carl Softky went along in the field on several of the most difficult trips.

Above all, I wish to express my gratitude to my wife, Doreen, who accompanied me in the field on one occasion, typed the rough draft of the report, and provided the entire financial support for the study.

II. PETROLOGY AND STRATIGRAPHY

In the Higgins Mountain area, most of the stratigraphic units must be defined in petrographic terms, and therefore stratigraphy and petrology must be discussed together.

The eastern part of the area is underlain by phyllites, greenschists, and greenstones of pre-Tertiary age. A small body of medium grade hornblende-quartz-dioritic gneiss is believed to be a klippe of a thrust from the east. Medium grade hornblende-plagioclass schists may be part of the same tectonic unit as the gneiss, or may be in place and represent a westerly increase in metamorphic grade.

Scattered exposures indicate the presence of a body of diorite which may have intruded the Swauk formation. The Swauk formation apparently has been intruded by labradorite porphyry and by peridotite. Dikes of andesite, labradorite porphyry, and diabase also cut the Swauk formation. The low grade metamorphic rocks have been intruded by basalt, diabase, and gabbro. A thick sequence of dacite flow rocks is in fault contact with the Swauk formation.

The western portion of the area is underlain by the continental clastic sedimentary rocks of the Swauk-Chuckanut formation (hereafter abbreviated as Swauk formation) of possible latest Cretaceous and definite Paleocene age. The dominant rock type is fine to medium grained arkose. Fine grained clastic rocks are subordinate to the arenites, and conglomerate is minor.

No attempt has been made to subdivide the Quarternary alluvial and glacial deposits or to study economic features.

A. METAMORPHIC ROCKS

Low Grade Metamorphic Rocks

The low grade metamorphic rocks which underly the eastern half of the Higgins Mountain area have been divided into two stratigraphic units on the basis of dominant rock types. The stratigraphic units are: the phyllite unit, consisting of ordinary phyllites, albite phyllites, albite schists, schistose conglomerate, and minor interbedded green-schists; and the greenschist unit, consisting of ordinary greenschists, blue-amphibole schists, and minor interbedded phyllites. The term "unit" will always be a part of the name of the stratigraphic units and will never be used in referring to the petrographic subdivisions. The rock types are described on a petrographic basis, regardless of their stratigraphic positions. Since the same rock types are contained in both stratigraphic units, and since the stratigraphic distinction is based on the relative abundance of these rock types, it is necessary to keep the stratigraphic units apart from the petrographic subdivisions and to define the petrographic subdivisions separately. They are: ordinary phyllite, containing sericite, quartz, and minor albite; albite phyllites and albite schists, containing sericite, quartz, and abundant albite; schistose conglomerate; ordinary greenschists, containing albite, epidote, tremolite or actinolite, and minor quartz and chlorite; and blue-amphibole schists, containing albite, epidote, blue amphiboles (sodic actinolite, glaucophane, crossite) and minor quartz and chlorite. In discussing these rocks, the unqualified word "phyllite" will be used to include ordinary phyllite, albite phyllite, and albite schist; the term "ordinary phyllite" will be restricted to those lacking abundant albite; "albite phyllite" will be used to include albite schists since the difference is in grain size, not in composition; the unqualified word "greenschist" will be used to include ordinary greenschists and blue-amphibole schists; the term "ordinary greenschists" will be restricted to those lacking abundant blue amphiboles.

All contacts seen between the phyllites and the greenschists are well defined. The color contrast between the green colored schists and the black phyllites is strong. The phyllites are finely schistose and flake off at the outcrop; the greenschists are less finely foliated and tend to break off in blocks and chunks (Fig. 2). The contacts are sharp and clear. No rocks intermediate in composition between phyllite and greenschist were seen in the area.

The contact between the two stratigraphic units, on the other hand, is transitional in terms of the ratio between phyllite and greenschist. In passing from the phyllite unit to the greenschist unit, one crosses a belt of interbedded phyllites and greenschists of various thicknesses. For convenience in mapping, the transitional interbedded zone is considered a part of the phyllite unit. This zone is well exposed in South Branch valley between 1½ to 2 miles above its junction with the Stillaguamish River. It is not known if this transitional zone exists throughout the area. East of the transitional interbedded zone, no greenschists were seen in the phyllite unit.

The relative stratigraphic positions of the greenschist unit and the phyllite unit are uncertain. The greenschist unit appears to lie above the phyllite unit. However, the structures are not well known and therefore the stratigraphic sequence is uncertain.

The low grade rocks are overlain by the Paleocene Swauk formation. Therefore they are older than Tertiary. No fossils have been found in the low grade rocks of this area and thus no dating is possible on the available evidence other than pre-Tertiary.

For convenience, the greenstones are discussed with the greenschists. The relations of the greenstones to the other rocks are uncertain. They are probably not part of the greenschist unit.

Figure 2

Phyllite (right) and greenschist (left) contact in the transitional interbedded zone in the valley of South Branch about 2 miles above its junction with the Stillaguamish River. The finely schistose phyllite has broken away in large flakes, leaving a ragged outcrop. The less finely foliated greenschist has broken away in chunks and blocks, leaving a more massive appearing outcrop. In the photograph, the color of the greenschist registers as light gray, and the phyllite as a darker gray. The actual contact is shown by a sharp change in color tone just to the left of the small log in the center of the picture.

Phyllites

The phyllites include three related rocks: (1) ordinary phyllites; (2) schistose conglomerate; and (3) albite phyllites and albite schists.

As a rock name, phyllite means a dense, schistose, rock characterized by abundant fully recrystallized sericte but in which other minerals, generally quartz and a little albite, may be entirely clastic or in any degree of recrystallization. This is the most abundant of the rocks of this petrographic subdivision. The conglomerate is very minor compared to the phyllite, only one outcrop of interbedded schistose conglomerate was discovered in the present area. Albite phyllite and albite schist differ from ordinary phyllite by having conspicuous quantities of albite. The ordinary phyllites contain 15% or less of albite, the albite phyllites and albite schists, 30% or more. The relations of the albite phyllite to the ordinary phyllites are uncertain but they appear to be intimately interbedded. However, the albite phyllites are more or less restricted to Swede Heaven.

The phyllites are exposed in the valley of the North Fork of the Stilliguamish River between North Mountain and South Fork Ridge, in the valley of South Branch, in the steeper tributary stream beds which descend the sides of these valleys, and on logging roads on the south end of South Fork Ridge and the west side of North Mountain. There are occasional outcrops on the densely wooded slopes of the hills where the soil cover is often as thin as one foot. The root systems of fallen trees often removed the soil when the tree fell. Rock exposures as much as twenty feet in diameter were formed in this fashion. Finding outcrops on the wooded slopes is by no means hopeless but plotting such outcrops in a map is not easy. Small amounts of phyllites are interbedded in the greenschists on South Fork Ridge.

ordinary phyllites

The color of the ordinary phyllites is usually dark gray to black but it occasionally may be light gray. The color may be uniform or there may be narrow banding with darker sericite and graphite rich bands contrasting with lighter bands of quartz and albite or with quartz exudation lenses. The rock is dense.

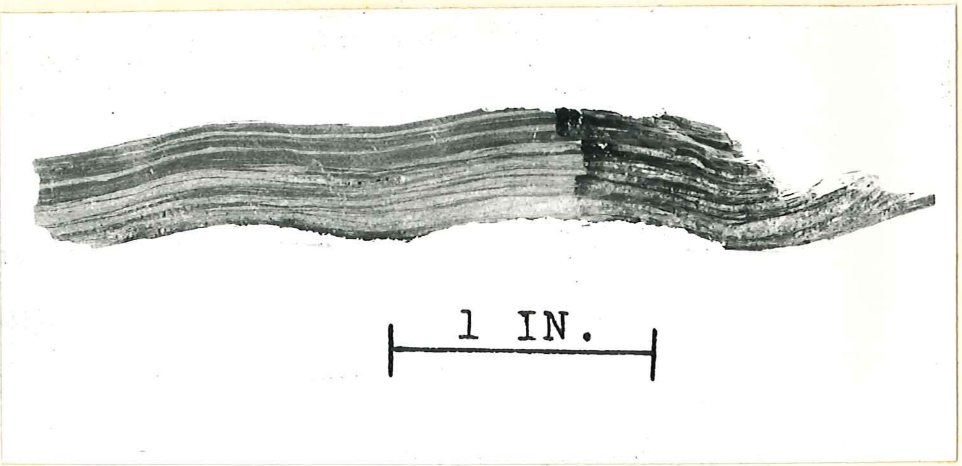
Closely spaced strong foliation characterizes the ordinary phyllites. The schistosity planes usually have been deformed into folds ranging from a microscopic size to small folds several inches high and a foot across. Usually the folds are open and without overturned limbs, but there has been some isoclinal folding and shearing out of folds. Exudation lenses of quartz are common in the more deformed ordinary phyllites. More than one schistosity frequently is present but may not be apparent in outcrop. Typical outcrops are shown in Fig. 3 and a microscopic fold is shown in Fig. 5.

The composition of 7 typical ordinary phyllite specimens studied in thin section ranges from 20 to 75% quartz, 1 to 15% albite, 10 to 70% sericite, 2 to 20% graphite, and accessory chlorite, pyrite, magnetite, and limonite. The average of the essential minerals is 45% quartz, 10% albite, 40% sericite, and 5% graphite. The average grain size of the quartz and albite is about 0.05 mm., the largest being about 1 mm. and the smallest less than 0.01 mm. In phyllites with crystallization foliation, the quartz and albite are sub-rectangular and form a pavement texture. Similarity in size and shape and the rarity of twinning make the albite difficult to distinguish from the quartz unless numerous grains are examined in convergent light. The compositional bands of quartz with minor albite are less than 1 mm. thick (Figs. 4 and 5). Quartz exudation lenses may be several inches thick and a foot long. In the field they may be distinguished from the ordinary compositional bands by their size, by the presence of cavities, and by their having displaced schistosity; under the microscope, by sutured textures, larger grain size, and absence of albite (Fig. 6). Post-crystalline shearing has affected most of the ordinary phyllites, causing undulous extinction in the quartz, especially in the larger grains. The sericite ranges from sub-microscopic shreds and wisps to flakes and plates about 0.01 mm. thick and 0.1 mm. long. Occasional plates are up to 0.05 mm. thick. The graphite is finely divided and is deceptive as to the amount actually present since it often coats the surfaces of other minerals, especially sericite. The pyrite ranges from about 0.05 mm. up to grains as large as 7 mm. Euhedral cubic crystals are common. The larger grains may be enclosed in envelopes of quartz up to 1 mm. thick. The larger pyrite grains have displaced the schistosity.

The first schistosity, s_1, is delineated by compositional banding and crystallization foliation shown by strong preferred orientation not only of the sericite but also of the elongated quartz and albite (Fig. 5). This is at least form orientation. It is not known if the orientation is at the same time lattice orientation. No recrystallization occurred during any of the later periods of shearing. The second schistosity, s_2, ranges from incipient to intense. In the incipient stage, the trace of s_2 is marked by widely spaced, irregular films of graphite (Fig. 5). In the more intense stages, the sericite cut by the actual shear planes has been pulled into s_2, but the sericite more remote from the shear planes has remained in s_1. As the intensity of deformation increased, the s_2 planes became more numerous and closely spaced. More and more of the sericite was pulled into s_2. In the ultimate stages, the elongated grains of quartz and albite also have been rotated into s_2. S_1 may have been virtually obliterated (Fig. 7). The third schistosity, s_3, was identified in very few localities. Its trace is marked by films of graphite cutting across the traces of s_1 and s_2. This schistosity apparently never developed beyond the incipient stage. Fig. 8 shows the time relations of the different schistosities.

Since little recrystallization accompanied the formation of s_2, it is a plane of weakness along which the rock tends to split. Therefore the most conspicuous surface in outcrop is often s_2. This may not be apparent in the field (Fig. 9).

Most of the ordinary phyllites have one, two, or three lineations in various combinations of strength of development. The lineations are marked by minute folds of the schistosity. These various lineations have been formed by drag folding and by the intersections of the schistosity planes. It is rarely possible to distinguish between the two types in the field. Although in the specimens studied in thin section the strongest lineations were found to be from the intersections of the schistosity planes, insufficient work has been done to justify any generalizations. An ordinary phyllite with three lineations from the intersection of schistosity planes is shown in Fig. 10.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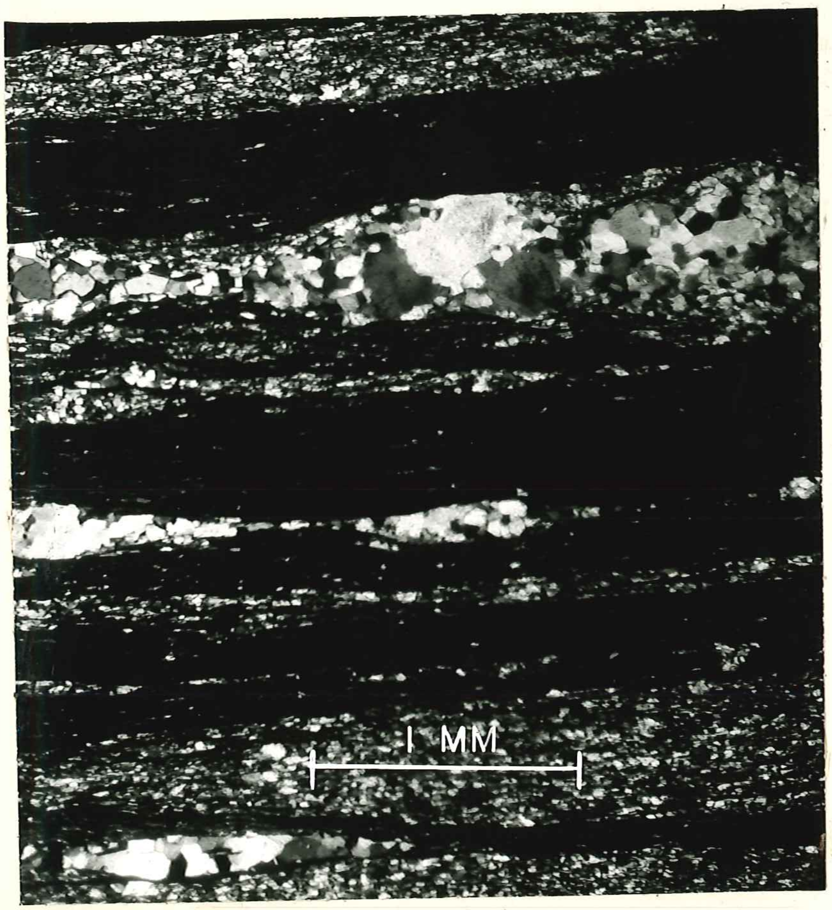
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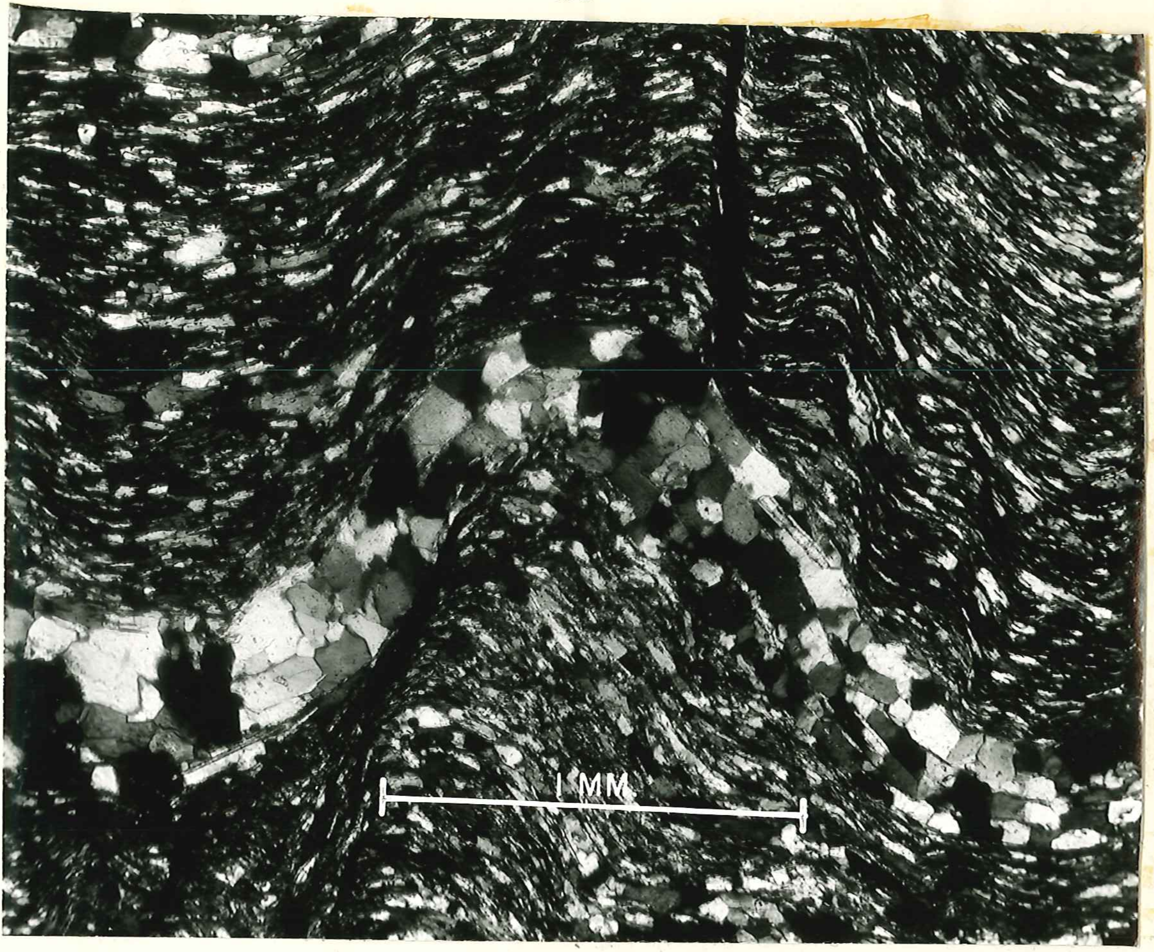
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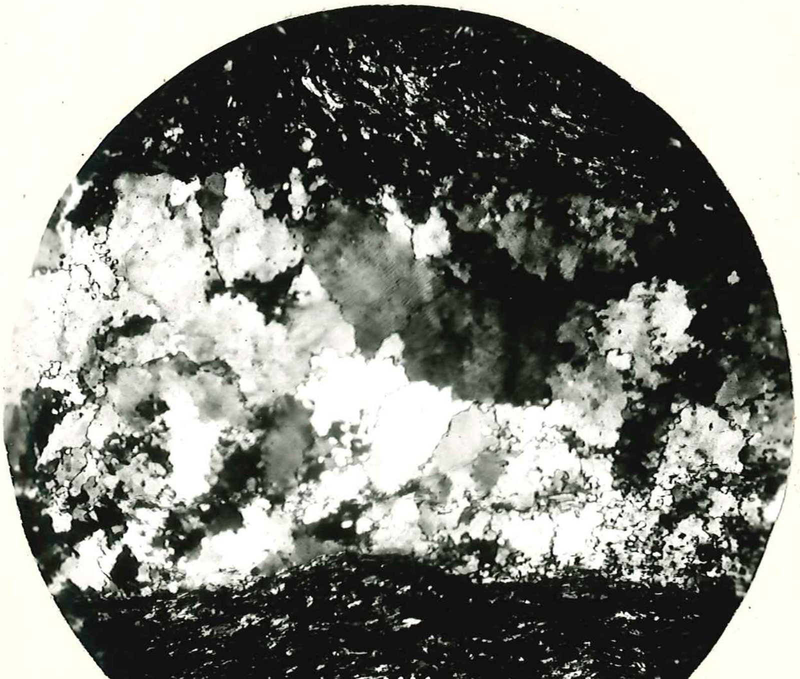
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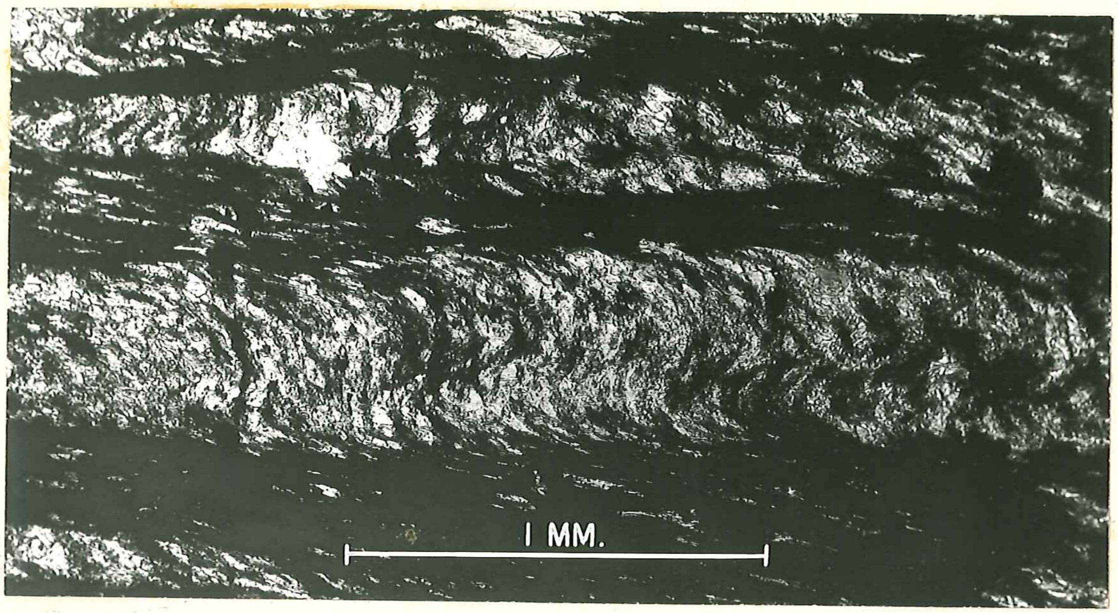
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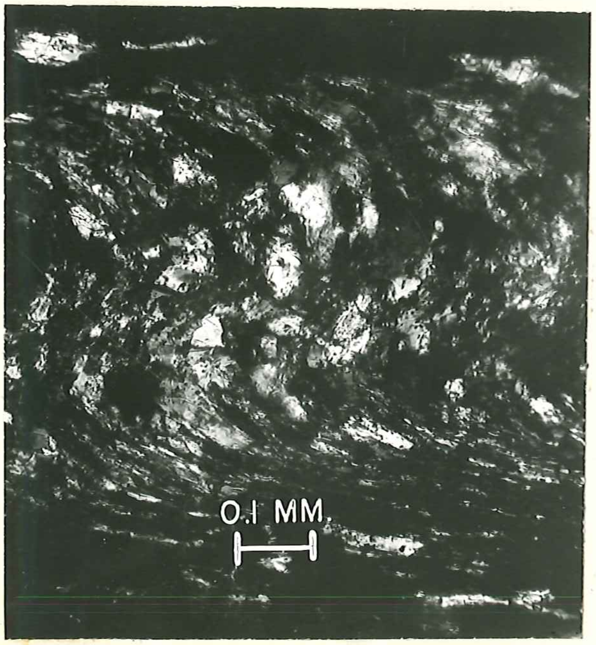
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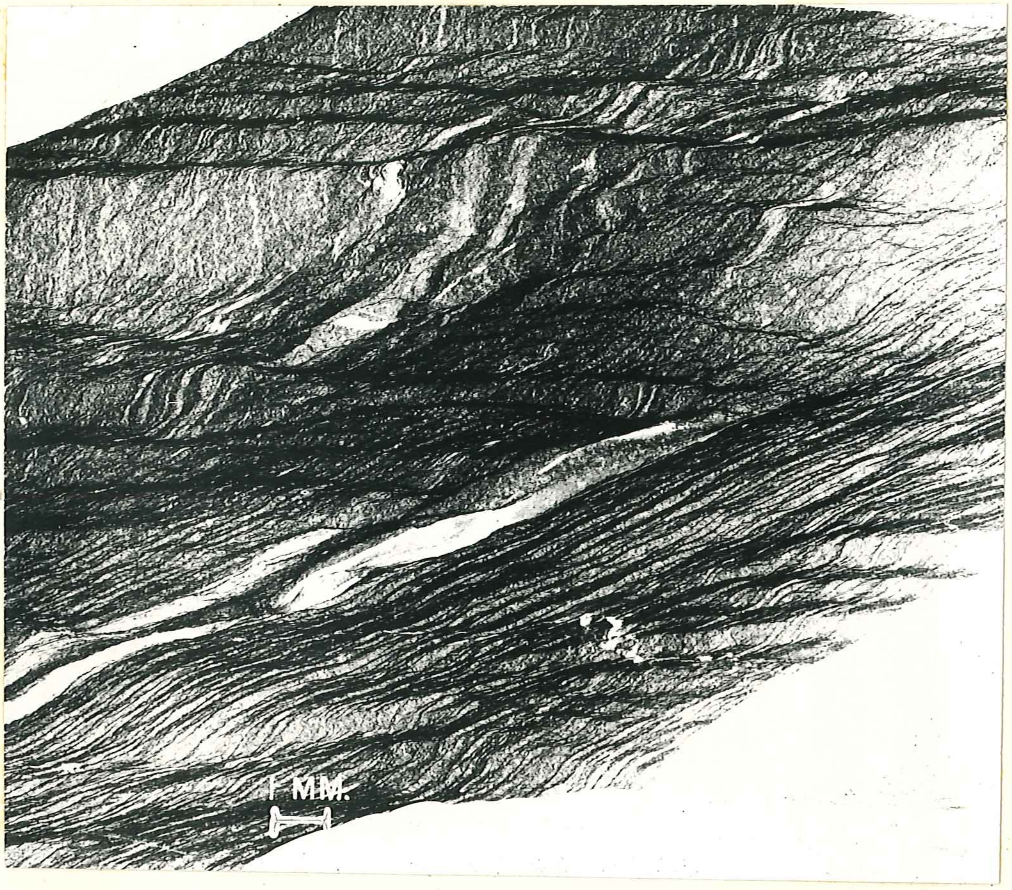
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Fig. 9 Outcrop of ordinary phyllite in which the most prominent planar surface is s_2. The surface which strikes from left to right and dips away from the observer was proved to be s_2 by thin section study of an oriented specimen. The thin section is shown in Fig. 8 and the handspecimen in Fig. 10.

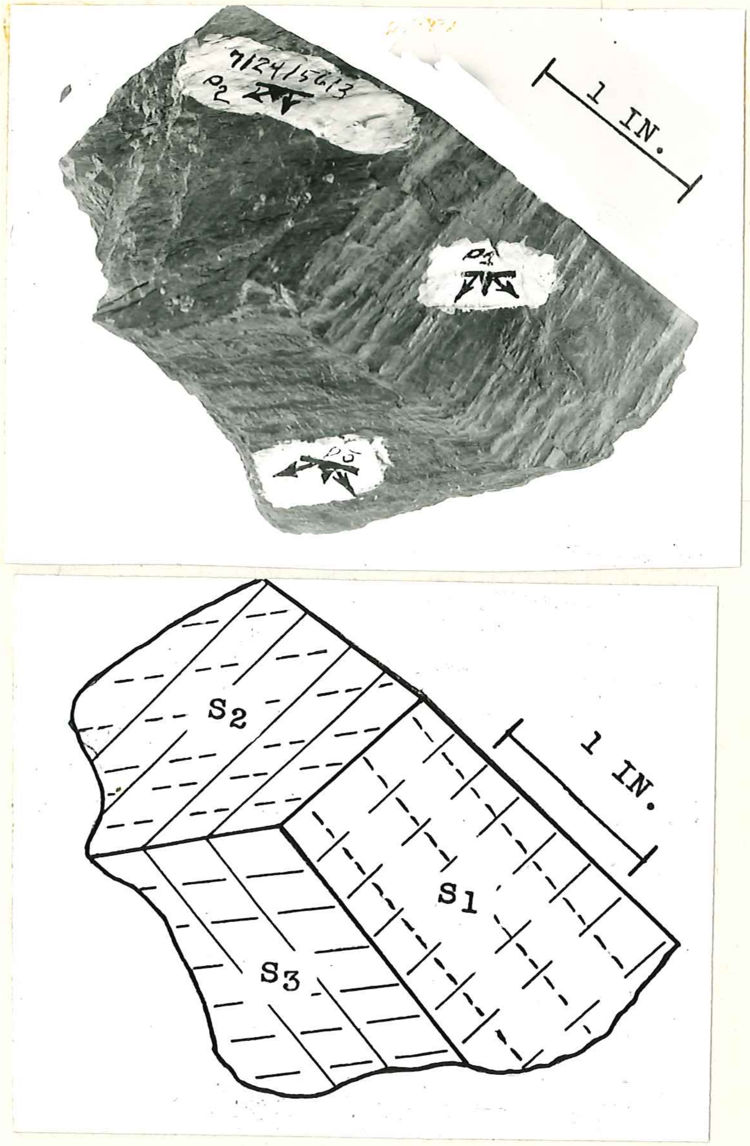


Fig. 10 Lineations from the intersection of schistosity planes in an ordinary phyllite which has three s planes.

A. Handspecimen showing three s planes and the directions of the lineations on each surface.

B. Sketch showing positions of the traces of the intersections of the s planes.

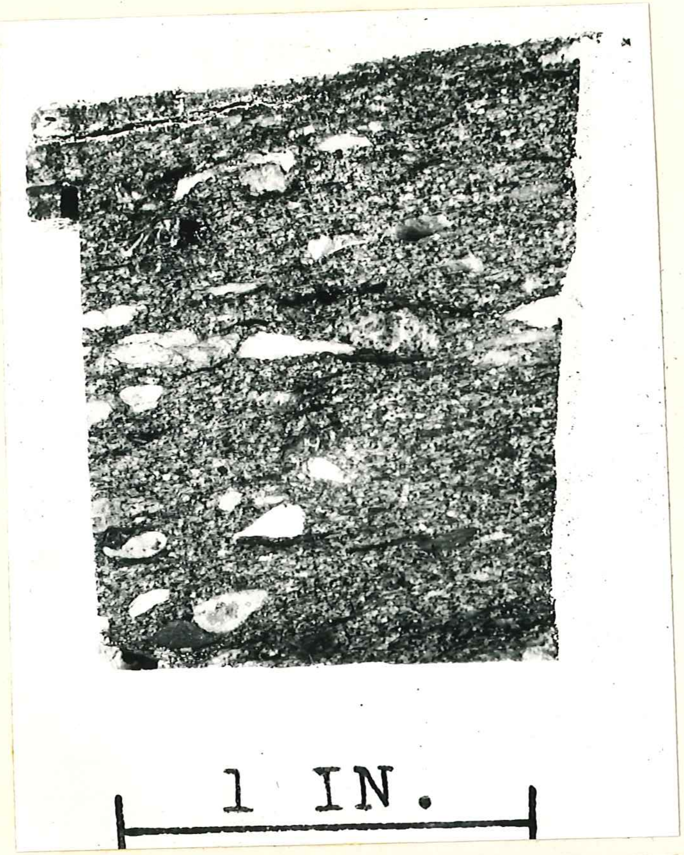
schistose conglomerate

The locality where coarser material is intercalated in the phyllite is about ¼ mile west of the North Fork of the Stillaguamish River at a point about ½ mile north of its junction with Crevice Creek. The schistose conglomerate is between 50 and 100 feet thick. Since the schistosity is not as well developed as in the enclosing phyllites, the rock appears comparatively massive in outcrop. Closer inspection reveals that it is strongly foliated. The rock appears to be poorly sorted. Most of the larger grains are fine pebble size--4 to 6 mm.--and most of the groundmass grains are less than 1 mm.--coarse sand and smaller. Preferred orientation in s of the elongated pebbles is weak (Fig. 11).

The rock consists of 40% rock fragments and 60% groundmass. Of the total rock, 35% is pebbles of quartzite and chert and 5% is pebbles of fine-grained volcanic rocks. In the matrix, 45% of the total rock is fragments of quartzite and chert and individual crystals of quartz and albite, 1-2% is muscovite and sericite, 10% is altered biotite and 1-2% is leucoxene.

Essentially clastic textures are preserved with cataclastic textures superposed. The pebbles are subangular to subrounded. The maximum size is 7 mm. Most of the pebbles are very fine grained quartzites or even finer grained cherts. The few volcanic rock fragments are mainly composed of laths of plagioclase 0.1 to 0.2 mm. long. The composition of the feldspar is now albite. No mafics are present but there is a small amount of quartz.

The groundmass consists of angular to sub-angular fragments of chert, quartzite, and volcanic rocks as well as individual crystals of muscovite, biotite, quartz, and twinned and untwinned albite. The micas may be as long as 3 to 4 mm. but the grain size of the other minerals ranges from a maximum of 1 mm. down to submicroscopic. The pleochrism of the biotite ranges from strong to very pale. The larger grains of both micas lie in the foliation but the smallest wisps and shreds of sericite may have any orientation among the grains of the groundmass. In contrast to the abundant recrystallization of sericite which characterizes the enclosing phyllites, these tiny unoriented sericites represent the only recrystallization which has occurred in the conglomerate.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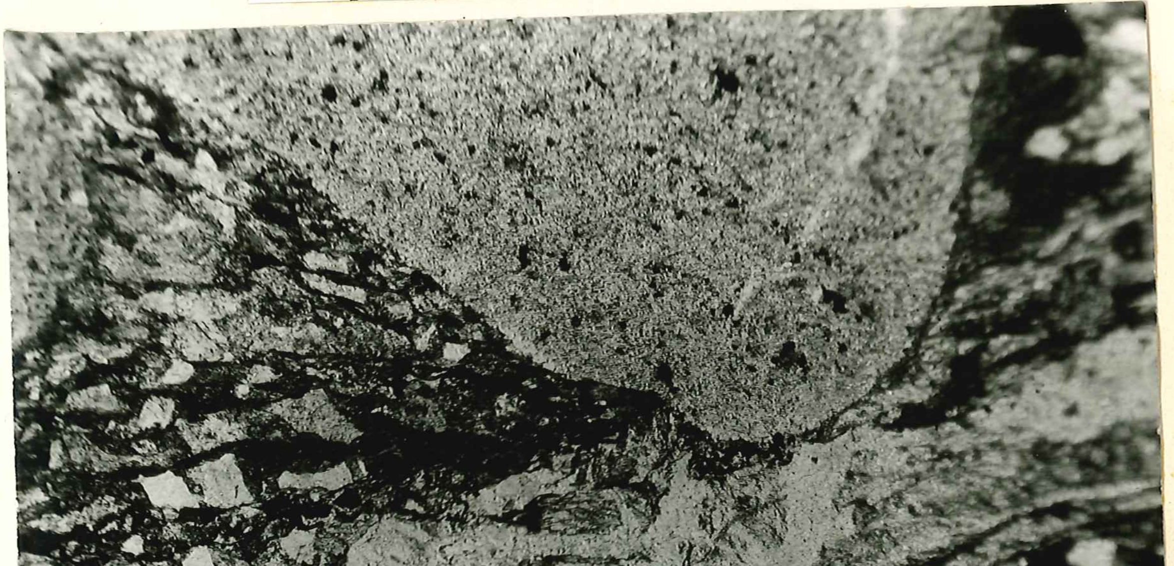
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albite phyllites and albite schists

Most of the albite phyllites (including the albite schists) are on Swede Heaven. One occurrence was found on the east end of Middle Fork Ridge and there are some intercalations of such rocks in the main greenschist belt along South Fork Ridge.

The color of these rocks varies more than that of the ordinary phyllites. Light to dark shades of gray are more common than black. The presence of small amounts of cafemic minerals may cause greenish hue. A few rocks with large amounts of cafemic minerals are light grayish greens. The colors are sometimes uniform but more often there are light and dark compositional bands or mottling caused by light-colored porphyroblasts or light colored lenticles of quartz and feldspar. Albite porphyroblasts as large as 1.5 mm. may be seen on some of the schists, but megascopically visable grains of any mineral are generally no larger than 0.5 mm. Light colored lenticles several millimeters across are common but they are aggregates of small grains rather than porphyroblasts. Quartz exudations similar to those described in the ordinary phyllites are found occasionally. The muscovite is rarely megascopically visable, even in rocks with conspicuous albite porphyroblasts. The schistosity is generally coarser and the grain size larger than in the ordinary phyllites, the deformation of the schistosity is sometimes more intense than in the ordinary phyllite. Isoclinal folding and shearing off of folds on a scale of less than an inch has occurred in some of the albite phyllites. More than one schistosity may be present but this may not be apparent in the field. Typical outcrops are shown in Fig. 12.

The composition of albite phyllites studied in thin section ranges from 1 to 50% quartz, 5 to 60% sericite, and 30 to 75% albite. The average of the essential minerals is 30% quartz, 20% sericite, and 40% albite. In all but one specimen, chlorite is present in amounts ranging from a trace to as much as 20%. Minerals present in some but not all of the rocks are: epidote group, up to 2%; leucoxene, up to 2%; graphite up to 10%; and pumpellyite, up to 30%. Traces of tremolite, sphene, stipnomelane, pyrite, tourmaline, lawsonite (?), and late carbonate are present in a few of the specimens.

The quartz grains range in size from submicroscopic up to 0.2 mm. in the groundmass. Quartz in exudation lenses is coarser, up to 0.4 mm. Undulous extinction is common in all occurrences of quartz. The albite forms porphyroblasts or is groundmass grains indistinguishable from quartz except under convergent light. Porphyroblasts are absent in three of the specimens, in the remainder they form from 1 to 60% of the rock. The maximum size of the albite porphyroblasts is 1.5 mm. Twinning is rare, both in the groundmass and in the porphyroblasts. Sericite, tremolite, graphite, clinozoisite, and epidote inclusions in the porphyroblasts frequently are aligned in trends which are remnants of the pre-porphyroblast schistosity of the matrix (internal s = s_i). The allignment of the inclusions in the albite porphyroblasts (s_i) usually parallels the direction of the external s_1 (s_{e1}). These prophyroblasts grew under essentially static conditions after a non-porphyroblastic schist was formed under synkimematic conditions (Fig. 13). S-parallel minerals not needed to make the albite were engulfed but not distrubed by the porphyroblasts. Those components of minerals assimilated by the porphyroblasts which were not used to make albite were segregated as tiny new mineral grains. Calcium, aluminum, and silica plus some iron went into clinozoisite and epidote; magnesium went into tremolite which is rare in the groundmass of these rocks but is a common inclusion in the porphyroblasts. This included s (s_i) is an indicator of the original direction of s_1 in rocks in which post-crystalline shearing has more or less eliminated s_1 outside of the porphyroblasts. The curved s_i (Fig. 14) is not the result of a static growth of porphyroblasts across a previously folded schistosity (Helecitic structure), but it represents an incipient stage of the s-shaped patterns so well known from snow ball garnets. This kind of curved s_i represents rotation during porphyroblastic growth, that means growth under synkinematic conditions. Thus the porphyroblastic albite growth has not occurred during a later and altogether unrelated episode of metamorphism but represents a late stage of the same episode of metamorphism during which the schistose matrix was crystallized. The porphyroblastic growth began during the close of the synkinematic phase (late-kinematic stage), continued into and reached its greatest development after the end of the deformation (post-kinematic phase).

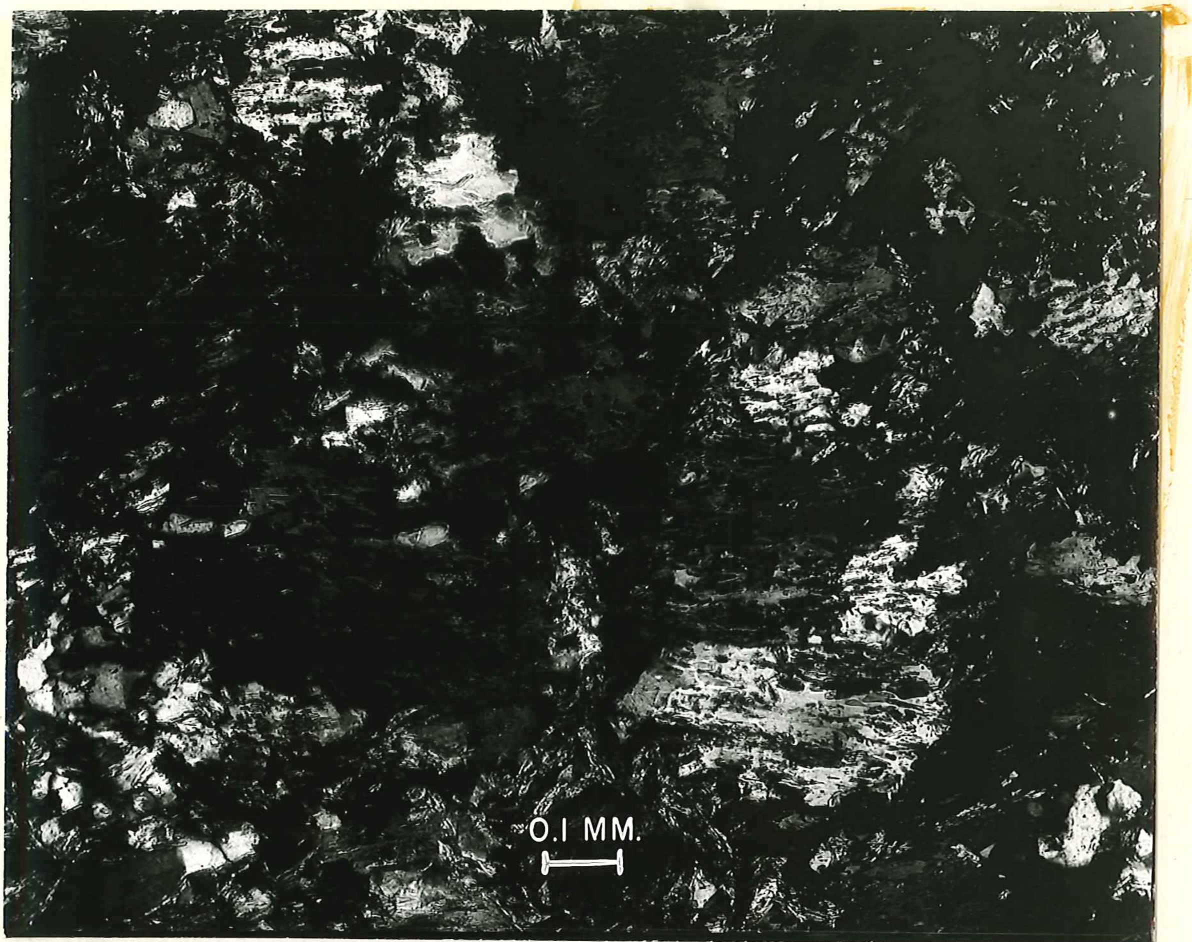
Most of the sericite ranges from submicroscopic shreds and wisps to crystals 0.02 mm. thick and 0.08 mm. long. In a few of the schists, the sericite is a large as 0.08 mm. thick and 0.4 mm. long. The chlorite forms as individual crystals ranging in size from submicroscopic to 0.004 mm. thick and 0.02 mm. long. It also makes lenticular felted aggregates which are as much as 0.4 mm. across. Clinochlore occurs about twice as often as pennine, the two seldom occurring in the same rock. The epidote group minerals usually are clinozoisite or iron-poor epidote; one specimen contains zoisite. The epidote group minerals usually range in size from submicroscopic to 0.05 mm.; in one albite schist a few grains of clinozoisite are as large as 0.5 mm. Most of these minerals are in the quartz-albite groundmass but grains up to 0.07 mm. are included in the albite porphyroblasts. The leucoxene occurs in grains a few hundreths of a millimeter in diameter and in cumulophyric aggregates of submicroscopic grains. Graphite acts as a pigment in the darker rocks; as in the phyllites, it masks the other minerals by coating their surfaces and it marks the traces of post-crystalline shearing. Pumpellyite is present in two specimens, mostly as submicroscopic wisps and shreds in the groundmass.

The s_1 is represented by compositional banding, alignment of inclusions in albite porphyroblasts (s_i), preferred orientation of some of the sericite and chlorite, and, in a few of the rocks, preferred orientation of elongated albite porphyroblasts. Post-crystalline shearing has affected all of the specimens studied. The results of this shearing range from undulous extinction in quartz through incipient stages of s_2 to intense development of s_2 (Fig. 13 through 17). The traces of the incipient stages of s_2 are not conspicuous in the rocks with low graphite and chlorite contents. However, if either graphite or chlorite is present in sufficient amounts, they will often mark the trace of s_2 even in rather incipient stages (Fig. 15). The alignment of the inclusions in the porphyroblasts indicates the direction of s_1 even in these schists in which s_2 has nearly obliterated s_1 outside the porphyroblasts. No s_3 has been found in these rocks.

As in the ordinary phyllites, the lack of recrystallization during the formation of s_2 made it a plane of weakness. Therefore s_2 often is the most conspicuous planar surface in outcrop. In the coarser grained rocks, it is sometimes possible to tell s_1 from s_2 megascopically.

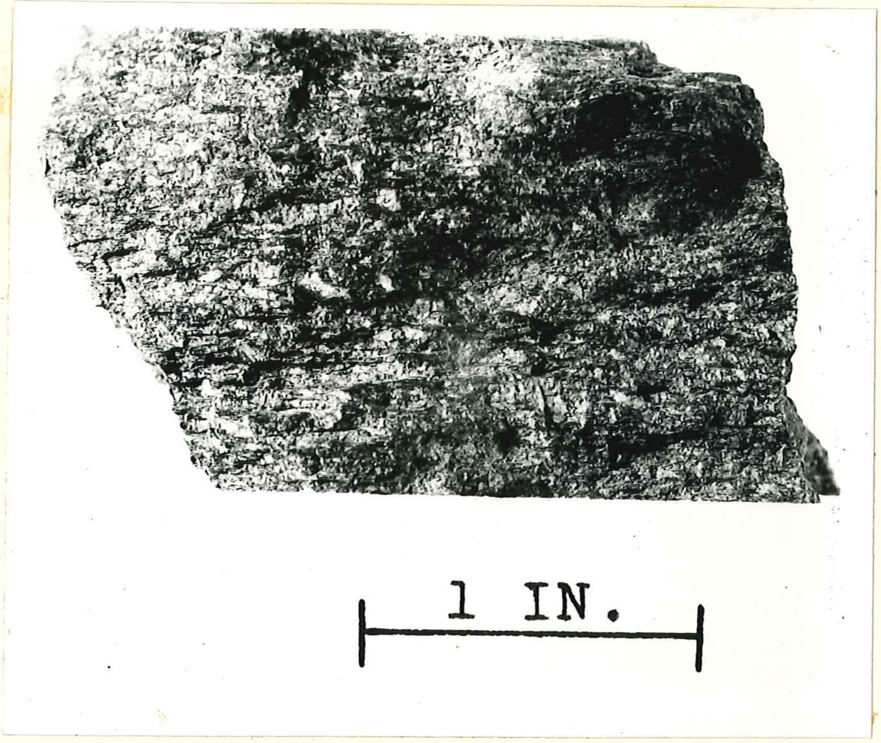
Intense folding and shearing of s_1 appears to be limited to a few less competent beds. Isoclinal folding and shearing off of folds occur in a rock containing 60% sericite and 40% albite (Fig. 17). This is an incompetent rock compared to the average type which contains only 20% sericite and 70% quartz and albite. It is likely, though, that the total deformation of these rocks is actually about the same as that of the phyllites and, because the albite-quartz rich beds are relatively competent, the deformation had to be taken up selectively by the less competent beds.

Lineations are not as numerous or as varied as in the ordinary phyllites. The intersection of s_1 and s_2 causes ridges about 1 mm. across on the schistosity planes of about a quarter of the specimens studied. Lineations from drag folds on the same scale as the lineations from the intersection of s planes generally are lacking in the albite phyllites and albite schists. A lineation is formed in the more intensely folded rocks by the axes of the minor folds of s_1. These folds are on the order of one to several inches across. Because these rocks are relatively coarse grained compared to the ordinary phyllites, the nature of the lineations may sometimes be recognized in the field even if s_1 cannot be distinguished from s_2.


0.1 MM.


0.1 MM.

Fig. 15 Macrophotograph showing the incipient stage of s_2 in albite phyllite. S_1 is from left to right and is marked by compositional banding. S_2 is from lower left to upper right and is marked by widely separated irregular films of graphite. Ordinary light.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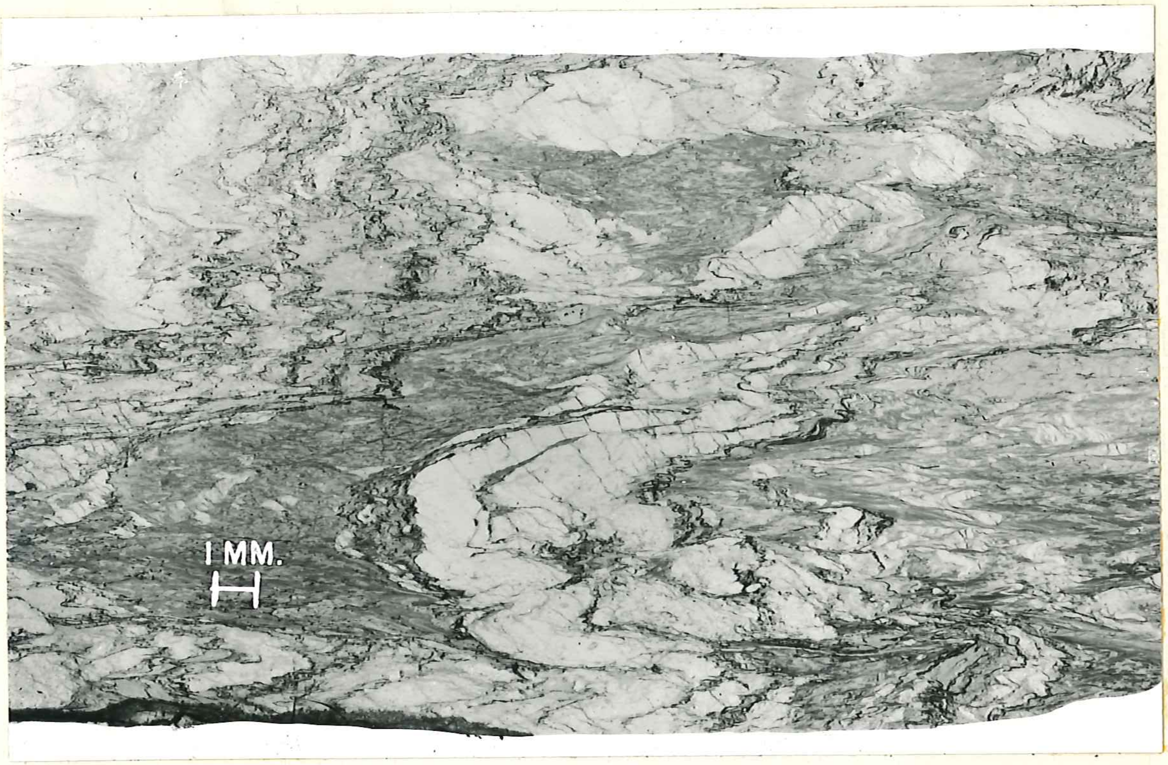


Fig. 17 Macrophotograph showing isoclinal folding of s_1 and shearing out of those folds in albite phyllite. The leucocratic bands are albite, the darker areas sericite. This rock contains 60% sericite and 40% albite. Fig. 15 shows that a rock from the same outcrop which contains 30% sericite and 60% albite and quartz lacks this tight folding.

Greenschists

The main body of greenschist forms a belt on South Fork Ridge, generally at elevations above 2500 feet. The main body is exposed in many places along the crest and on cliffs on the sides of the ridge. In addition, several beds of greenschist, the individual thickness of which varies from a few feet to several hundreds of feet, are intercalated in the phyllites in a half mile wide belt to the east of the main greenschist body (Fig. 18). On Swede Heaven, south of South Fork Ridge, some small exposures lie along the strike of the main belt and have internal structures with strikes parallel to those of the main body.

The greenschists include ordinary greenschists, blue-amphibole schists, and greenstones. The essential minerals of the ordinary greenschists are abundant albite, epidote, and tremolite or actinolite with minor quartz and chlorite. The blue-amphibole schists are different only in that the amphiboles are various combinations of sodic actinolite, glaucophane, and crossite. The blue-amphibole schists contain relatively smaller amounts of albite and relatively greater amounts of amphibole than the greenschists. The average composition of the specimens of the two rock types which were studied in thin section is:

	ordinary greenschist	blue-amphibole schist
albite	40	25
epidote	25	30
amphibole	25	40
quartz	tr.	3
chlorite	5	3

On the geological map these two rock types cannot be separated because they are intimately interbedded; any one small outcrop may have both greenschist and blue-amphibole schist. No special search was made for rocks which "look blue", yet of the 18 specimens studied in thin section, 9 are blue-amphibole schists. It is thus obvious that the blue amphibole schists are widely distributed within and form a large proportion of the greenschist unit.

The greenstones may not be related genetically to the greenschists and blue-amphibole schists but are included in this unit since they represent the static equivalent of the metamorphic zone under which the corresponding schistose rocks were formed. The mineral assemblage is essentially the same as in the greenschists. The greenstones are on South Fork Ridge, but at lower elevations than the main greenschist body.

<u>ordinary greenschists</u>

The ordinary greenschists are usually light to medium grayishgreen; a few are moderately dark gray-green. The color is seldom uniform. Megascopically visible grains of albite and epidote form light colored flecks and spots on some of the rocks. On others there are light and dark colored compositional bands a few millimeters thick. In a few rocks there are segregation lenses and bands of pale greenish yellow epidote. Few of the rocks are megoscopically entirely dense; most of them have abundant visibly grains of albite, epidote, and amphibole. The usual maximum grain size is about 0.5 mm. Several albite porphyroblasts together often form aggregates up to 1.5 mm. across which may appear to be single crystals in hand specimen. The greenschists are strongly foliated but schistosity is less perfect than in the phyllites. No evidence has been found for more than one schistosity. Because the compositional bands differ in their resistance to weathering, sometimes the schistosity stands out in relief (Fig. 19).

The composition of the 9 ordinary greenschists studied in thin section ranges from a trace to 5% quartz, 25 to 50% albite, 2 to 50% epidote, 1 to 15% chlorite, and 3 to 40% tremolite or iron-poor actinolite. The averages of these minerals are: a trace of quartz, 40% albite, 25% epidote, 5% chlorite, and 25% amphibole. In addition some of the ordinary greenschists contain sericite and muscovite, up to 5%; sphene and leucoxene (probably mainly after sphene), mostly present though ordinarily not in excess of 3%, but up to 30% in one specimen; and pyrite, up 2%. Lawsonite (?) in the amount of 2% occurs in one specimen which also has 2% pumpellyite and 1% stilpnomelane.

The quartz forms groundmass grains usually less than 0.05 mm. in diameter. Convergent light is necessary to distinguish it from clear albite except when the quartz is strained. Ordinarily it is quite inconspicuous. The albite is often porphyroblastic. The albite ranges in size from

0.01 mm. to 0.5 mm. Several albite porphyroblasts in aggregates up to 2.5 mm. across may appear to be one crystal in hand specimen (Fig. 20). In some of the ordinary greenschists, the albite grains are subrectangular and, especially in sections cut parallel to the lineation, the elongated crystals lie in s. Most of the albite contains aligned inclusions of epidote, amphibole, sericite, and finely divided opaques. The direction of alignment of these inclusions (s_i) usually parallel the schistosity outside the albite grains (s_e). A few of the porphyroblasts have curved trends of inclusions. Reasoning similar to that used for the porphyroblasts in the albite schists suggests that the porphyroblast formation began during the late stages of synkinematic metamorphism and extended into a postkinematic phase.

The epidote forms anhedral grains ranging from sub microscopic to as large as 0.3 mm. Some of the larger crystals are subhedral. Aggregates consisting of many small and/or several large grains make up lenticular masses up to 1.5 mm. across. Segregation lenses and bands of essentially epidote plus a little quartz and amphibole are common and may be as thick as several millimeters. The epidote generally is colorless and nonpleochroic. In two specimens there are faint yellow colors in the cores of some of the larger crystals. The maximum birefringence ranges from 0.018 to 0.040. The negative 2V is generally about 80°.

According to Winchell's diagram of the variation of optical properties of the series clinozoisite-epidote (1933, p. 313), these epidotes range from 10 to 20% of the iron epidote molecule. In one specimen, the iron molecule is 25%.

The chlorite is usually clinochlore. Better formed individual crystals are submicroscopic to 0.015 mm. thick and 0.15 mm. long. Usually the chlorite occurs as lenticular felted aggregates up to 0.5 mm. across. Sericite and muscovite are present in 6 of the specimens as grains from 0.01 mm. thick and 0.15 mm. long up to 0.1 mm thick and 0.3 mm. long. Sphene and leucoxene, largely derived from sphene, are present in nearly all of the rocks. They range in size from submicroscopic to 0.02 mm. Pyrite occurs in 3 of the specimens in grains ranging from a few hundreths of a millimeter to 0.3 mm. Lawsonite (?) is included in albite pophyroblasts in one specimen in which stilpnomelane formed as an alteration product along fractures and pumpellyite occurs as scattered aggregates of submicroscopic crystals.

The lawsonite (?) forms euhedral rectangular crystals about 0.1 mm. wide and 0.2 mm. long included in albite porphyroblasts, together with plates of muscovite up to 0.05 mm. thick and 0.2 mm. long, and with rectangular subhedral grains of clinozoisite about 0.1 mm. wide and 0.2 mm. long (Fig. 21). The lawsonite (?) has a maximum birefringence of 0.019. The interference colors are normal. The optic plane lies across the elongation, the length is fast, and extinction is parallel. Two directions of cleavage at right angles to each other are visible in some of the grains. The optic angle and sign could not be determined. Clinozoisite is distinguished from the lawsonite (?) by inclined extinction, lower birefringence, abnormal interference colors, and the presence of only one direction of cleavage. It is possible that the mineral is prehnite rather than lawsonite but the two directions of cleavage and the rather low birefringence are more indicative of lawsonite. The euhedral nature of the crystals and their presence within the albite porphyroblasts indicates that they are a main assemblage mineral of the period of porphyroblastic growth. The association with the slightly iron-bearing clinozoisite suggests that there was little iron in the minerals assimilated in the porphyroblasts. After the small amount of iron was used up in slightly iron-bearing clinozoisite, the anorthite component went into lawsonite. The groundmass of this rock is fairly low in iron. It contains 10% epidote with an iron molecule content of 20%.

The amphiboles are pure tremolite in 2 specimens, mostly tremolite in 2, iron-poor actinolite in 4, and actinolite in 1. Some of the actinolite grades into sodic actinolite. The amphiboles range from submicroscopic acicular grains to prismatic crystals 0.15 mm. thick and 0.5 mm. long. The prismatic faces and amphibole cleavages are well developed; terminations are usually ragged. The amphiboles lie with their elongation generally parallel to s. In some of the rocks, the elongation of the amphiboles is also parallel to the lineation, in others the grains lie in haphazard attitudes within s. The amphiboles bend around the porphyroblasts of albite, giving the impression that they were shouldered aside during the growth of the porphyroblast. The albite porphyroblasts include a few amphiboles of the same dimensions as those in the groundmass, but the general size of the included amphiboles is much smaller. These tiny acicular included grains appear to be the same amphiboles as those of the groundmass.

The amphibole group is a complex isomorphic series with a number of end members and numerous intermediate members. In the greenschists, three types are present: tremolite and actinolite, the end member and intermediate member of the series tremolite-actinolite-ferrotremolite (Winchell, 1933, p. 245); and sodic actinolite, an intermediate member in the series actinolite-sodic actinolite-glaucophane or crossite (Misch, oral communication). In all of the amphiboles in the ordinary greenschists of the area, the optic plane is parallel to the elongation of the crystals and the length is slow. Most optic data is of little value in seperating tremolite from actinolite. In these ordinary greenschists, the tremolite has a maximmm birefringence of about 0.020, the negative 2V is nearly 90°, and the extinction angles between z and c in (010) range from 15 to 20°. The actinolite has a maximum birefringence of about 0.022, the negative 2V is between 80 and 90°, the extinction angles between z and c in (010) range from 17 to 20°, and there is a faint pleochroism, with z= faintly pale green to pale green, y = faint grayish green, x = colorless to very pale yellow. The distinction between tremolite and actinolite is essentially made on the basis of the absence or presence of pleochroism. The actinolite in these rocks usually has very faint colors, and probably is close to the tremolite end of the series. The sodic actinolite is similar to the actinolite except z:c in (010) is 12° and the pleochroism is z = very pale green with a bluish cast to pale bluish green, y = faint grayish to bluish green, and x = faint yellow. The sodic actinolite usually occurs as the cores of zoned actinolite crystals. The quantity present in rocks classed as ordinary greenschists is very minor compared with that present in rocks classed as blue amphibole schists.

There is a fairly constant relation between the kind of amphibole present and the amount and iron molecule content of epidote in the rock. Tremolite occurs in the rocks with the less and iron-poorer epidote, and actinolite in those with more and iron-richer epidote.

The schistosity of the ordinary greenschists is marked by compositional banding, elongated amphiboles, aligned inclusions in the albite porphyroblasts, preferred orientation of the albite porphyroblasts when they are elongated, and preferred orientation of some of the mica and chlorite. Lineations are not common. Since there is little post-crystalline shearing and no s_2, lineations from the intersections of s planes are lacking. In a few of the specimens, the elongated amphiboles show a lineation which may be visible in hand specimen. The significance of this lineation is not known. Since there is little post-crystalline shearing, this lineation is a result of the deformation during the synkinematic metamorphism in which the schist was formed, and probably represents b lineation.

blue-amphibole schists

The overall color of the blue-amphibole schists usually is a medium bluish-green. The tone is often darker and the color more uniform than in the ordinary greenschists. Megascopically visible minerals are less common. Grains of albite up to ¼ mm. in diameter are visible in several of the specimens. There are a few irregular segregations of light greenish-yellow epidote but compositional bands of epidote are rare. Amphiboles as much as 1 mm. long are visible in some of the specimens.

The megascopic differences between the ordinary greenschists and the blue-amphibole schists are slight. In general, the blue-amphibole schists are bluish, are often darker and generally more uniform in color, composition, and grain size, and are finer grained than the greenschists. These are gross features of the blue-amphibole schists as a whole; individual specimens of the two rock types can be very similar in megascopic appearance.

The difference between the ordinary greenschists and the blue-amphibole schists is the presence of abundant quantities of sodic actinolite, glaucophane, and crossite in the latter. Misch's unpublished data on the optical properties of the blue amphiboles are the basis for the study of these minerals in the area investigated: the blue amphiboles are the sodic members of the system actinolite-sodic actinolite-glaucophane-crossite; an unnamed uniaxial transition member exists between glaucophane and crossite; "cross-actinolite" is a rare form of sodic actinolite with crossite orientation (Misch, oral communications and lecture notes).

The compositions of the 9 blue-amphibole schists studied in thin section range from a trace to 10% quartz, 10 to 45% albite, 15 to 60% epidote, 0 to 10% chlorite, and 20 to 65% sodic actinolite, glaucophane, and crossite. The average amount present of these minerals is 3% quartz, 25% albite, 30% epidote, 3% chlorite, and 40% amphibole. Minerals found in some but not all of the schists are: muscovite and sericite, up to 2%; sphene and leucoxene after sphene, up to 5%; stilpnomelane, up to 2%; and traces of pyrite and carbonate.

The quartz forms aggregates of strained or unstrained crystals which sometimes form pavement texture, or it occurs as scattered groundmass grains 0.02 to 0.25 mm. which are indistinguishable from albite except under convergent light. The albite differs from that described in the ordinary greenschists in that it is less often porphyroblastic, the maximum grain size being about 0.2 mm. The amount of albite present in the blue-amphibole schists is about 15% less than in the ordinary greenschists.

There is an average of 5% more epidote in the blue-amphibole schists than in the ordinary greenschists. This epidote was a somewhat larger average grain size and reaches a maximum size of as much as 0.5 mm. The iron content is higher than in the ordinary greenschists; thus distinct pleochroism is fairly common, the birefringence ranges between 0.027 and 0.050 and the (-) 2V ranges between 70 and 80°. According to Winchell, (1933, p. 313), these properties indicate an epidote ranging from 20 to 35% of the iron epidote molecule.

Chlorite is apparently absent in 2 of the specimens, is pennine in 5 and clinochlore in 2. Muscovite and sericite are present in 4 specimens in plates about 0.03 mm. thick and 0.15 mm. long. Sphene and leucoxene which probably is mostly after sphene are present in 4 specimens, and pyrite in 3. Stilpnomelane has formed as an alteration product along fractures in 4 specimens.

Of the 9 blue-amphibole schists studied in thin section, 2 contain only sodic actinolite and 7 contain various proportions of sodic actinolite, glaucophane, and crossite. The blue amphiboles generally are zoned and it is difficult to estimate the amount of each kind present. Very approximately, the distribution of blue amphiboles in the sections studied is:

specimen	sodic actinolite	glaucophane	crossite
9/22/55/7	15%	5%	-
7/15/565B	15	10	1
7/17/56/1	20	30	trace
7/17/56/5	trace	50	trace
7/26/56/3B	15	20	trace
8/19/56/2	25	25	15
8/20/56/4	20	-	-
8/20/56/7	50	-	-
8/20/56/11	25	15	trace

Based on the above determinations, the average of the blue-amphibole schists contains perhaps 20% sodic actinolite, 20% glaucophane, and less than 1% crossite.

The blue amphiboles range in size from acicular tiny grains to crystals as much as 0.2 mm. thick and 0.8 mm. long. The larger crystals are usually thicker in proportion to their length than are the smaller crystals. Most of the largest crystals are crossite. The general size seems to range between 0.02 and 0.1 mm. in thickness and 0.2 and 0.5 mm. in length. Prismatic faces and amphibole cleavage are strongly developed, terminations usually are ragged. Most of the crystals are sharply parallel to s except where they bend around small albite porphyroblasts. In many of the schists there is a strong lineation marked by the alignment of the amphiboles. In lineated rocks, masses of fine grained amphiboles lie with their crystal faces touching. The crystal boundaries are difficult to distinguish from the cleavages in such occurrences. The blue amphiboles are earlier than the albite porphyroblasts: they are included in the porphyroblasts, they have been displaced by them. Most of the included amphiboles are aligned parallel to s_e, but a few follow curved patterns (Fig. 22).

Glaucophane forms independent crystals, cores of zoned crystals largely composed of sodic actinolite, or zones between the uniaxial member and sodic actinolite in crossite-cored grains. When glaucophane is present in the rocks of the area, it is always more common than crossite, the crossite usually being very minor. The optic plane of glaucophane lies in (010). The maximum birefringence is about 0.020. The maximum 2V is estimated to be (-)50°; other (-) 2V's are estimated to be 40, 25, 15, 10, and 5°. The measured extinction angles Z:c in (010) are 10°, 4°, and 2°. The pleochroism is: X = colorless to pale yellow; Y = faint bluish violet to violet; Z = faint blue to blue. The birefringence, optic angle, and extinction angle all decrease as the composition approaches the uniaxial member and crossite, but the intensity of absorption increases. The uniaxial member forms a zone between glaucophane and crossite in zoned crystals with crossite cores. Sometimes the cores of crystals appear to consist entirely of the uniaxial member without crossite. No independent crystals of the uniaxial member were seen. The uniaxial zone is so vaguely defined in the crystals that little was learned about it except that it gives a uniaxial negative figure. Crossite generally occurs in cores of zoned crystals. The outer zones may pass from crossite through the uniaxial member and glaucophane to sodic actinolite, or the glaucophane zone may be missing, or, rarely, the crossite may pass directly into the unusual variety of sodic actinolite which has crossite orientation ("cross-actinolite"). The optic plane of crossite is normal to (010), lies across the elongation, and is not far from (001). The maximum birefringence is much lower than that of glaucophane but the interference colors are to some extent masked by the strong absorption and dispersion. Extinction is difficult to see because of the low birefringence, masked interference colors, and especially the dispersion. Measured extinction angles for Y: c in (010) are 9°, 7°, 5°, and 3°. The (-)2V is 50°. The pleochroism is: X = colorless to light yellow; Y = "inky" or "smokey" blue; and Z = "smokey" violet to "smokey" blue violet. Sometimes there is a faint greenish cast to the more intense absorptions of Y and Z. The intensity of absorption is generally much greater than that of glaucophane. However, some of the lighter crossite has the same absorption as some of the darker glaucophane. Light-colored crossite is distinguished from glaucophane by the position of the optic plane in grains large enough to give interference figures. If the grain is too narrow to give a figure, a (100) section of crossite shows length fast and a (100) section of glaucophane has length slow. A (100) section is recognized by parallel extinction, low birefringence, and pleochroism in blue and violet.

Sodic actinolite forms independent crystals or tips or rims on zoned crystals of glaucophane or crossite. Sodic actinolite is the most abundant of the blue amphiboles in the schists of the area investigated. It is never absent in any of the thin sections containing blue amphiboles, at least in the form of tips on zoned crystals. The optic properties vary between those of actinolite and those of glaucophane, depending upon the relative proportions of the two molecules. Very little was determined on the variations of 2V in sodic actinolite. However, since the 2V of actinolite is quite large and th e 2V of glaucophane is moderate to small, intermediate values would be expected. One sodic actinolite has a (-)2V of 60°. The extinction angle Z:c in (010) decreases from a value of 20° in actinolite to 10° in glaucophane. Measured extinction angles are: 19°, 18°, 17°, 16°, 14°, 13°, 12°, and 11°. In one zoned crystal, the extinction for the greenish tip is 17°, and the extinction for the greenish blue core is 12°. The pleochroism changes gradually from that of actinolite towards that of glaucophane. Therefore, in sodic actinolite, Y ranges from grayish green to violet with a greenish hue, and Z ranges from bluish green to greenish blue. Throughout the series, X remains colorless to light yellow.

The blue amphiboles in this area are almost invariably zoned. The individual zoned crystals contain two or more varieties. The most common form of zoning is shown in Fig. 23: a glaucophane core with a sodic actinolite rim (or tip). Many of the small prismatic grains of glaucophane are zoned in this manner. Crossite sometimes forms the cores of crystals of similar size and shape in which the uniaxial transition member should intervene between the crossite and the sodic actinolite unless the latter is "cross-actinolite". In crystals of these dimensions, the optic orientation of the sodic actinolite tip or rim seldom can be determined, and the uniaxial zone may be virtually imperceptable.

Another common type of zoning, usually apparent only in the relatively wider crystals, is shown in Fig. 24. The core is glaucophane with an intensity of absorption similar to that of the lighter crossite. A zone of lighter glaucophane intervenes between the core and the sodic actinolite rim.

A zoned crystal composed of 5 varieties is shown in Fig. 25. In this grain there is a marked difference between the zoning on the two ends of the crystal. On one end, the dark crossite core passes into a narrow band of the uniaxial member and a somewhat wider band of glaucophane, and then into a zone of sodic actinolite which is itself progressively more actinolitic towards the tip. At the other end, there is a broad zone of a light colored blue amphibole next to the dark crossite core. It is impossible to tell if this light blue zone is crossite with a very small 2V or if it is the uniaxial member because the orientation precludes exact determination of the optic axial angle. This zone grades into a sodic actinolite tip.

Two unusual crystals are shown in Fig. 26. One end of individual I passes from crossite into what appears to be "cross-actinolite". The interference figures on the "cross-actinolite" are poor but the optic plane seems to lie across the elongation. The other end appears to have a tip of ordinary sodic actinolite. This crystal also shows light colored crossite which indeed was taken for glaucophane until the optic orientation was determined.

It is thus indicated that the zoning of the blue amphiboles varies from relatively simple to rather complex. Although no single crystal was found which showed zoning from crossite all the way to pure actinolite, zoning from crossite to an intermediate sodic actinolite is shown in Fig. 25. True actinolite is rare in the blue-amphibole schists of the area but the tips of some of the sodic actinolite prisms sometimes pass into an amphibole with properties close to that of actinolite. There can be little doubt as to the isomorphic nature of this series when so much of the system can be shown in regular gradational succession within the boundaries of a single crystal.

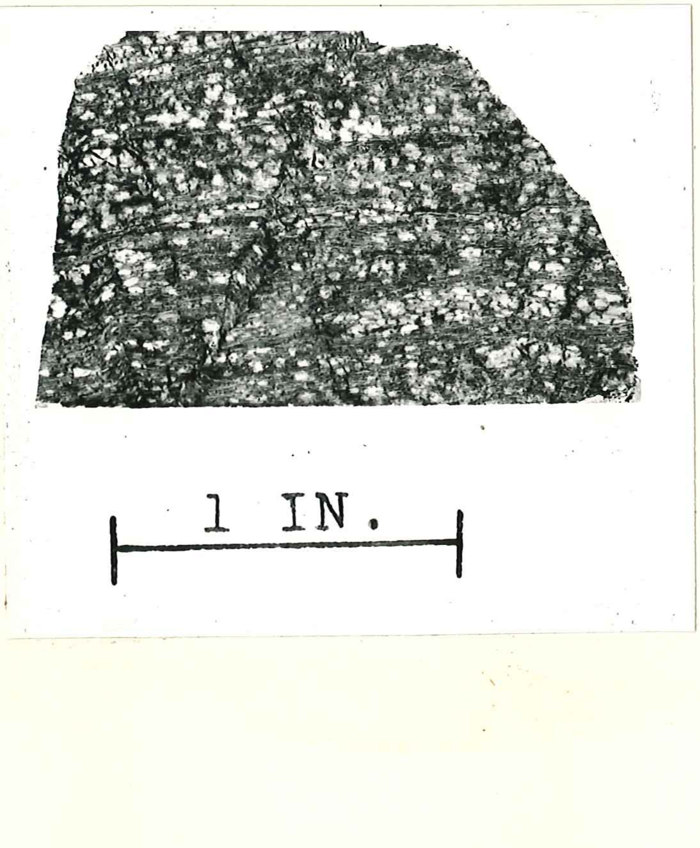
There is no apparent relation between the amount of epidote and the kind of blue amphibole present. Compared to the ordinary greenschists, the average content of epidote in the blue-amphibole shists is about 5% higher. This epidote of the blue amphibole schists contains about 5% more of the iron molecule. The blue amphibole schists containing only sodic actinolite have less epidote than the average, but their epidote contains more of the iron molecule.

greenstones

The area underlain by greenstones is on the wooded slopes on the south end of South Fork Ridge at elevations between 2500 and 3000 feet. Greenschists are exposed at elevations above 3500 feet. Unaltered diabase and gabbro outcrop further west at the same elevations as the greenstones.

One specimen of the greenstone contains 5% quartz, 35% albite, 10% epidote, 50% actinolite, and accessory leucoxene, some of which is after sphene. The grain size is from extremely small to as much as 0.08 mm. The quartz is indistinguishable from the albite except under convergent light. The epidote is pleochroic in pale yellow. It appears to contain about 20% of the iron molecule. The pleochroism of the actinolite is: X = pale yellow; Y = Z = light grayish green. There is rough parallelism of the actinolite, forming a weak schistosity.

Although chlorite appears to be absent in this specimen, the association of albite plus epidote is indicative of the low grade zone of metamorphism.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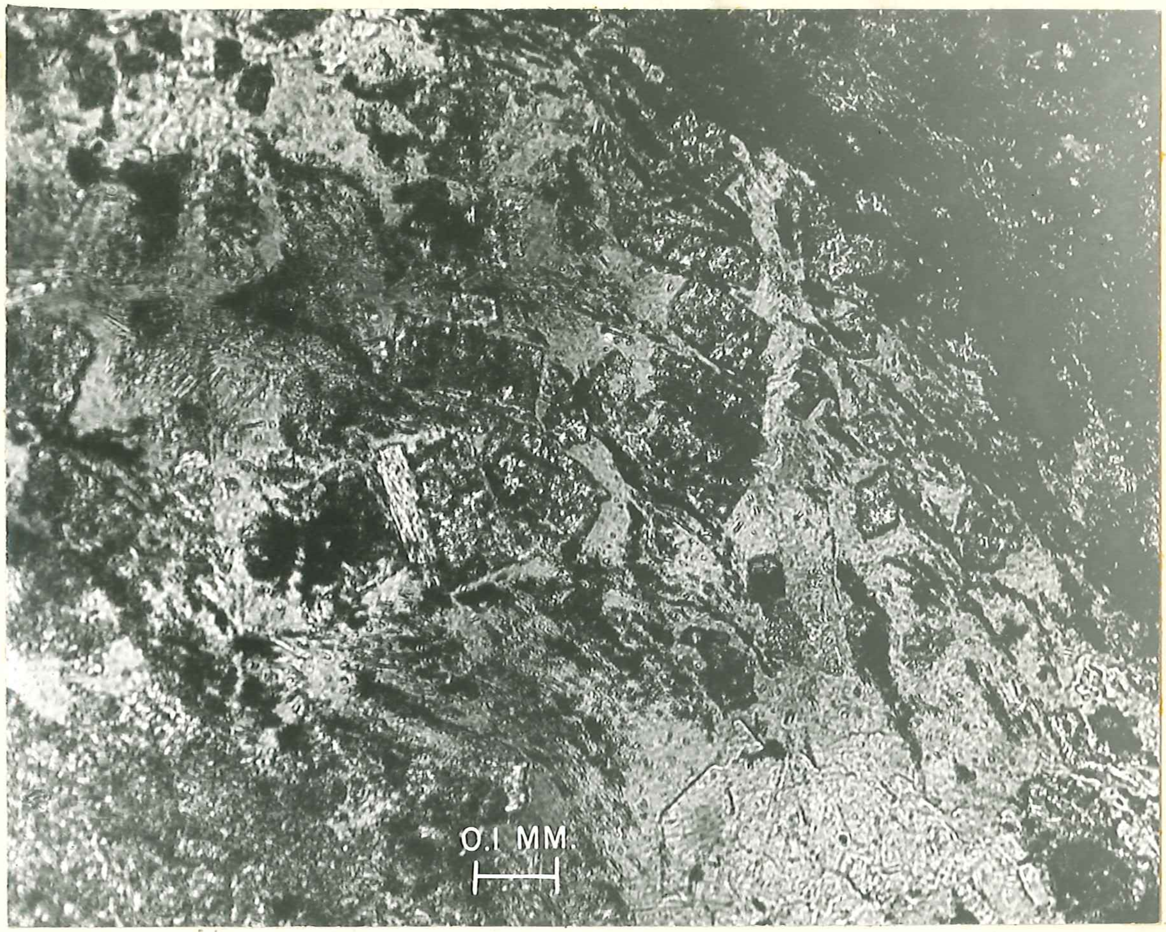
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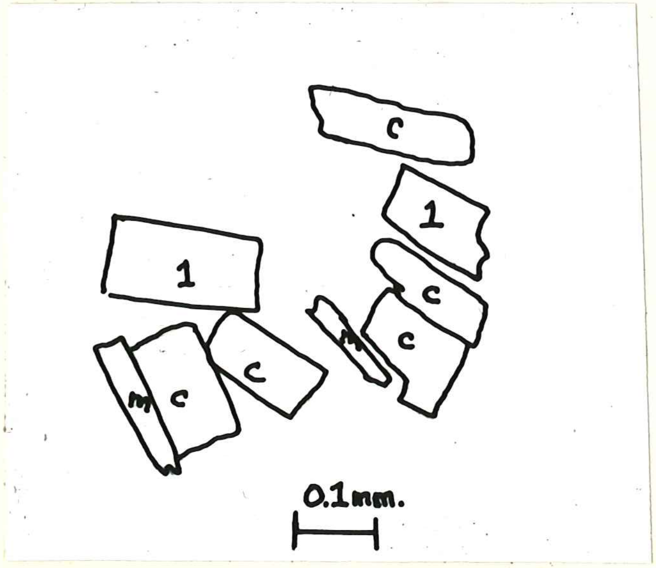
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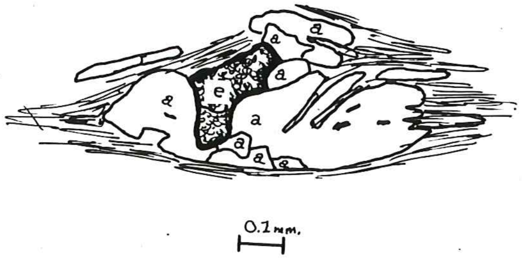
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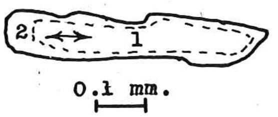
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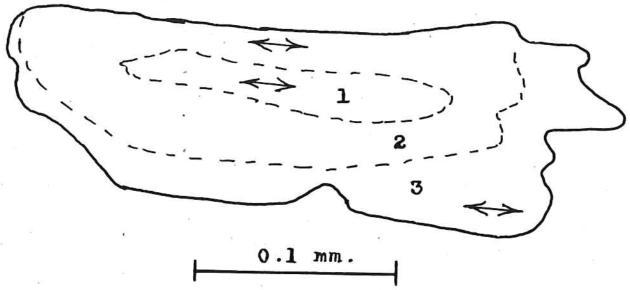
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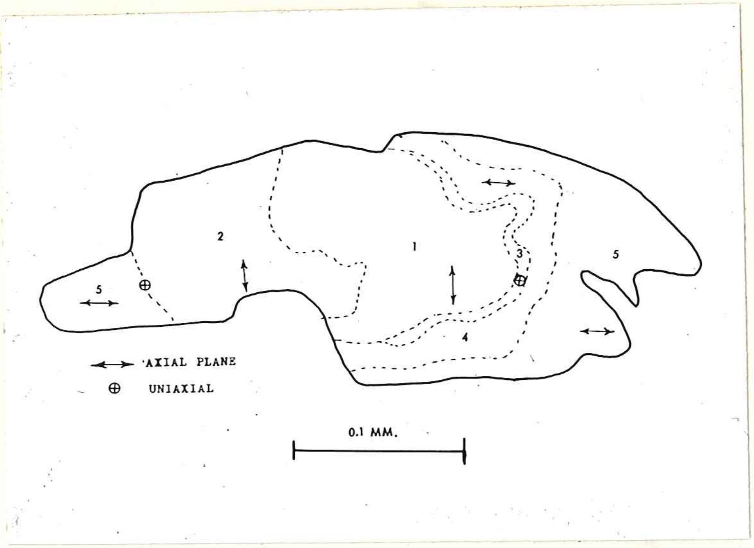


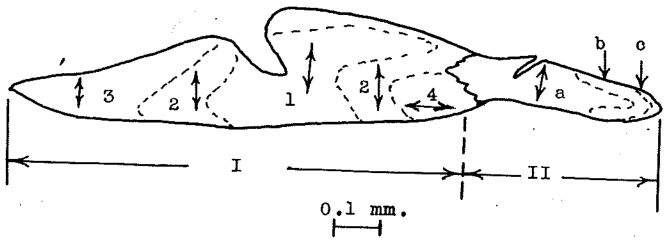
centered uniaxial figure but is too vaguely defined to permit a study of the pleochrism.

4. Glaucophane. (-)2V 50 to 60°. Length slow.

    Y = pale violet
    Z = light blue

5. Sodic actinolite. (-)2V could not be estimated but it is larger than in any other zone. Length slow.

    Y' = pale green with yellowish cast, grading into grayish green towards the tips.
    Z' = pale bluish green in the area close to the glaucophane or crossite contact, grades into moderately bluish green towards the tips.



Individual II:

a. Crossite core medium dark. Near optic axis figure with small negative 2V. Length fast.

Y = moderately pale grayish blue, intensity between that of 1 and 2.
Z = pale smokey violet

b. Uniaxial transition member ? Nearly centered optic axis figure, (-)2V apparently 0. Extinct throughout rotation of stage.

length = pale blue
across = pale violet

c. Narrow rim of sodic actinolite, orientation uncertain. Pale green with bluish cast in all positions.

Petrogenesis and Correlation of the Low Grade Metamorphic Rocks

The phyllite unit and the greenschist unit are subdivisions of a large body of low grade metamorphic rocks. On the east, this body is composed of phyllites; on the west, it is dominantly greenschists but with minor amounts of interbedded phyllites and albite schists. The contact between the two areas is transitional; in going from the phyllites to the greenschists, one passes across a belt of alternating greenschists and phyllites. Both units have undergone low grade synkinematic metamorphism and contain typical low grade mineral assemblages. The mutual interbedding, the transitional contact, and the identical metamorphism are evidence that the two units were metamorphosed together as one body. The later, entirely cataclastic, deformation affected only the phyllites, but some of the phyllites so affected are interbedded in the main greenschist body. During this later deformation, the greenschists were competent and the deformation was taken up selectively by the intercalated phyllites. In a similar manner, the albite rich layers of the albite schists were competent relative to the phyllites.

The phyllites were formed by low grade synkinematic metamorphism of argillaceous sedimentary rocks. The greenschists were formed by low grade synkinematic metamorphism of basic volcanic rocks. There are several noteworthy features in the low grade rocks of the area: (1) the high albite content in some of the rocks of the phyllite unit and the presence of albite porphyroblasts in both units, and (2) the presence of the blue amphiboles in the greenschist unit.

In studying the low grade rocks, several chemical analyses were computed from the modes. A chemical analysis computed from a mode is liable to many errors, among which are: personal error in identifying minerals and determining the mode; optically indistinguishable minerals (sericite-paragonite); and isomorphous minerals for which the relations between optical properties and compositionare not fully understood (amphiboles, K content of plagioclase). The following discussions of the chemistry of the low grade rocks is based on such determinations and must be regarded as a general discussion of only approximate data.

Petrogenesis of the ordinary phyllites

Assuming that the mica is sericite and that there is no K in the albite, and ignoring minor constituents such as chlorite, limonite, pyrite, etc., the computed chemical analysis from the average composition of the ordinary phyllites is 69% SiO_2, 18% Al_2O_3, 2% Na_2O, 5% K_2O, 4% C, and 1% H_2O. Since the minor amounts of femics present in the ordinary phyllites were ignored, the figures for this analysis are higher than they should be. Allowance for these uncomputed constituents could be made by deducting several percent from the analysis, particularly from the values for SiO_2 and Al_2O_3. After making such an allowance, these values are close to those of the average shales listed by Pettijohn (1949, p. 271). The Na_2O and K_2O are similar to the average of the analyses of roofing slates listed by Clarke (1924, p. 553), Dale (1906, pp. 34 and 35), and Eckel (1904, p. 25). These analyses of roofing slates are pertinent since they represent the composition of rocks derived from shales in a geosynclinal depositional sequence which under slightly more intense isochemical metamorphism would have become phyllites. In the roofing slates, the analyses usually show slightly more than 1% of Na_2O and 2-4% K_2O. Such values would be expected for phyllites derived from shales. The ordinary phyllites of the area contain 2% Na_2O and 5% K_2O. Therefore an argillaceous sedimentary rock of the composition of an average shale would be the most probable source for the ordinary phyllites.

In its simplest form, an argillaceous sedimentary rock contains quartz, clay minerals and K and Na absorbed by the clay minerals. Under low grade metamorphism, clay minerals of the kaolinite and montromillonite types combine with quartz and the absorbed K to form sericite. The illite clay minerals require only a very small change in composition to make sericite, only the replacement of OH by O. The Na may combine with clay minerals and quartz to make albite or it might go into the sodium mica paragonite. Paragonite is optically indistinguishable from sericite.

petrogenesis of the albite phyllites

Under the same conditions as listed above, but allowing for 5% clinochlore, the analysis of the average composition of the albite phyllites is 69% SiO_2, 18% Al_2O_3, 2% MgO, 4% Na_2O, 2% K_2O, and 1% H_2O. These values are higher than they should be since there usually is a small amount of epidote, leucoxene, sphene, etc., in the albite phyllites. Allowance for the uncomputed Ca, Fe, Ti, etc., could be made by deducting several percent from the analysis, particularly from Al_2O_3 and SiO_2. In this analysis, Na_2O is considerably in excess of K_2O. In the albite phyllites with the maximum contents of albite, the Na_2O runs 7-9% against about 1% K_2O. These values are very much larger than in the average shales and the roofing slates. The mineralogical expression of this high Na_2O is the high albite content in the albite phyllites and albite schists.

The albite phyllites contain albite in amounts greater than that which should form in the isochemical metamorphism of an average argillaceous sedimentary rock. This albite is in part porphyroblastic, but albite porphyroblasts are not confined to the phyllite unit alone. The greenschist unit contains albite porphyroblasts also, although these generally are smaller and less numerous than in the phyllite unit. Nevertheless, the largest albite porphyroblasts seen in the area are in a greenschist which is close to the phyllite unit contact. Rather than become involved in the terminology of sedimentary petrology, it would be better to state that a sedimentary rock containing abundant quartz, plagioclass and some cafemics would, under isochemical metamorphism, produce an albite phyllite. Such a rock would be an arkose in most classifications of sedimentary rocks. The albite component of the existing plagioclase would recrystallize into albite and the anorthite component plus the existing cafemics would go into epidote, chlorite, etc.

To the east and north of the mapped area, rocks which apparently are an extension of the phyllite unit include fine grained schistose arkoses and arkosic siltstones which have essentially clastic textures with superposed cataclastic textures. Several thin sections of these rocks have been studied. The mineral compositions are similar to the albite phyllites of the mapped area, but the rocks have not fully recrystallized. It is probable that the albite phyllites are the fully recrystallized equivalents of these schistose arkoses and arkosic siltstones.

Although an arkose or arkosic siltstone is the most probable source of the albite phyllites, the simple presence of abundant original plagioclase does not fully explain the porphyroblasts of albite, especially since some of the porphyroblasts are in the greenschists.

The data on the albite porphyroblasts in the mapped area are as follows: The albite porphyroblasts are post- and late-kinematic. They occur in most the albite schists and phyllites, including those interbedded in the greenschists, and in some of the greenschists themselves. In some of the rocks, as little as 1% of the albite present is porphyroblastic, but in others all the albite is porphyroblastic. The albite porphyroblasts are in physical and chemical equilibrium with the surrounding rocks. The maximum albite content of the albite schists does not exceed that of the nearby schistose arkoses and arkosic siltstones. The largest porphyroblasts seen are in a greenschist which is very close to the contact with albite phyllites.

Most of the above data favor a short-range transfer of albite constituents within the low grade rock unit. Nevertheless, some trigger mechanism seems needed, and something must control the irregular distribution of the porphyroblasts. This very well could be some minor introduction of sodium from an outside source.

Therefore, the albite phyllites are most likely derived from a sedimentary rock with a composition close to that of an arkose. In the late-and post-kinematic stages of low grade metamorphism, albite porphyroblasts formed under essentially isochemical conditions, but some introduction of sodium may have occurred.

petrogenesis of the greenschists

Greenschists may be derived from dolomitic shales or from intermediate to basic igneous rocks. If the ordinary greenschists and the blue-amphibole schists had been derived from sedimentary rocks, there probably would have been some rocks deposited with compositions between that of dolomitic shale and that of average shale or feldspathic siltstone. Low grade metamorphism would have produced rocks intermediate in composition between the greenschists and the interbedded phyllites. No such intermediate rocks have been seen in the present area. All the contacts seen between the greenschists and the phyllites are sharp. The lack of intermediate rock types and the sharp contacts indicate that the two metamorphic rock types were derived from two unrelated parent rocks. This, and the rather uniform composition of the greenschist, indicates that the greenschists were most probably derived from basic igneous rocks. The interbedding with phyllites shows that these basic igneous rocks were volcanic rocks rather than intrusive rocks.

In order to get some idea of the chemical composition of the greenschists, an analysis was computed for the average of the ordinary greenschists, assuming the amphibole is to be an iron poor actinolite. This analysis was compared with the actual chemical analyses obtained by Misch (oral communication) for similar greenschists which contain an apparently iron poor actinolite and come from the Shuksan greenschist unit. The computed chemical analysis differed greatly from the actual analyses, especially in iron. Thus there seems to be little value to the chemical analysis computed from the mode of a greenschist. The optical properties of amphiboles in relation to their composition are too poorly known. Epidote also is a source of error. There seems to be no way of determining the chemical composition of a greenschist with reasonable accuracy without an actual chemical analysis.

Without chemical data, little can be said as to the exact composition of the parent rocks of the ordinary greenschists and blue-amphibole schists of the present area. The minerological composition and the field relations indicate that these schists were derived from basic volcanic rocks. A number of chemical analyses of similar rocks from the Shuksan greenschist unit (Misch, oral communication) show their compositions to be similar to that of olivine-free, plagioclase-rich basalts. Such original rocks are the probable source of the ordinary greenschist and blue-amphibole schists of the present area also.

The blue-amphibole schists are intimately interbedded with ordinary greenschists. There is no evidence of greater or lesser shearing or of higher temperature in the blue-amphibole schists. There was no difference in the physical conditions under which the two rock types were formed. In the present area, no separate, distinct glaucophane schist facies exists. The reason for the formation of the blue-amphibole schists can only be chemical. The average blue-amphibole schists of the present area contain somewhat more, and somewhat iron richer, epidote than do the average ordinary greenschists. The blue-amphibole schists may form in a higher iron environment, but the evidence is not conclusive in the present area.

metamorphism of the low grade rocks

The low grade rocks probably were derived from an interbedded sequence of shales, feldspathic siltstones and andesitic to basaltic volcanic rocks. These rocks were isochemically metamorphosed under low grade synkinematic conditions into phyllites and greenschists. During the late and post kinematic phases, albite porphyroblasts grew, partly with the aid of transfer of sodium within the body, and perhaps with some minor introduction of sodium from outside.

Following this period of constructive metamorphism, entirely cataclastic metamorphism created a second schistosity in the phyllites. This s_2 is not uniformly developed; some phyllites apparently escaped entirely, others were intensely sheared. The greenschists were competent under this shearing and the movement was taken up selectively by the intercalated phyllites. It is not clear whether s_2 was developed by renewed operation of the same stresses which were responsible for s_1 or whether s_2 is the result of an unrelated and altogether later episode of deformation. Too little is known about s_3 to permit evaluation of its cause.

correlation of the low grade metamorphic rocks

The phyllite unit apparently continues beyond the mapped area eastwards to the Sauk River and northwards to the Skagit River. The relationships of the phyllite unit to the little metamorphosed pre-Tertiary sedimentary and volcanic rocks in the vicinity of Sutter Mountain are not known. South of the Suiattle River and east of the Sauk River, Vance (1957) mapped the "Gold Hill phyllites". Bryant (1955, p. 27) tentatively correlated the phyllites north of the Suiattle River and east of the Sauk River with those subsequently designated "Gold Hill" by Vance. North of the Skagit River, Misch (1952, p. 7) mapped equivalent phyllites, part of which he named "Goat Mountain phyllite" (oral communication).

The "Gold Hill" type of phyllites are very similar to the rocks of the phyllite unit of the present area. Few fully recrystallized albite phyllites have been reported from the Gold Hill phyllite (Vance, 1957). The Gold Hill contains some fine grained feldspathic siltstones or microarkoses which may be the non-recrystallized equivalents of the albite phyllites. The phyllite unit probably is part of the "Gold Hill" but definite correlation must be deferred until the area between the present area and the Sauk and Skagit Rivers have been studied.

North of the present area, greenschists and blue amphibole-schists outcrop south of the Skagit River on the strike of the greenschist unit. They are well exposed along the Finney Creek road southwest of the Clendenen Creek and again south of the Skagit River near Hamilton (Shedd, 1922, p. 97). Along Finney Creek, some of the schists contain abundant crossite. South of the present area, Vance (1957) mapped the "Clear Creek" crossite schists on the lower slopes of Jumbo Mountain. These crossite schists are on the strike with the greenschist unit of the present area. Therefor, greenschist unit is part of a more or less continuous belt of greenschists which may extend as much as 15 miles to the north of the mapped area and which also may extend to the south. Crossite, uncommon in the mapped area, is found both to the north and to the south.

Misch (oral communication) has given the name "Shuksan greenschist unit" to a belt of greenschists and blue-amphibole schists which extends southeastward from Mt. Shuksan to the Skagit River. The Shuksan greenschist unit, together with the Goat Mountain phyllites, have been thrust over little metamorphosed pre-Tertiary sedimentary and igneous rocks. South of the Skagit, and east of the Sauk River, Bryant has mapped the southern extension of the Shuksan greenschist unit. Vance has also recognized the Shuksan greenschist unit south of the Suiattle River and proved that, together with Gold Hill phyllites, they have been thrust over little metamorphosed pre-Tertiary sedimentary and igneous rocks on Prairie Mountain.

The rocks of the Shuksan unit are similar to those of the greenschist unit of the present area. The average mineral compositions reported by Vance (1957) and Bryant (1957, pp. 22 and 23) show a little more epidote and somewhat less albite than are found in the greenschist unit of the present area. These differences are from 5% to 15%, which is not very large. Vance, Bryant, and Misch (oral communication) report iron rich epidotes. Vance found subequal amounts of crossite and glaucophane; Bryant, about 3 times as much crossite as glaucophane; and Misch, much more crossite than glaucophane. In the present area, the epidote is not iron rich, and crossite is very minor compared to glaucophane. North and south of the present area, crossite does occur in greenschists which are on the strike with the greenschist unit. The relative abundance of crossite to glaucophane is not known for these schists.

The petrographic difference between the rocks of the Shuksan greenschist unit and those of the greenschist unit of the present area are small. In view of the lack of data on the northward extension of the greenschist unit, and on the structural relationships between the Shuksan greenschists east of the Sauk River and the greenschist unit of the present area, the data available at the time this report is written do not permit stratigraphic correlation.

Medium Grade Metamorphic Rocks

Hornblende-Quartz-Dioritic Gneiss

Hornblende-quartz-dioritic gneiss outcrops in a hill at the north edge of the Stillaguamish valley north of Fortson at the foot of the eastern end of Higgins Mountain. This hillis rounded, east-west trending ridge rising several hundred feet above the valley floor which is at an elevation of 500 feet at the base of the hill (Fig. 27). The relations of the gneiss to the surrounding rocks are obscured by dense vegetation and alluvial or glacial cover. The Swuak formation outcrops in the small valley north of the hill of gneiss and again on the southern slopes of Higgins Mountain.

In outcrop (Fig. 28), the gneiss is uniform in appearance with about two-thirds coarse, lenticular, white to buff plagioclase; minor, finer grained, intergranular, clear quartz; and one-third, anhedral, ragged, greenish-black hornblende evenly distributed throughout the rock. The maximum grain size of the hornblende and plagioclase is about 5 mm. Schistosity is marked by preferred orientation of the elongated plagioclase and hornblende. (Fig. 29). Occasional finer grained, dark colored clots (Fig. 30), consist of two-thirds hornblende, one-third plagioclase, and minor quartz. The rock has been sheared on widely spaced, irregular surfaces. Fine grained light green bands along the shear planes have been caused by retrogressive alteration.

Thin sections of three typical specimens of the coarse grained gneiss contain 5 to 20% quartz, 60 to 70% plagioclase, 10 to 20% hornblende, and minor biotite, magnetite, epidote, zoisite, chlorite, and carbonate. Much of the quartz is intergranular. The grain size varies from 0.2 to 0.6 mm. Sutured textures and undulous extinction are common. The quartz has attacked the plagioclase: narrow rims of decalcified plagioclase surround pseudopod-like projections of quartz extending into the plagioclase; the contacts between plagioclase and quartz are often cuspate with the points of the cusps pointing towards the quartz; and small, rounded grains of plagioclase are included in the quartz. The plagioclase crystals are as much as 5 mm. long. They often are zoned in an irregular, patchy fashion The composition ranges from andesine, An 40, to labradorite, An 60. Andesine appears to be more abundant than labradorite. The crystal outlines are irregular, not only where the plagioclase has been engulfed by the quartz but also along the contacts with the hornblende. Most of the plagioclase is somewhat altered. In many grains there is a more or less centrally located clump of very fine grained, semi-opaque material which is white in reflected light. Many grains contain a great deal of very fine grained sericite. Carbonate fills cracks in some of the crystals of plagioclase. Some albite seems to be associated with the intergranular, fine grained, quartz. The hornblende has a

(-) 2V of 70 to 80°, an extinction of Z:c = 16 to 18°, and a pleochroism of :X = light yellow, Y = Z = light green. The crystals are ragged, particularly along the contacts with plagioclase. A few of the hornblende crystals contain inclusions of quartz. Partial to complete alteration to chlorite, epidote, and carbonate is common. The epidote and chlorite sometimes form pseudomorphs after hornblende. Not all of the epidote minerals are retrogressive; some euhedral zoisite may be a main assemblage mineral.

One thin section of a fine grained, dark colored clot in the gneiss contains about 10% quartz, 40% plagioclase, 40% hornblende, and 5% magnetite and pyrite. The quartz has attacked the plagioclase in the same manner as described for the coarse grained gneiss. The plagioclase is andesine, An 40. Along some of the contacts with plagioclase, the hornblende is pale and weakly pleochroic. Pseudopod-like projections of plagioclase sometimes extend into the hornblende. Wedges of plagioclase extend into the hornblende along its cleavages. Fig. 31 shows the relations of the minerals in the fine grained mafic clots.

The hornblende-quartz-dioritic gneiss is not an igneous rock. Feldspars do attack mafics during the late stages of crystallization of an igneous melt, but the reaction series requires that they be sodic plagioclases or potassium feldspars. In the hornblende-quartz-dioritic gneiss, the hornblende is replaced by intermediate to calcic plagioclases with which hornblende would have been stable in an igneous melt. The scattered inclusions of quartz in the amphiboles are also indicative of a metamorphic origin of the rock. Quartz is a very late mineral in the reaction series and would not ordinarily be included in a mineral which should have crystallized out earlier.

The fine grained clots probably are the partially feldspathized and partially silicified remnants of an ortho-amphibolite. The coarse grained gneiss is the result of more advanced feldspathization and silification of the ortho-amphibolite during synkinematic regional metamorphism of the hotter medium grade.

The gneiss certainly is entirely out of harmony with the low grade metamorphic environment of the present area. Progression in type and grade of regional metamorphism from isochemical and low grade to allochemical and hotter medium-grade does not take place in the distance of one mile. Further, there is no corroborating evidence of such a progression north or south of the locality in question. The gneiss must have been moved into its present position by tectonic means. The mechanism of transporting the gneiss was most probably large scale overthrusting; this point will be discussed below in the chapter on structures.

Petrographically, the hornblende-quartz-dioritic gneiss has a striking resemblance to the Eldorado unit of the Skagit gneisses to the northeast. The Eldorado has been thrust to the west, (Misch, oral communication). Further, there are strong similarities to the gneissose quartz-dioritic, and amphibolitic rocks of two klippen north of Glacier (Misch, oral communication), and of the klippe at Helena Ridge to the southeast (Vance, 1957). Still further south, the Mt. Baring klippe of Yeats (1956, p. 8) contains amphibolites and partially granitized amphibolites. In view of the petrographic similarities and the regional structures involved in the above mentioned rocks, the hornblende-quartz-dioritic gneiss is tentatively correlated with the Eldorado gneiss, and, even more tentatively, with the Helena Ridge rocks. The Mt. Baring unit is too dissimilar to permit lithologic correlation, but appears to belong in the same structural unit.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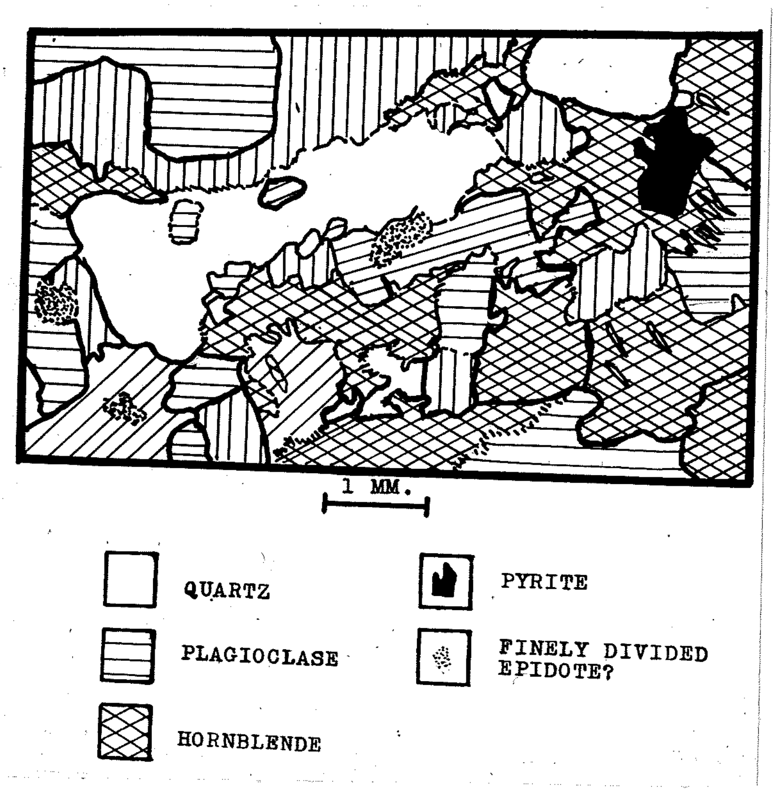


Fig. 31 Sketch of a portion of a fine grained mafic-rich clot in the hornblende-quartz-dioritic gneiss. Evidence of replacement of plagioclase by quartz is: cuspate contacts with the cusps pointing towards the quartz; and isolated, rounded inclusions of plagioclase in the quartz. Evidence of replacement of hornblende by plagioclase is: pseudo podlike projections of plagioclase extending into hornblende; and wedges of plagioclase along the clevages of hornblende.

Hornblende-Plagioclase Schist

Hornblende-plagioclase schist is exposed underneath the Swauk along the northeast face of Round Mountain (Fig. 32), and in some very small outcrops on the south side of Round Mountain. In outcrop, the hornblende-plagioclase schist is fine grained, and moderately dark grayish-green. It is considerably darker than the greenschists. The hornblende-plagioclase schist is finely banded in light and dark layers a fraction f a millimeter thick. The distribution of the hornblende-plagioclase schist and its relations to the other rocks is obscured by faulting, intrusions of serpentine and diorite, and by hydrothermal alteration of the schist itself.

One thin section of hornblende-plagioclase schist contains 15% quartz, 40% plagioclase, 15% epidote, 20% green hornblende, and traces of pyrite and sphene. The quart, forms groundmass grains and sheared out lenticles which have undulous extinction. The grain size of the quartz ranges from 0.015 to 0.1 mm. with most of the grains falling in the more fine-grained range. The plagioclase is sometimes twinned and zoned, but more often it can be distinguished from the quartz only under convergent light. The composition ranged from oligoclase, An 25, to andesine, An 45. The plagioclase forms groundmass grains 0.015 to 0.03 mm. in size and porphyroblasts up to 0.25 mm. in size. The epidote is mostly about 0.03 mm. in size, and a few grains are as large as 0.15 mm. It is colorless. The maximum birefringence is generally about 0.018 but a few grains reach 0.024. The epidote appears to contain between 10 and 20% of the iron epidote molecule. A few of the hornblende crystals reach a thickness of 0.3 mm. and a length of 0.5 mm., but most of them are smaller. The maximum birefringence is about 0.020. The extinction Z:c is 16 to 17°. The pleochroism is :X = light yellow; Y = medium yellow with greenish hue; and Z = moderately intense green with bluish hue. This appears to be common green hornblende.

Most of the rocks classed as hornblende-plagioclase schists have been hydrothermally altered into rocks with a mineral assemblage of: quartz, albite, stilpnomelane, calcite, chlorite, and sphene. The appearance in hand specimen and outcrop remains about the same, except the color is often lighter. The textures and structures visible in thin section are little changed. The recrystallization caused by this hydrothermal alteration is incomplete, sporadic, and in no way comparable to a truly metamorphic reconstitution.

The mineralogical composition of the hornblende-plagioclase schist is similar to that of some kinds of gneisses, but the rock is too fine grained to be classed as a gneiss. It appears to differ from the hornblende-quartz-dioritic gneiss in containing less plagioclase and more mafics, especially epidote.

The relations, if any, of the hornblende-plagioclase schist to the hornblende-quartz-dioritic gneiss are uncertain. The schist is a medium grade rock, but it has undergone much less feldspathization and silica introduction than the gneiss. The gneiss apparently was derived from an ortho-amphibolite which was ultimately derived from a basic igneous rock. The ortho-amphibolite contained about 2/3 hornblende. The hornblende-plagioclase schist has a much lower hornblende content than the relics of amphibolite in the gneiss. Thus, the hornblende-plagioclase schist is not a less granitized equivalent of the hornblende-quartz-dioritic gneiss. It may be a part of the same structural unit as the gneiss. However, north of Finney Creek, Vance (oral communication) has found garnet amphibolites which lie more or less on strike with the hornblende-plagioclase schist. If these garnet amphibolites should be in place, they would indicate a westward increase in metamorphic grade from the greenschist facies to the amphibolite facies. At present, too little is known to permit correlation of the hornblende-plagioclase schist with either the gneiss or the garnet amphibolites.

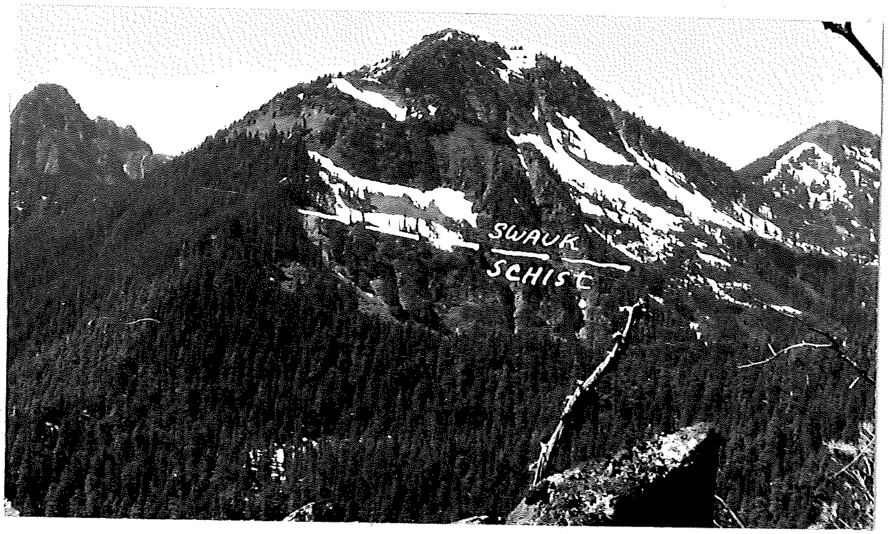


Fig. 32 Northeast face of Round Mountain showing the Swauk formation overlying the hornblende plagioclase schist.

B. IGNEOUS ROCKS

Most of the igneous rocks of the present area are of intermediate to basic composition. One large body of flow rock is dacite, but the rest of the igneous rocks are of dioritic, gabbroic, or ultrabasic composition. Of the igneous rocks, the Granite Lake labradorite porphyry has the largest outcrop area, about five square miles, part of which lies outside of the area covered by the geologic map. The dacite flows on the north end of Round Mountain Ridge have an outcrop area of at least 2-3 square miles and perhaps more. The rest of the igneous rocks have quite small outcrop areas.

The relative ages of the igneous rocks to the country rocks are sometimes obscure. The Swauk formation has been intruded by dikes of labradorite porphyry, dikes of diabase, and serpentine. The Swauk dips away from the Granite Lake labradorite porphyry body, suggesting that it has been displaced by its forceful intrusion. The relations of the andesites and diorites on the east end of Round Mountain are undertain, but they are earlier than the serpentine and may be responsible for the contact metamorphic effects observed in the nearby Swauk. Any igneous rocks affecting the Swauk are, of course, Tertiary. Gabbros, diabases, and basalts on Swede Heaven and South Fork Ridge are younger than the phyllites and greenschists.

Plutonic Rocks

Diorite

On the southeast end of Round Mountain, about 1½ miles southwest of the summit of Coney Pass, porphyritic diorite is found in several scattered outcrops. Some outcrops of andesite porphyry are found in the same area. The relations of the diorite outcrops to each other and to the other rocks is obscured by soil cover, forest, serpentine intrusions, and intense hydrothermal alteration of the diorite. Several of the outcrops of diorite contain greatly altered inclusions of country rock. Serpentine coats the joints of the diorite in one outcrop and forms several outcrops topographically higher than the diorite.

The Swauk formation shows evidence of contact metamorphism along the base of the cliffs a short distance to the west of the diorite outcrops. This could have been caused by the intrusion of the diorite or it could have been caused by peridote (now serpentine) which has intruded both the diorite and the Swauk. Some of the inclusions in the diorite appear to be altered sedimentary rock. If this altered rock is from the Swauk, the diorite would be later. Too little is known to permit definite relative age determination of the Swauk and the diorite. It is quite uncertain as to whether the diorite outcrops belong to one or to several intrusive bodies.

Too little is known about the diorite to permit detailed discussion. In outcrop, the diorite is light brownish gray to medium greenish gray and is flecked with abundant white plagioclase phenocrysts up to 1.5 mm. in diameter. Two thin sections studied in detail contain 30 to 40% plagioclase phenocrysts, a few unaltered phenocrysts of hornblende, and 25 to 30% alteration products of hornblende (calcite, pennine, chlinochlore). The fine grained groundmass is plagioclase, carbonate, chlorite, opaques, and minor quartz. In one specimen, the plagioclase phenocrysts are zoned andesine and labradorite; in the other, the plagioclase phenocrysts have been altered to albite. Other thin sections contain inclusions of country rock which appear to be greatly altered sedimentary rock (Swauk?), phyllite, and hornblende-plagioclase schist.

Granite Lake Labradorite Porphyry

Leucocratic porphyritic rock outcrops in many places around Granite Lake. This rock is the "granite" for which the lake is named. Actually the rock is of gabbroic composition and, if it were a granular textured rock, it could be classed as a hornblende-bearing leuco-gabbro. Exposures are excellent, especially in the cliffs about ½ mile southwest of Granite Lake. The rock breaks into blocks up to 3 feet across along well developed, widely spaced joints (Fig. 33). Most of the outcrops are littered with these large blocks, creating a typical pattern easily recognized on air photos by its jumbled appearance and its conspicuously light color (Fig. 34).

The relations of the labradorite porphyry body to the other rocks is unknown to the north and east, and obscured by glacial till to the south. West of Granite Lake, the Swauk formation dips away from the labradorite porphyry body. These dips are nearly at right angles to the regional dip of the Swauk to the north and south. These dips may indicate that the Granite Lake labradorite porphyry intruded the Swauk.

The labradorite porphyry is usually a fairly light greenish gray and weathers nearly white. The rock flecked with abundant white to buff plagioclase phenocrysts up to 4 mm. long and with considerably lesser amounts of greenish black hornblende phenocrysts up to 3 mm. long and 1 mm. thick. Hydrothermal alteration has produced color variations such as greenish brown and red.

Four thin sections studied in detail contain 1 to 2% quartz phenocrysts, 20 to 60% plagioclase phenocrysts, and 5 to 20% brown hornblende phenocrysts plus the alteration products of hornblende. The fine grained groundmass consists essentially of plagioclase but sometimes contains a little quartz and/or biotite. Almost every specimen studied has been affected by hydrothermal alteration of varying intensity. The hornblende has been altered to carbonate, chlorite, stilpnomelane, quartz, magnetite, and leucoxene;

the plagioclase to carbonate and sericite. Alteration has started with the hornblende, then affected the fine grained groundmass, and finally the plagioclase phenocrysts.

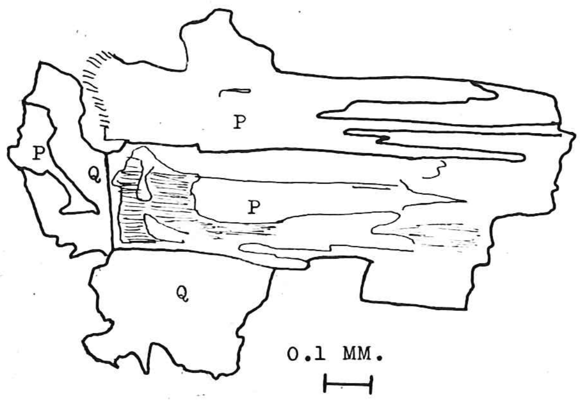
In some of the specimens studied, quartz formed as phenocrysts of the main igneous assemblage immediately following the plagioclase phenocrysts. There appears to be no quartz associated with the fine grained plagioclase which makes up the groundmass of these specimens. The quartz phenocrysts are as much as 0.2 mm. across and often are plastered against the crystal faces of subhedral plagioclase phenocrysts. No evidence of reaction is visible along the crystal boundaries between the two minerals. However, the boundaries of the quartz which are not up against the plagioclase are highly irregular and sometimes cuspate with the cusps pointing towards the groundmass (Fig. 35A). Isolated aggregates of quartz phenocrysts with irregular cuspate boundaries are also found (Fig. 35B). At some time after the quartz phenocrysts were formed, they must have been exposed to a medium in which quartz was not stable and the phenocrysts were partially resorbed. In other specimens, the quartz is a deuteric mineral which occurs both in the groundmass and as porphyroblasts. This quartz has attacked both the phenocrysts and groundmass grains of plagioclase (Fig. 35C). Quartz also occurs as a result of silica release during the hydrothermal alteration of hornblende. This quartz is associated with other alteration products in pseudomorphs after hornblende.

The plagioclase phenocrysts are up to 4 mm. long. They generally are zoned with labradorite cores and andesine rims. Thin rims of oligoclase followed by albite are found on some of the phenocrysts. A few phenocrysts exhibit oscillatory zoning. The average compositions of 19 plagioclase phenocryrsts determed on the universal stage are: 5 andesine and 14 labradorite. Nine of the phenocrysts are labradorite as calcic as An 60 to An 65. The phenocrysts range from anhedral to euhedral. Glomerophyric aggregates are common. Many of the crystals are cut by multiple, irregular, transverse fractures. Alteration to sericite and carbonate ranges from incipient to complete. Few phenocrysts have remained completely unaltered.

The groundmass plagioclase crystals are anhedral to subhedrally lath-shaped and range in size from 0.01 to 0.04 mm. The groundmass plagioclase may be less calcic than the phenocrysts but more data is needed to be certain. The compositions are difficult to determine because of the small size, and because the groundmass plagioclase is much more often fully altered than are the phenocrysts. Glomerophyric aggregates and multiple transverse fracturing are lacking in the groundmass feldspars.

The hornblende forms anhedral to euhedral grains up to 3 mm. long and 1 mm. thick. The pleochroism is: X = light yellowish brown; Y = Z = medium to dark brown.

Most of the hornblende is altered to stilpnomelane, chlorite, carbonate, quartz, magnetite, and leucoxene.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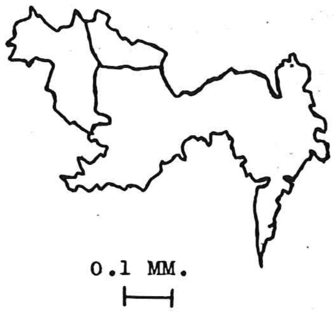
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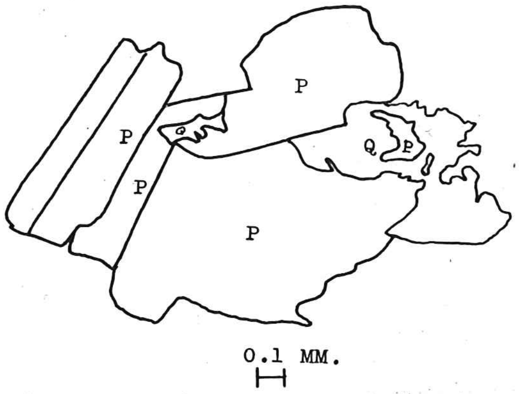
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Gabbro

A hill rising above the east side of Segelson Creek on the western slope of Swede Heaven is composed of gabbro and associated basic and ultrabasic rocks. The coarse grained gabbro has been saussuritized and therefore is a light "watery" green. The finer grained less altered diabasic rocks are a slightly darker, fresher looking green. The associated serpentinized peridotite is black.

One thin section of the saussuritized gabbro contains about 40% augite and 60% saussuritized plagioclase. The augite is in anhedral grains up to 8 mm. across. Much of the augite is turbid, suggesting incipient alteration. The saussurite forms masses up to 10 mm. across which are pseudormorphs after plagioclase. The saussurite is an aggregate of very tiny grains of minerals which are difficult to identify because of their extreme smallness. These minerals seem to be epidote, zeolites, prehnite, and sericite.

Two specimens of finer grained basic rocks associated with the gabbro were studied in thin section. One specimen contains 5% green hornblende phenocrysts and 15% plagioclase phenocrysts. The plagioclase has been altered to albite. The phenocrysts are up to 3 mm. long. The groundmass grains are 0.04 mm. and smaller. The minerals of the groundmass are pyroxene (?), iron-poor actinolite, sphene, and minor pyrite, leucoxene, and (questionably) feldspar. This rock probably is an altered basalt. The other specimen contains 60% chlorite, and 5% leucoxene. The feldspar is now oligoclase. The texture is more or less diabasic, but the plagioclase crystals tend to be stubby rather than lath shaped. This rock probably is a partly altered diabase.

One thin section of serpentenized peridotite associated with the gabbro contains 90% antigorite, 10% magnetite and a few relict grains of pyroxene and olivine.

Serpentine

Serpentine is found above the diorite outcrops and below the Swauk formation in the vicinity of the Forest Service shelter 1½ miles southwest of the summit of Coney Pass. In the cliffs at the shelter, serpentine is imbedded in the Swauk formation as lenticular masses several feet across. The Swauk formation at this locality is a medium grained feldspathic quartzose arenite which has undergone some baking and induration which is probably due to contact metamorphism. The serpentine could be boulders in the Swauk formation but since there is a lack of boulders of material other than serpentine, it more likely has been intruded into the Swauk formation as peridotite. South and east of the shelter, massive serpentine forms small cliffs and sheared serpentine forms irregularly shaped sloping outcrops (Fig. 36 and 37). North of the shelter sheared serpentine underlies the Swauk formation. About a thousand feet lower in elevation, south of the shelter, serpentine coats the joints of diorite. Because of the friable nature of the sheared serpentine, little soil can form on the steeper slopes of the outcrops. The sheared serpentine outcrops usually are barren of vegetation other than grasses and cause brownish to reddish blotches on the generally green landscape. Some of the serpentine appears to have been derived from a peridotite intrusion which is later than the diorite and the Swauk formation. It is uncertain as to whether the massive serpentine and the sheared serpentine are parts of the same body or different bodies which may be of different ages.

One thin section of serpentine collected from the small cliff just south of the shelter contains 85% antigorite, 10% carbonate, 5% magnetite, and 1 to 2% relict olivine. The carbonate does not react with dilute hydrochloric acid. It may be magnesite.

Dike Rocks

Andesite

Andesite occurs as: (1) altered andesite porphyries southwest of Coney Pass; (2) fine grained dikes cutting the Swauk formation on Round Mountain; and (3) a knob, now of spilitic composition, on the west side of South Fork Ridge.

The geological relationships of the andesite porphyry southwest of Coney Pass are not entirely clear as has been stated above when the associated diorite was discussed. The andesite porphyry ranges in color from light brown to light to moderately dark green. It is flecked with white plagioclase phenocrysts and brownish to greenish black hornblende phenocrysts. In some of the specimens, the phenocrysts approach 50% of the rock. These specimens are, according to customary classification, on the boundary between diorite porphyry and andesite porphyry. One such specimen, collected about ½ mile east of the Forest Service shelter on the Coney Pass trail, contains 2 to 3% quartz phenocrysts, 40% plagioclase phenocrysts, and 20% alteration products in pseudomorphs after amphibole (about equal amounts of carbonate and of chlorite plus a little stilpnomelane). The plagioclase is now albite. The phenocrysts are up to 2 mm. long. The groundmass is composed of grains 0.004 to 0.02 mm. in diameter. The composition of the groundmass is difficult to determine because of the small grain size. It includes quartz, plagioclase, and stilpnomelane. This specimen appears to be closely related to the diorite. About a mile north of the shelter and a few hundred yards west of the headwaters of Deer Creek, other specimens of porphyritic andesite were collected from what appears to be a dike. This andesite porphyry may be an offshoot of the body of diorite porphyry to the south or it may be an independent rock body. The andesite porphyry contains 20 to 30% plagioclase phenocrysts. Apparently it does not contain amphibole phenocrysts or alteration products of amphibole phenocryrsts. The plagioclase phenocrysts are from 0.5 to 1.5 mm. long. In one specimen, the phenocrysts are now albite, in the other, they are still andesine. The groundmass is exceedingly fine grained, the crystals averaging about 0.01 mm. maximum diameter. The groundmass contains a great deal of indeterminable material which appears to be altered glass plus some minerals identified as plagioclase, quartz, stilpnomelane, and chlorite. Vesicles are filled with quartz, stilpnomelane, and zeolites.

Dikes of fine grained andesite cut across the Swauk formation on the southeast face of Round Mountain and again on the northeast face, west of Upper Hawkins Lake. These andesites are dense rocks ranging in color from dark gray to dark greenish gray. Some are very similar in megascopic appearance to some of the siltstones and argillites of the

Swauk formation. Tiny phenocrysts and flow structures distinguish the andesites from the Swauk formation. Occassionally the fine grained andesites contain amgydules. In one outcrop the fine grained andesite is a breccia with fragments up to ½ inch across in a light gray matrix. In thin section, the fine grained andesite contains abundant lath-shaped plagioclase crystals ranging from a few thousandths to a few hundredths of a millimeter in length. Flow structures are sometimes shown by the alignment of the plagioclase laths. The plagioclase is andesine. The groundmass of the rock is exceedingly fine grained and contains altered glass, rod-shaped magnetite, and a little pyrite.

A knob of spilitic rock stands out on the southwest side of South Fork Ridge, about 0.5 mile east of Segelson Creek at a point 1 mile southeast of the summit of Coney Pass. The rock is a light green, rather featureless rock with megascopically visible calcite in veins and in the groundmass. In thin section it contains 70% plagioclase, small amounts of epidote, chlorite, sphene, leucoxene, and pumpellyite, and 10% late quartz and 15% secondary calcite. The plagioclase is now albite. It forms a felted groundmass of small laths. The epidote forms small veins. The chlorite occurs as scattered patches and the pumpellyite as small isolated crystals. The quartz grains are subrectangular with scalloped edges. They fill the spaces between the plagioclase grains. Some of the quartz has undulous extinction. The calcite forms relatively large masses and veins. This rock probably formed by alteration of an andesite.

Labradorite Porphyry

Labradorite porphyry apparently cuts the Swauk formation on top of the highest peak on Higgins Mountain at a point about 1500 feet north of the lookout, and again on the crest of the ridge, about 3000 feet west of the lookout. These outcrops are little more than broken masses of rocks and no relations with the Swauk formation could be seen. On the northeast face of Round Mountain, a labradorite porphyry dike cuts the Swauk formation (Fig. 38). Other dikes, apparently of labradorite porphyry, cut the Swauk formation along Round Mountain Ridge to the north (Fig. 39). The relations, if any, of the labradorite porphyry dikes to the Granite Lake labradorite porphyry are not known.

The labradorite porphyries are light gray to light brownish gray and are flecked with abundant white to buff phenocrysts of plagioclase and with black to greenish black phenocrysts of amphibole. The plagioclase phenocrysts may be as much as 4 mm. long, the amphibole, 2 mm.

The labradorite porphyry from north of the Higgins Lookout contains 30% plagioclase phenocrysts and 20% amphibole phenocrysts. The plagioclase crystals usually are zoned. Normal zoning is most common but some phenocrysts exhibit reverse or oscillatory zoning. The average composition is labradorite. The amphibole is weakly pleochroic with: X = colorless to light yellow; Y = pale yellowish green; and Z = pale bluish green. Marginal alteration to biotite is common and many grains are fully altered to biotite or chlorite. The amphibole may be a bleached green hornblende which now is more or less of actinolitic composition. The groundmass is composed of grains 0.02 to 0.06 mm. in maximum diameter. The minerals are mostly plagioclase and quartz plus a little biotite. The relative proportions are difficult to determine because the crystals are small and are intergrown in a mosaic. However, there seems to be considerable quartz in the groundmass, perhaps as much as 10% or more.

The labradorite porphyry from west of the Higgins Lookout contains about 60% plagioclase phenocrysts and 15% pseudomorphs after amphibole phenocrysts which are composed of pennine, carbonate, and minor quartz. The plagioclase phenocrysts are zoned, and some exhibit oscillatory zoning. The average composition is labradorite. The plagioclase is partly altered to sericite along cracks and cleavages. The goundmass consists of laths of plagioclase up to about 0.02 mm. long. These laths generally form a felted mass between the phenocrysts but there is some parallelism suggestive of flow structure. It is not certain whether there is any quartz in the groundmass. If there is, it is very minor. The quartz associated with the amphibole pseudomorphs represents silica released during alteration and is not part of the main assemblage of the rock.

On Round Mountain, an irregular dike of labradorite porphyry 1 to 2 feet thick cuts the Swauk formation (Fig. 38). There is anaureole of leaching, baking, and iron staining up to 10 feet wide on each side of the dike. The labradorite porphyry contains 20% plagioclase phenocrysts and 5% pseudomorphs after amphibole phenocrysts which are composed of carbonate, pennine, quartz, and stilpnomelane. The plagioclase is zoned with andesine rims and labradorite cores. The average composition is labradorite. Many of the plagioclase phenocrysts contain abundant tiny grains of sericite and carbonate. The groundmass consists mostly of anhedral plagioclase a few hundredths of a millimeter in size and of tiny shreds and clumps of chlorite and stilpnomelane. Quartz is absent except as the result of the release of silica by the alteration of amphibole.

The rocks of the labradorite porphyry dikes differ from those of the Granite Lake labradorite porphyry in that quartz phenocrysts are lacking and in that such amphibole as has escaped alteration is green hornblende rather than brown. The contents of plagioclase and mafics are about the same for the two rock types. The dikes are from 3 to 4 miles distant from the outcrop area of the Granite Lake body. They may not be part of the same intrusion, but they may be derived from the same source.

Basalt and Diabase

Diabase cuts the Swauk formation on the southern slopes of the east end of Round Mountain. Basalt and diabase are found on South Fork Ridge, but the relations to the other rocks are uncertain there.

The diabase on the eastern end of Round Mountain is dark gray-green and is flecked with abundant white to buff plagioclase grains and lesser quantities of greenish black mafics. Diabasic texture is conspicuous in hand specimen. In thin section, the rock contains 50% labradorite in laths up to 2 mm. long, 45% augite, and 2 to 3% magnetite.

On the southern end of South Fork Ridge, diabase and basalt form scattered outcrops in the woods. No contacts with other rocks were seen. The basalts are dark greenish gray and the diabases are lighter greenish gray, are flecked with white to buff plagioclase laths, and are stained with iron oxides. One coarse grained diabase has plagioclase laths up to 2 mm. long. In thin section, this specimen contains 40% plagioclase and 60% pyroxene. The plagioclase is zoned with an average composition of labradorite. The rims are andesine, and some of the cores are as calcic as bytownite. Some of the pyroxene is diopsidic augite and some, with small 2V's, is pigeonite.

Extrusive Rocks

Dacite

Dacite occurs north of the Hawkins Lakes on Round Mountain Ridge and on the next ridge to the east. Outcrops are found in the woods, in several large exposures on Round Mountain Ridge and in the stream bed between the ridges, just south of Deer Creek. The dacite appears to be separated from the Swauk formation by a high angle fault (Fig. 40), but its relations are not known elsewhere. There is no evidence as to the relative ages of the dacite and the Swauk formation. The thickness of the dacite is in excess of 1000 feet. The very small grain size and the presence of glass suggest that the dacites are flows.

The dacite is aphanitic and is usually buff with reddish brown iron oxide stains which follow fractures and also are irregularly distributed through the rock. Color variations are dull greenish to yellowish brown, light green, and black. Flow structures are sometimes visible in hand specimen as alignments of phenocrysts and streaks of dark colored inclusions. The phenocrysts of quartz and plagioclase are up to 1 mm. in diameter. The phenocrysts are few and are scattered in the dense groundmass (Fig. 41 and 42).

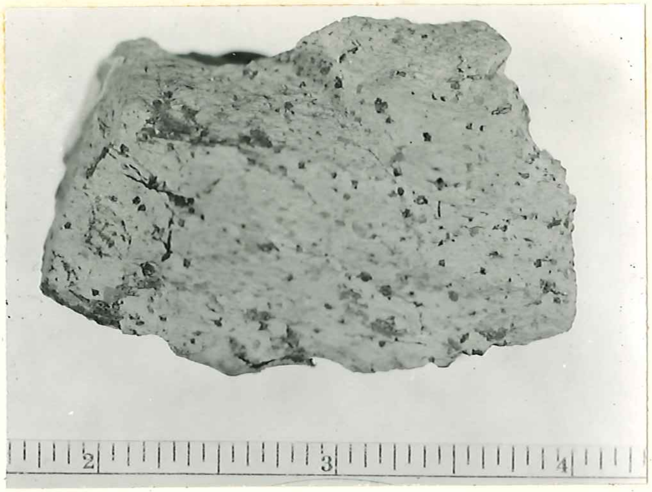
A specimen of light green dacite studied in thin section contains 5 to 6% quartz phenocrysts and 4 to 5% plagioclase phenocrysts. The plagioclase is andesine. The

The groundmass comprises 90% of the rock and consists mainly (80%) of an interlocking mosaic of grains ranging in size from barely visible to no more than about 0.01 mm. The groundmass grains are too small to be optically determined. They are presumed to be plagioclase and/or quartz. About 10% of the groundmass is tiny shreds and wisps of sericite which are roughly aligned, probably by flow structure. This sericite may have formed by devitrification of glass.

A thin section of a specimen of buff dacite is similar except that the plagioclase has been altered to a felted mass of sericite. Thin sections of specimens of black and yellowish brown dacite are mostly devitrified glass with alighed microlites of andesine.

East of Lower Hawkins Lake a sheared dacite with a groundmass largely recrystallized into sericite was found near low grade schistose rocks which are believed to be derived from hornblende-plagioclase schist. The relations of this outcrop to the main body of dacite are unknown.

Fig. 40 Dacite outcrop on the east side of Round Mountain Ridge, north of the Hawkins Lakes. The high angle fault contact between the Swauk (left) and dacite (right) runs from the top of the ridge at the upper left down to the valley out of the picture at the lower right.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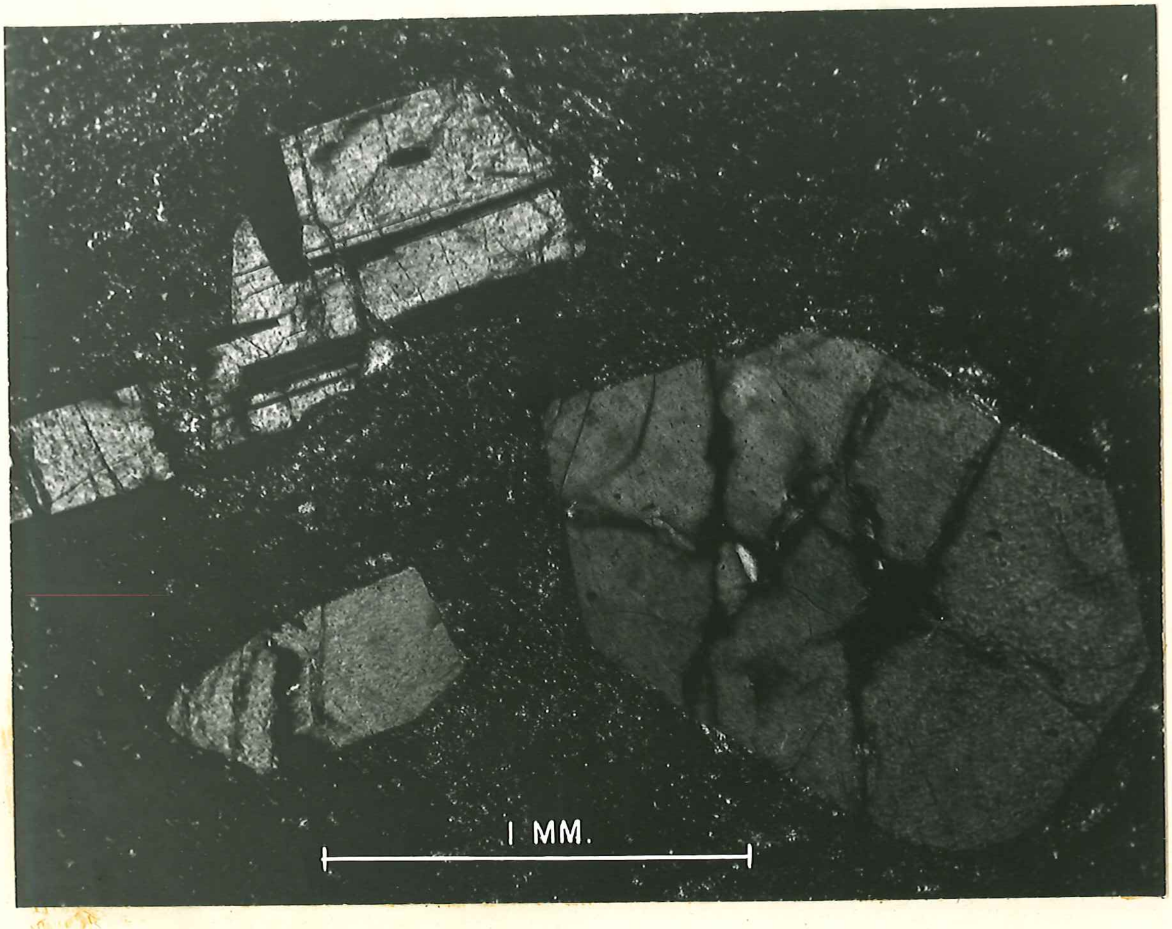
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C. SEDIMENTARY ROCKS

Swauk-Chuckanut formation

Most of the western half of the present area is underlain by a maximum of 8000 feet of arkoses, siltstones, and conglomerates. These rocks are part of the continental arkoses of latest Cretaceous to Eocene age which are common in the Cascade Mountains of Washington. In eastern Washington, these arkoses are called the Swauk formation (Russell, 1900, p. 100); in western Washington, the Chuckanut formation (McClellan, 1927, p. 136). These two formations represent the same unit and in the present area, the arkoses are called "Swauk-Chuckanut", and are abbreviated as "Swauk".

The Swauk formation of the present area forms a large, assymetrical, faulted syncline. On the northwest, the Swauk formation unconformably overlies altered igneous rocks. North of Hawkins Lake, dacites are in fault contact with the Swauk formation. On Round Mountain, the Swauk formation unconformably overlies medium grade metamorphic rocks. At the headwaters of Deer Creek, at Coney Pass, the Swauk formation unconformably overlies the low grade metamorphic rocks. The Swauk formation is covered on part of the south end of South Fork Ridge and is here exposed only in the bed of Cascade Creek (Fig. 45). On the south face of Higgins Mountain, the Swauk formation on the west limb of the syncline disappears under a cover of talus and glacial till. If the thickness of 8000 feet is correct, the base of the Swauk formation should not be exposed here. A few miles to the west of the present area, the base of the Swauk formation comes to the surface again, but the relations to the underlying altered igneous rocks and low grade metamorphic rocks are not known.

The typical rock of the Swauk formation is a fine to medium grained arenite. Crossbedding is lacking in most of the arenites. Quartz is the dominant mineral but feldspar is almost always present in substantial quantities. In many of the arenites, quartz and feldspar are present in subequal quantities; in a few, the feldspar exceeds the quartz. The bulk of the arenites of the Swauk formation are arkoses. Dominantly quartzose arenites are less common. Minor thicknesses of pebble conglomerates composed dominantly of quartz and chert are intercalated in the arenites, and are more common in the lower portion of the formation. A basal conglomerate containing locally derived material was found east of Ricks Creek. Fine-grained clastic materials appear to be subordinate to the medium grained materials. The fine-grained clastic rocks are dominantly siltstones; shales appear to be much rarer. Some of the fine grained clastic rocks have become argillites, at least partly by contact metamorphism.

The Swauk formation is fairly thickbedded; massive arkose beds 8 to 10 feet thick are common. Large outcrops clearly show bedding and jointing (Figs. 43 and 51). Dip slopes are common (Fig. 52). Small outcrops tend to be featureless except for faint bedding, because of the massiveness and thickness of the arkoses (Fig. 44 and 45).

Petrography of the Swauk formation

Arenites

The typical arenite of the Swauk formation is light gray to light brownish gray or brown and is speckled with grains of mafic minerals (Figs. 46 and 47). The arenites are composed of subangular to subrounded detrital particles principally of the fine sand size (Wentworth, 1922, p. 377). Three rather crude mechanical analyses of typical Swauk arenite average about 15% medium sand, 60% fine sand, and 20% very fine sand.

Thin sections of 9 typical arenites from the Swauk formation contain 20 to 70% quartzose material (quartz, chert, quartzites, etc.), biotite, and other dark minerals. Orthoclase is abundant in 2 specimens from the stratigraphically lower portion of the Swauk formation and is questionably present in amounts no greater than a trace in 3 specimens from the stratigraphically higher Swauk formation, In a cursory examination of the heavy minerals from several disaggregated specimens, magnetite, epidote, spinel, garnet, rutile, leucoxene, sphene, and apatite were identified.

In thin section, the detrital grains are subangular to subrounded (Fig. 48). The quartzose component includes grains of quartz and particles of chert and other quartzose rocks such as fine grained quartzites and quartzose phyllites. Up to half of the quartzose component may be such rock particles. The plagioclase usually is partly to fully altered to sericite. No plagioclase with a composition more clacic than sodic oligoclase (An 20) was found in any of the specimens studied. Albite is more abundant than oligoclase and Ab 100 is common. It is probable that the plagioclase originally was more clacic and has been decalcified under authegenic conditions after deposition. The micas often have been bent around grains of quartz or feldspar. Biotite is far more common than muscovite. The biotite is commonly bleached and is often partially altered to chlorite. Most of the chlorite in the rock probably was derived from biotite. The cement usually is argillaceous material which has, in part, become sericite. There is a small amount of quartzose matrix in some specimens and perhaps some siliceous cement. Calcareous material is rare.

Chips of 25 additional specimens of Swauk arenites were etched by hydorfluoric acid and stained with sodium cobaltinitrite (Fig. 47). The HF did not affect the quartz but frosted the feldspars. The sodium cobaltinitrite caused a yellow stain on the potassium feldspar and did not affect the plagioclase. The chips were examined under the binocular microscope and the amounts of the minerals were estimated with the aid of a grid. The specimens examined contain 20 to 95% quartzose material (quartz, chert, quartzite, etc.), 2 to 60% plagioclase, 0 to 10% potassium feldspar and up to 15% muscovite, biotite, and other dark minerals. Potassium feldspar is present in 11 specimens, all of which are from the stratigraphically lower part of the Swauk formation.

The thin section and chip studies show that most of the Swauk arenites are fine grained arkoses containing 40 to 60% quartzose material (quartz, chert, quartzite) and 40 to 50% feldspar. Plagioclase is the dominant feldspar. Orthoclase is never present in amounts greater than 10% and is more common in the stratigraphically lower portions of the formation. Nearly pure quartz arenites are subordinate and all gradations exist between the arkoses and the quartz arenites.

conglomerates

The typical conglomerate of the Swauk formation occurs in beds seldom more than a foot thick. It is intercalated in the arenites as lenses and thin stringers which are sometimes no more than one pebble in thickness. Nearly all of the granules and pebbles are grayish quartzose material (quartz, chert, and quartz rich schists and phyllites). Pebbles of volcanic or plutonic rocks are rare. The pebbles usually are subrounded to rounded. The largest pebbles seen in the quartzose conglomerates are about 1½ to 2 inches in maximum diameter.

East of Ricks Creek, a conglomerate at the base of the Swauk formation overlies altered volcanic rocks. The actual contact was not seen. The dominant rock types in the pebbles and cobbles are arkoses, indurated siltstones, and greenstones. Other rock types present are mica schist, phyllite, greenschist, shale, light colored volcanic rocks, and granitic rocks. The maximum size of the cobbles is about 6 inches. The arkose pebbles are foliated and resemble schistose arkoses which are interbedded in the phyllites to the east of the Stillaguamish River. The greenstones resemble the underlying altered volcanic rocks. This is believed to be a basal conglomerate.

siltstones and shales

The fine-grained clastic rocks of the Swauk formation usually are somewhat darker than the arenites. Black, dark gray, and medium to dark browns are common colors. The fine-grained clastic rocks usually are quite featureless, even the bedding often being obscure. Most of these rocks contain abundant silt sized particles and are classed as siltstones. A few are almost lacking in silt and are classed as shales. Some of the siltstones are quite hard and show abundant recrystallization of mica in the thin section. These rocks are classed as argillites.

Because of the small grain size, compositions are difficult to determine in thin sections. Generally, the specimens studied contain 50 to 80% quartz and feldspar, 20 to 40% micas, and up to 10% mafics and opaques. The quartz is usually in distinct particles. Fragments of quartzose rocks are lacking. The feldspars are sometimes twinned plagioclase.

Untwinned plagioclase or potassium feldspar is very difficult to detect. It is often impossible to tell quartz from feldspar because the grains are too small to give an interference figure. The mica is all sericite, all sericitiform biotite, or both. The micas often appear to have recrystallized after deposition of the rock. The recrystallization of sericite can occur by authigenesis but biotite usually requires an outside source of heat. Some of the fine grained clastics with abundant recrystallized mica are close to bodies of igneous rocks and may have undergone contact metamorphism. Igneous rocks were not found near all of the argillites and the reasons for the recrystallization of the micas in some of the rocks are not clear.

Correlation of the Swauk-Chuckanut formation

North and west of the present area, Jenkins mapped the "Coal Measures" of Whatcom (1923) and Skagit (1924) counties. In the Skagit county report, he shows a few square miles of the "Coal Measures" near Rick's Creek in the present area and mentions a few thin seams of coal there (p. 54). According to his map, a "narrow synclinal trough" of the "Coal Measures" extends southeasterly from the Skagit River between Cumberland and Loretta Creeks and strikes towards the Ricks Creek area. McClellan (1927, p. 136) gave the name "Chuckanut formation" to the arkoses and conglomerates on the northern half of Lummi Island in the San Juan group. These rocks were regarded as equivalent to the strata along Bellingham Bay to the southeast. Glover re-investigated the coal-bearing formation of Whatcom county and called it the "Chuckanut formation" (1935, p. 69). Weaver (1937, pp. 75-90) designated two standard sections and noted that the time interval represented by the deposition of the Chuckanut formation probably began in latest Cretaceous time and extended through Paleocene and Eocene time. He regards this time interval as the same as that represented by the deposition of the Swauk and Roslyn formations and notes that the conditions of deposition could not have been very different. Near Glacier, Misch found fossil plants, some of definite Paleocene and others of probable latest Cretaceous age (1952, p. 10 and oral communication).

North of the present area and south of Hamilton, Landes (1901, p. 32) collected fossil plants from near Day Creek and Coal Creek, apparently from the "narrow synclinal trough" (Jenkins, op. cit.). These plants were identified by Knowlton (in Landes, op. cit.):

<u>Thuja interrupta</u> Newberry
<u>Glyptostrobus europaeus</u> (Brongnart) Heer
<u>Quercus banksiaefolia</u> Newberry
<u>Quercus coriacea</u> Newberry

According to LaMotte (1952): <u>Thuja interrupta</u> has been reported from the Paleocene Ft. Union formation of North Dakota and also from the Paleocene in Montana, Alberta, and Saskatchewan as well as from the Eocene or Oligocene of British Columbia;

Glyptostrobus europaeus is a wide spread and wide ranging form which has been reported from the Paleocene to the Pliocene in localities as widely separated as British Columbia, Texas, Tennessee, Greenland, and Switzerland; and the two species of Quercus have been reported only from Washington and British Columbia. It is apparent that these plants either have too great a time range or too limited geographic distribution to furnish critical age dating. About all that can be concluded is that the assemblage is probably early Tertiary.

In the present area, occasional leaves were found throughout the section of the Swauk formation but none of the specimens collected could be identified (Chaney, personal communication).

In eastern Washington, the Swauk formation was named by Russell (1900, p. 100). The type area at Swauk Creek was designated by G. O. Smith (1904). Since then, there have been many investigations of this formation. The latest and most comprehensive papers are by Willis (1950) and Alexander (1956). The reader is referred to these papers for a discussion of the Swauk formation.

South of the present area, W. S. Smith mapped the Swauk formation in the Skykomish Basin (1916). More recently, several graduate students at the University of Washington have been mapping the western Cascades south of the present area. Immediately to the south, Vance (1957) mapped continental arkoses which he correlated with the Swauk formation. Further south, arkoses which may be part of the Swauk-Chuckanut unit are being mapped by Yeats and Sauers (oral communications).

Plant fossils have been found throughout the Swauk formation. Most of the collections in the literature are evaluated in Willis (1950, pp. 87-94) and need not be discussed here. The results of these paleo-botanical investigations may be summarized as follows: The early workers assigned an Eocene age to the flora on the basis of forms also found in the Ft. Union formation of the northern Great Plains. The Ft. Union formation is now considered to be Paleocene in age. Willis concluded that the Swauk formation is for the most part Paleocene in age but parts of it may be latest Cretaceous or early Eocene (1950, pp. 93-94).

In view of the above mentioned studies of the Swauk and Chuckanut formations, it appears that Weaver was correct in suggesting (1937, p. 90) that the Chuckanut and Swauk formations are in part contemporaneous and accumulated under similar physical conditions. The work since Weaver's paper suggests that the Swauk and Chuckanut formations once may have been a more or less continuous unit extending across the present area of the Cascade Mountains. It is therefore proposed that the two units tentatively be considered one formation. For the present, the unit should be regarded as the "Swauk-Chuckanut" formation. If the investigations to the south of the present area should demonstrate that they are indeed the same formation, the name "Swauk" should be used since it has precedence. In the present report, the name is abbreviated by using "Swauk" alone, but it is used in the sense "Swauk-Chuckanut".

Fig. 43 South face of Higgins Mountain showing the thick beds and the jointing in the Swauk formation. Looking east from a point below the lookout which is on the skyline in the background.

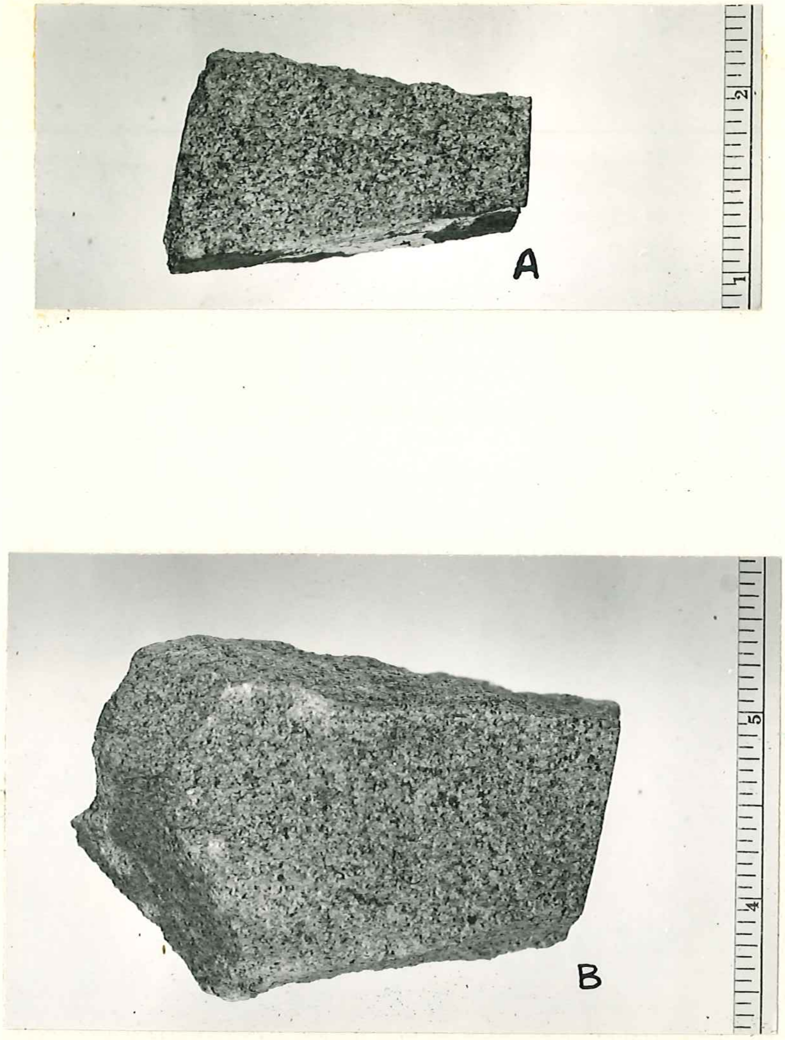


Fig. 46 Handspecimens of typical fine grained arkoses from the Swauk formation. A is from the upper portion of the formation, near the lookout on Higgins Mountain. B is from the lower part of the formation, near Ricks Creek. The faint bedding is from left to right.

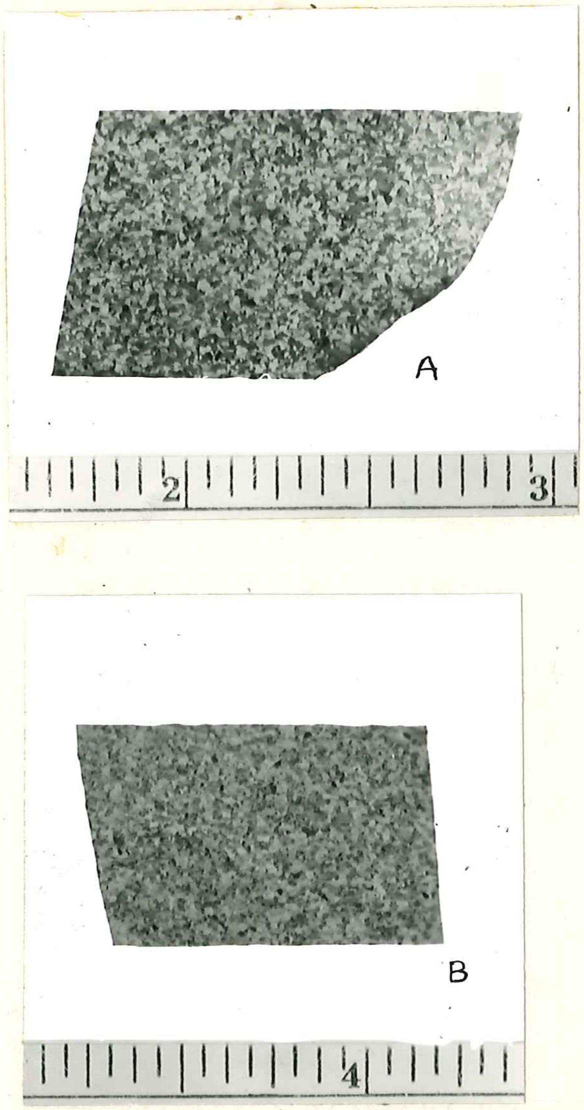
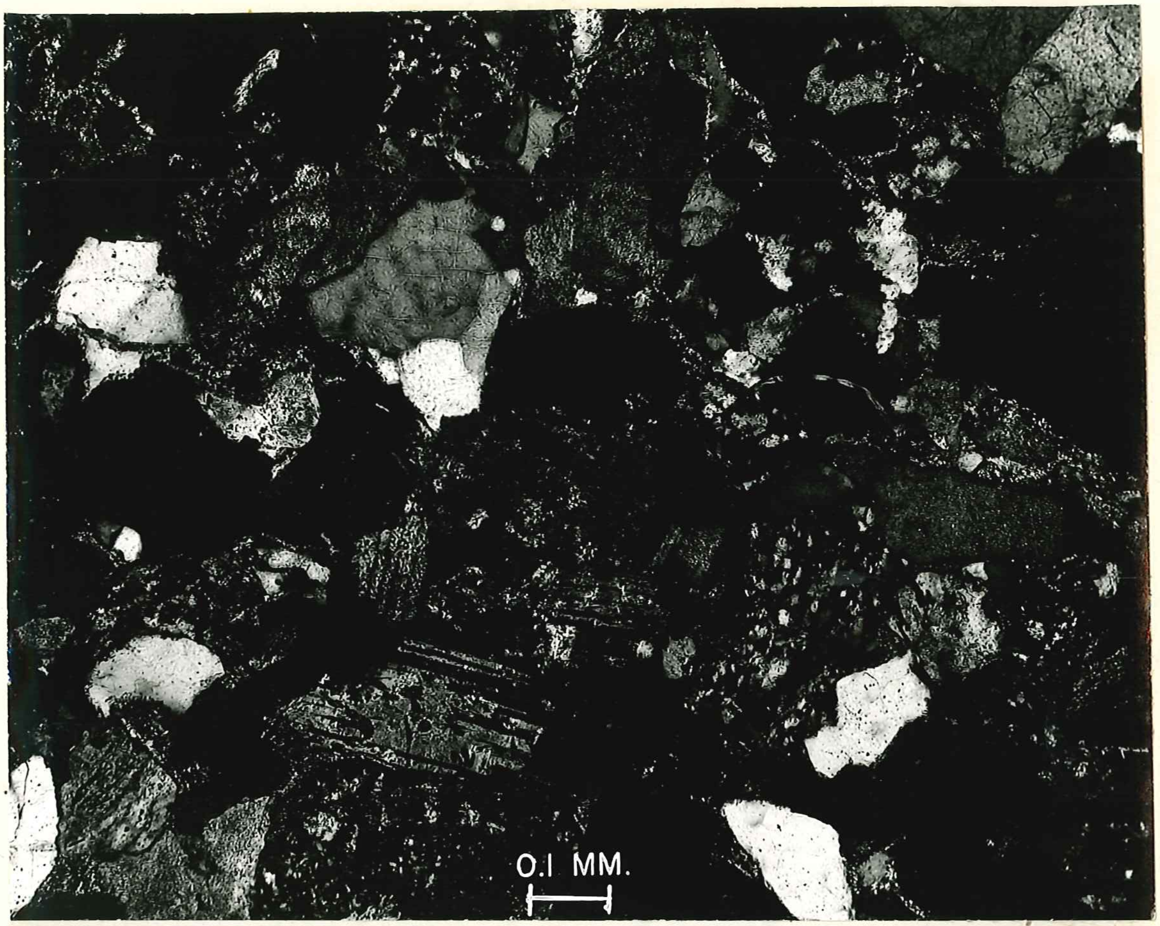


Fig. 47 Etched and stained chips from the fine grained arkoses shown in Fig. 46. Frosting of plagioclase shown on the chip from A. The chip from B contains both plagioclase and orthoclase but the yellow stain is not apparent in the photograph.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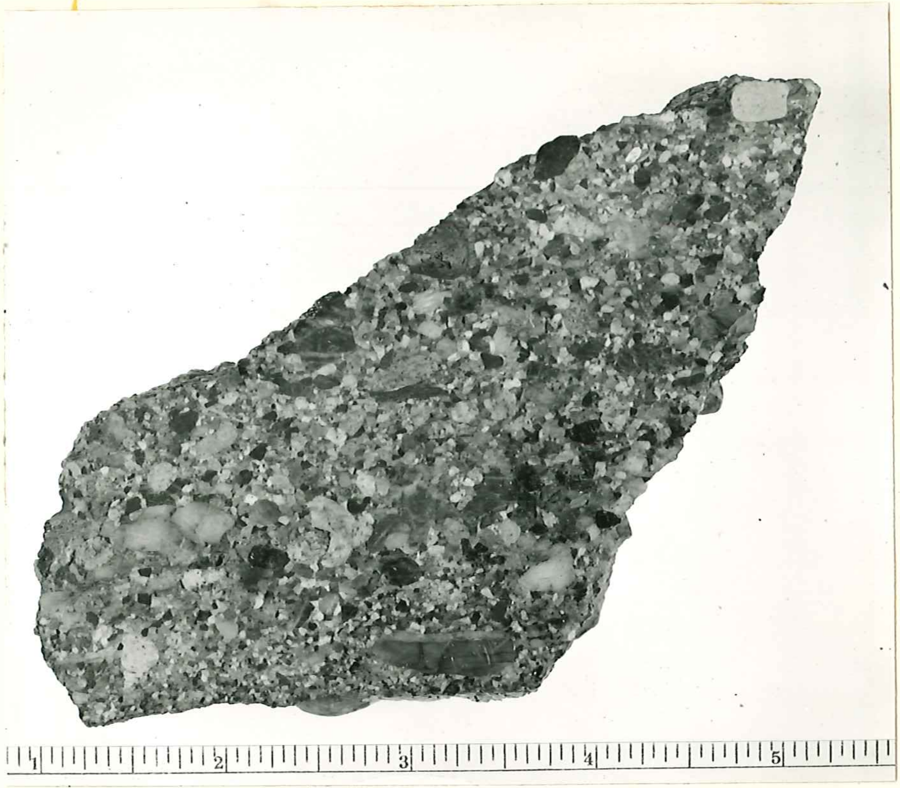
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III. STRUCTURE

The structures of the Higgins Mountain area fall into two groups: (1) those which do not involve the Swauk formation and therefore are pre-Tertiary in age, and (2) those which involve the Swauk formation and are therefore Tertiary in age. In most of the areas where the former structures are displayed, the Swauk formation is absent. Unless the Swauk formation can be shown to truncate structures in the pre-Tertiary rocks, it might be objected that the age of such structures cannot definitely be stated to be pre-Tertiary. However, the association of these structures with the definite pre-Swauk synkinematic regional metamorphism and the known structural history of the Northern Cascades leave no doubt that these structures are pre-Tertiary.

PRE-TERTIARY STRUCTURES

The structures of the pre-Tertiary rocks may be subdivided into (1) those involving only the low grade metamorphic rocks, and (2) those involving the medium grade metamorphic rocks.

Internal Structures of the Low Grade Metamorphic Rocks

The internal structures of the low grade rocks are not exposed except for the details of schistosity, lineation, compositional banding, etc. discussed in the chapter on petrology. Sub-isoclinal folding is common in the low grade rocks of nearby areas (Vance, 1957; Misch, oral communication), and probably exists in the Higgins Mountain area also.

The attitudes of the schistosity planes of the greenschists are fairly constant. The strikes are almost always west of north and usually fall between N30W and N60W. The dips usually are steep, generally between 70° and 90°. Southwesterly dips are much more common than northeasterly dips. If the folding is isoclinal, the predominantly southwesterly dips indicate that the folds are overturned to the northeast. Lineations shown by the alignment of elongated minerals, probably b lineations, lie within the plane of schistosity and plunge either to the northwest or southeast at angles of usually less than 45°. These attitudes were caused by the forces acting during the period of constructive metamorphism and the greenschists were competent during the later periods of penetrative mechanical deformation.

The attitudes of the schistosity planes of the phyllites are not uniform. Two planes of schistosity are often present in the phyllites and a third s plane sometimes has developed. In the field, it is often impossible to determine the age relations of the various s planes. Random dips and strikes cannot be used to unravel the structural complexities of the phyllites. On the geologic map, the plotted dips and strikes of the s of the phyllites are evaluated as follows: attitudes known to be on s_1 are plotted with a large solid dip and strike symbol, attitudes known to be on s_2 are plotted with a small solid symbol, and a large skeleton symbol is used for measurements on s planes for which the time relations are not known. Most of the measured dips and strikes belong to the last group. Too few data are available to permit any generalizations on differences, if any, between the attitudes of s_1 and s_2. The predominant strike of all the measurements on s planes in the phyllite is northwesterly but the range is from N-S to E-W. The dips of the s planes of the phyllites also vary. The measured dips range from 18° to 90° and are fairly evenly distributed throughout this range. There are many lineations in the phyllites. Most of them are caused by the intersections of s planes and some probably are minute drag folds, thus definitely representing b lineation. However, the causes of the lineations usually are not apparent without more detailed study than was done in this investigation. Many lineations were measured in the field but the relations of most of them to the tectonic framework are not known. Rather than clutter up the map with unevaluated data, the only lineations plotted for the phyllites are the axes of the minor folds of s. These are b lineation. The axes of the minor folds generally have a northwesterly strike and plunge either to the northwest or southeast. The angle of plunge is usually fairly gentle--less than 30°--but it may be as steep as 85°. These trends of b lineation imply that the axes of the larger scale folds of the phyllites have a northwesterly trend and fairly gentle plunge. These attitudes are comparable to those of the folding of the greenschists. Therefore the generally northwesterly trends of the fold axes of the phyllites are the result of the forces acting during the episode of constructive metamorphism. The later episodes of penetrative deformation have distorted the attitudes of the phyllites and created new s planes. The patterns of s_2 and s_3 are not apparent, and the nature of the forces responsible for them is unknown.

The greenschists are topographically, and apparently structurally, higher than the phyllites. The map pattern along South Fork Ridge suggests that the greenschists form the core of a synclinorium of greenschists and phyllites. The evidence would be more convincing if the phyllites were known to outcrop in Segelson and Deer Creeks on the west side of the main body of greenschists. This part of the area is largely unmapped. In the vicinity of Coney Pass, the Swauk formation apparently overlies the greenschist. The southeastern slopes of South Fork Ridge are wooded and no outcrops were found except for several knobs of igneous rocks and greenstones. The structure of this part of the area is further complicated by the presence, largely under cover, of the Swauk formation. At the present, it cannot definitely be stated that the synclinorium of greenschists and phyllites does exist.

The greenschists and phyllites together form a tightly probably sub-isoclinally, folded sequence with a northwesterly trend formed during the constructive metamorphism. The predominantly southwesterly dips in the greenschist indicate that the sub-isoclinal folds are overturned to the east. In the phyllites, later penetrative deformation has obscured the earlier structures. There is no evidence in the Higgins Mountain area which allows absolute dating of these older structures. To the north, Misch (1952 and oral communication) has found evidence of two pre-Tertiary orogenies. Misch dates the earlier as probable pre-Middle Jurassic and the later as post-Early Cretaceous. It is almost certain that the constructive metamorphism of the Higgins Mountain area occurred during the older orogeny. The penetrative deformation of the phyllites could date from the younger orogeny but it also might have occurred during the later phases of the older orogeny.

Structures of the Medium Grade Metamorphic Rocks

The few attitudes taken on the s of the hornblende-plagioclase schist found on the northeast face of Round Mountain have northwesterly strikes and moderate northeasterly or southwesterly dips. It is not known whether these rocks are part of the same tectonic unit as the gneiss found in the Stillaguamish Valley or whether they were formed in place by a westerly increase in regional metamorphic grade during the episode of constructive metamorphism.

The foliation of the hornblende-quartz-diorite gneiss strikes northeasterly, more or less at right angles to the general strike of the other metamorphic rocks. Most of the measured strikes fall between N45E and N65E. The dips are between 45° and 50° to the northwest.

The gneiss cannot be in place, and must have been moved into its present location by tectonic means, either by (1) faulting up from depth, or (2) thrusting in from the areas of medium grade metamorphic rocks which compose the Cascades to the east and northeast. No evidence has been found in the present area which proves which of these mechanisms has operated. The gneiss disappears under a cover of glacial till and dense vegetation and its base has not been found. The gneiss is situated in a topographically low position and, if in place, is stratigraphically at or near the base of the Swauk formation at the southeast flank of a synclinal downfold of Swauk rocks. Due to Quarternary cover, the Swauk formation has not been observed actually to overlie the gneiss. Only a hundred yards north of the gneiss, arkoses of the Swauk formation outcrop in the floor of a small valley at an elevation perhaps 100 feet lower than the top of the hill formed by the gneiss. The attitude of the bedding on this outcrop is not apparent. This arkose would be in place if the present hill of gneiss was an irregularity on the erosion surface which existed prior to the deposition of the Swauk formation and the arkoses filled in around it. Either the gneiss or the arkose could be out of place if some minor faulting had slightly uplifted the gneiss with respect to the arkose or if the arkose were a large landslide block. Although the position of the gneiss at or near the base of the Swauk formation suggests that the gneiss unconformably underlies the Swauk formation in the Higgins Mountain area, the data available is inconclusive.

There is no evidence in adjacent areas of gneiss having been faulted up from depth. Nor is there any reason to believe that the basement beneath the low grade metamorphic rocks in necessarily gneissose in the Higgins Mountain area.

There is abundant evidence of overthrusting of rocks very similar to the gneiss under discussion north and south of the present area; these rocks include dioritic gneisses, dioritized amphibolites, and amphibolites. Immediately to the south, Vance (1957) has mapped a klippe of amphibolite and hornblende gneiss on Helena Ridge, about 7 miles southeast of Darrington. Hand specimens and thin sections of these rocks are similar to the gneisses of the Higgins Mountain area. Further to the south, Yeats (1956, p. 8) has mapped a klippe of amphibolites and partially granitized amphibolites on Mt. Baring. Hand specimens and thin sections of these rocks are different from those of the Higgins Mountain area but they do represent the type of parent rocks from which the gneisses are derived. North of the Higgins Mountain area, Misch (oral communication) has found 2 klippen of dioritic gneiss and dioritized amphibolites overlying unmetamophosed upper Paleozoic volcanic rocks 1 mile south of the Canadian border north of the North Fork of the Nooksack River. Misch has found the apparent root zone of the thrust on the west side of Mount Eldorado northwest of Cascade Pass. The rocks of the thrust mass in this area are the quartz-dioritic and amphibolite-derived Eldorado gneiss, a subdivision of the elsewhere hetrogeneous Skagit gneisses which is distinguished by its homogeneity in composition and texture. Hand specimens and thin sections of Eldorado gneisses are strikingly similar to the gneisses of the Higgins Mountain area. In summary, klippen and probable klippen of Eldorado type gneisses and related amphibolitic rock types occur north and south of the present area along a northwesterly trending zone about 60 miles long. The minimum displacement of this thrust is about 30 miles. The scattered klippen of gneissose rocks are the straggling remnants of an overthrust of large dimensions which once covered much of this part of the Northern Cascades.

TERTIARY STRUCTURES

The most impressive topographic feature of the area is the south face of Higgins Mountain - a steep cliff nearly 6 miles long and up to a mile in height with thousands of feet of the Swauk formation exposed in the upper portions (Fig. 51). Viewed from the Stillaquamish Valley, the Swauk formation on the western part of the mountain appears to be nearly flatlying. Near the middle of the mountain, the dip abruptly becomes about 30° westerly. In the past, this change of dip on Higgins Mountain has been regarded as simply a fault. Actually, the south face of the mountain cuts diagonally across the northwest plunging nose of a northwest trending syncline in the Swauk formation. The beds on the western side of the Higgins Mountain actually dip to the north and northeast at moderate angles (Fig. 52). Viewed from Round Mountain or the eastern part of Higgins Mountain, the axis of the syncline and the reversals of dips can be seen in the ridge extending northwesterly in the direction of Granite Lake (Fig. 53). About 2000 feet north of the Higgins Lookout, the axis is exposed on the northeast side of the ridge (Fig. 54). However, a fault does appear to coincide with the position of the axial plane through Higgins Mountain. This fault either dies out to the north in a short distance or else swings away from the axial plane in a northerly direction and goes along Higgins Creek valley. The displacement of this fault is uncertain, but it is not likely that the displacement is very large since there seems to be about the same thickness of Swauk rocks on both limbs of the syncline. The effect of this faulting on the attitudes of the beds of the eastern limb of the syncline is unknown.

The slopes of Higgins Mountain are controlled by a combination of bedding and jointing. Stripped bedding surfaces are common (Fig. 52). The triangular shapes of the peaks on the east limb of the syncline follow prominent, steeply dipping, northeast and northwest striking joints. The western part of the south face, which is eroded in the west limb of the syncline, appears to be quite straight, but in detail it is composed of a series of more less triangular reentrants with sides paralleling the steep dipping, northeast and northwest striking joints.

There is some reason to postulate an east-west trending fault along the Stillaguamish valley more or less parallel to the south face of Higgins Mountain. The overall straightness of the south face, and the fact that this face cuts across the internal structure of the Swauk formation, suggest faulting. The Swauk formation is absent on the peaks south of the Stillaguamish, but the dips of the west limb of the syncline are sufficient to carry the projected base of the Swauk formation many thousands of feet above the tops of these mountains. The present face of the mountain is formed by scarp retreat under the control of bedding and jointing. It is not known if this alone is sufficient to cause such a long, straight, cross-cutting scarp. No fault is shown on the geologic map.

Faulting of the Swauk formation is more definite to the north and east. In the vicinity of Granite Lake and Rick Creek, the maximum thickness of the Swauk formation cannot be more than 3000 feet. The basement of altered volcanic rocks is exposed at an elevation of about 2500 feet. The Higgins Mountain syncline trends towards the Granite Lake area. Except for its north-plunging nose, the syncline has a nearly horizontal axis. At Higgins Mountain, the Swauk formation is between 6000 and 8000 feet thick and the base should be at elevations well below sea level. The great difference in basement elevations is most likely due to relative upfaulting of the basement and Swauk formation in the Rick Creek area.

On Round Mountain Ridge, the contact between the dacite and the Swauk formation is a high angle fault (Fig. 40). The age relations of the dacite and the Swauk formation are uncertain. If the dacite is younger, it would have been down-dropped relative to the Swauk formation. If the dacite is older, it would have been brought up. The southwesterly projection of this fault would coincide with the probable fault between the Rick Creek area and Higgins Mountain. However, it is not definitely known if these two faults are identical. Upfaulting probably occurred in the Rick Creek area, and this could mean that the dacites also were upfaulted.

On the northeast face of Round Mountain, faulting has exposed a basement of hornblende-plagioclase schist underlying the Swauk formation. Across the valley to the northeast, the Swauk formation outcrops at elevations about 500 to 1000 feet lower than the hornblende-plagioclase schist-Swauk formation contact on Round Mountain. The minimum displacement of this fault cannot be much less than 500 feet, the maximum displacement is unknown. The relations of this fault to the fault on Round Mountain Ridge are unknown.

The occurrence of the Swauk formation on the south end of South Fork Ridge probably is the result of faulting.

Fig. 51 The south face of Higgins Mountain viewed from the Stillaguamish Valley near Fortson. Nearly the entire length of the face is shown. The view is northwesterly, approximately along the strike of the axis of the syncline. The beds of the west limb are apparently horizontal, but close examination of the west limb near the axis will show the northerly true dip. A number of prominent joint surfaces and bedding planes are exposed on the higher part of the eastern limb.

Fig. 52 Dip slopes of the Swauk formation on Higgins Mountain. The view is southeasterly and very nearly along the strike of the axis of the syncline. Note the northerly true dips of the west limb (dip slope on the right). The axis and the fault pass through the area of broken rock in the center of the picture.

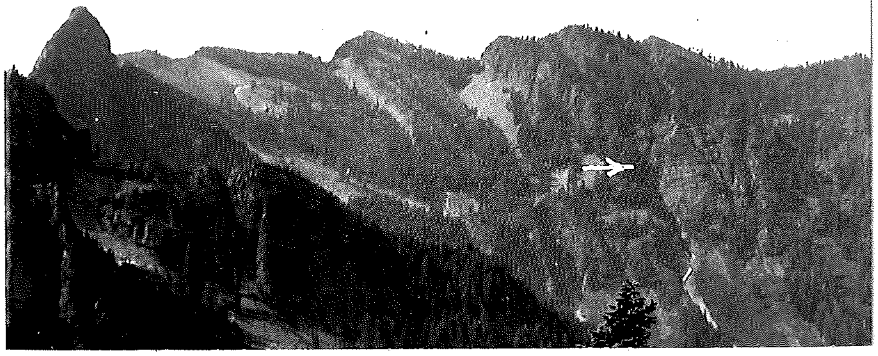

Fig. 54 The axis of the Higgins Mountain syncline, looking northwest from a point about 2000 feet north of the Higgins Lookout. Note the northeasterly dips at (1) on the left, the southwesterly dips at (2) on the right, and the reversal of dips in the center. The reversal of dips is best indicated by lines of vegetation curving across the chute.

IV. SUMMARY

The phyllites and greenschists are part of a single body of low grade metamorphic rocks. They may be correlated with similar rocks in nearby areas.

The phyllites were formed by the low grade isochemical metamorphism of shales and impure arkoses and arkosic siltstones of the eugeosynclinal depositional suite. Later penetrative deformation has considerably affected some of these phyllites to the extent that the original structures have been greatly altered or obliterated. There may have been two periods of such penetrative deformation. In the field, it is often impossible to tell which are the earlier and which are the later structures. Most of the lineations in the phyllites are the result of the intersections of s planes and are not mechanically significant features in the tectonic framework. The only reliable representatives of b lineation are the axes of the small (8 to 12 inches across) folds of s. The phyllites probably are equivalent to the Gold Hill phyllites of Vance and the Goat Mountain phyllites of Misch.

The greenschists were formed by the low grade isochemical metamorphism of intermediate to basic volcanic rocks. The greenschists resisted the later episodes penetrative deformation and their present internal attitudes show essentially the original metamorphic structures. The alignment of elongated minerals shows b lineation. The ordinary greenschists and the blue-amphibole schists are intimately interbedded and are isophysical. There is no separate and distinct glaucophane schist facies in the Higgins Mountain area. The occurrence of blue-amphiboles is controlled by chemical factors which are not fully understood but apparently include the iron content of the parent rock. Contrary to nearby areas, the dominant blue-amphibole of the Higgins Mountain area is glaucophane, rather than crossite. Additional work is needed to determine if the greenschists of the present area may be stratigraphically correlated with the Shuksan greenschists of Misch.

The gneiss in the Stillaguamish Valley North of Fortson is almost certainly a klippe of the Eldorado subdivision of the Skagit gneisses and is correlated with other klippen to the north and south. The hornblende-plagioclase schists may be part of the same tectonic unit as the gneiss, or it may be in place and represent a westerly increase in metamorphic grade.

An unusual variety of gabbro, labradorite porphyry, has apparently intruded the Swauk formation. Other rocks intrusive into the Swauk formation may include dioritic and peridotitic plutonic rocks and andesite, diabase, and labradorite porphyry dikes. Dacite flow rocks are in fault contact with the Swauk formation; their relative ages are unknown. Gabbros, basalts, and andesites have intruded the low grade metamorphic rocks, but their ages relative to the Swauk formation are unknown.

The Swauk-Chuckanut formation consists of continental clastic rocks. The dominant rock type is a fine to medium grained arkose which contains little or no potassium feldspar and no plagioclase more clacic than sodic oligoclase. Diagnostic fossils were not found in the Higgins Mountain area, but evidence in nearby areas indicates latest Cretaceous to Paleocene age.

The pre-Tertiary structures which are contemporaneous with the episode of constructive metamorphism probably are northwest trending subisoclinal folds overturned to the east. In the phyllites, these structures have been distorted by the later epiosdes of superimposed penetrative deformation, but the resulting major structural patterns, is any, have not been discerned. The map pattern suggests, but does not prove, that the greenschists form the core of a synclinorium the flanks of which are occupied by phyllites.

The gneiss is believed to be a klippe of an overthrust of large dimensions having a root near Mt. Eldorado. The gneiss is tentatively correlated with klippen of similar rocks to the north, north of Glacier, and to the south, on Helena Ridge and on Mt. Baring.

Much of the Swauk formationis involved in a northwest trending asymetrical syncline. A fault appears to follow the axial plane of the syncline through Higgins Mountain. The effect of this fault on the attitudes of the beds in the syncline is not known. Jointing and bedding control the slopes on Mt. Higgins and Round Mountain and result in precipitous cliffs. Because the cliff along the south face of Higgins Mountain cuts diagonally across the northwest plunging nose of the syncline, it is suggested that the cliff is tectonically controlled. The Higgins Mountain syncline appears to have been cross-faulted south of Granite Lake, and the pre-Tertiary basement north of the fault has been brought up relative to the Swauk formation on the south side of the fault. The dacite flows are in fault contact with the Swauk formation on Round Mountain Ridge. Extensions of the trends of the last two faults coincide, but it cannot be stated whether they are the same fault. On the northeast face of Round Mountain, faulting has exposed a pre-Tertiary basement of medium grade schists unconformably underlying the Swauk formation.

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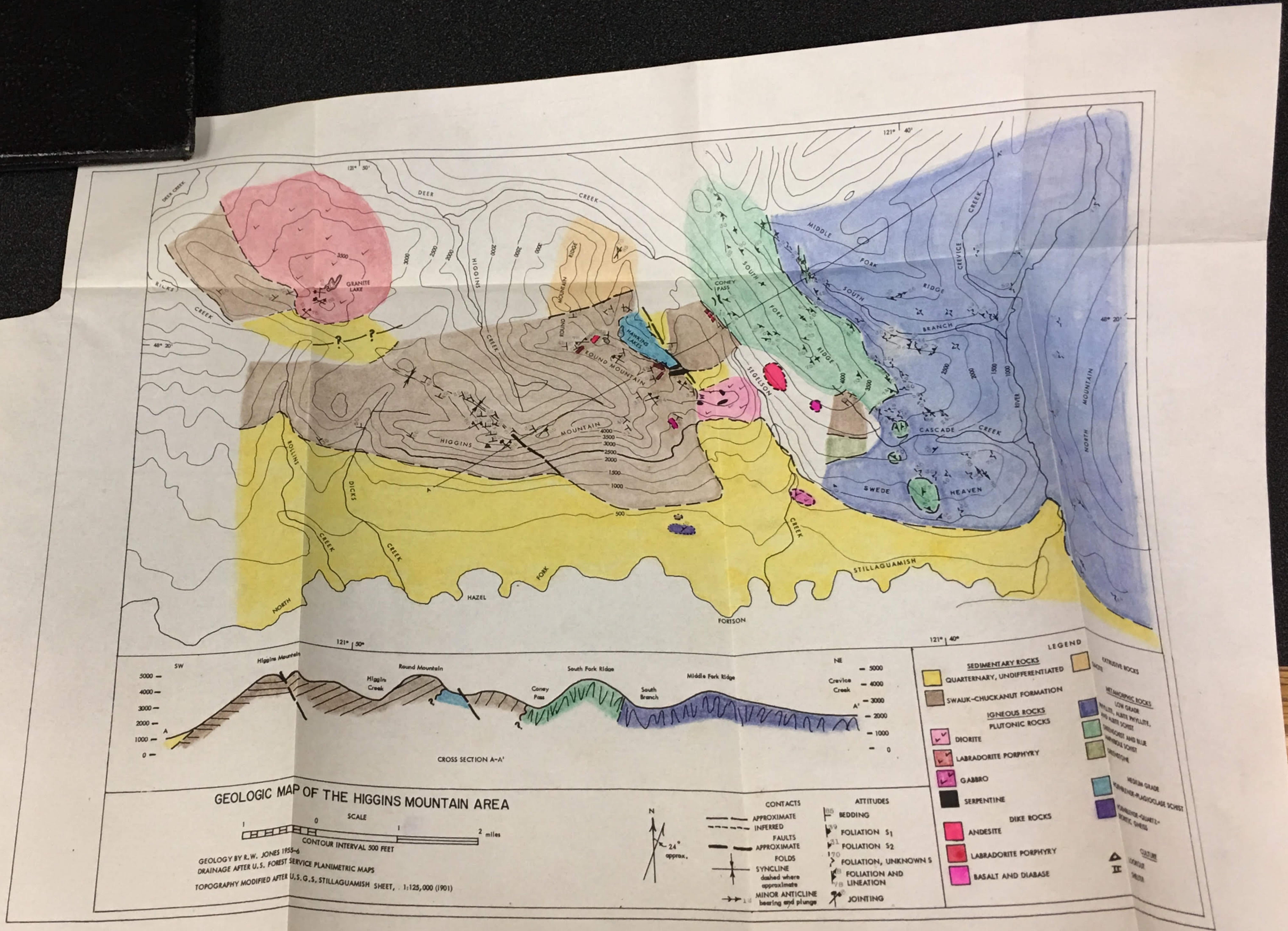

GEOLOGIC MAP OF THE HIGGINS MOUNTAIN AREA

GEOLOGY BY R.W. JONES 1955–6
DRAINAGE AFTER U.S. FOREST SERVICE PLANIMETRIC MAPS
TOPOGRAPHY MODIFIED AFTER U.S.G.S. STILLAGUAMISH SHEET, 1:125,000 (1901)